Lecture Notes in Mobility

Ciaran McNally · Páraic Carroll · Beatriz Martinez-Pastor · Bidisha Ghosh · Marina Efthymiou · Nikolaos Valantasis-Kanellos *Editors*

# Transport Transitions: Advancing Sustainable and Inclusive Mobility

## Proceedings of the 10th TRA Conference, 2024 Dublin, Ireland - Volume 6: Connected Mobility Ecosystems

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# Lecture Notes in Mobility


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Editors

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# Preface

We are pleased to publish the Conference Proceedings of the 10th Transport Research Arena (TRA 2024), held on April 15–18, 2024, in Dublin, Ireland. The conference brought together 4500 delegates from 57 countries who came together to discuss research findings, the latest innovations in policy, technology and practice, and the future directions of mobility and transport.

The conference tagline was *Transport Transitions: Advancing Sustainable and Inclusive Mobility*, and four primary conference themes were defined, namely

- Safe & Inclusive Transport
- Sustainable Mobility of People and Goods
- Efficient & Resilient Systems
- Collaborative Digitalization.

TRA takes place every 2 years, and TRA2024 featured an array of plenary sessions, ministerial sessions, strategic sessions and special sessions which took place alongside the technical program. A call for papers was issued in early 2023 which resulted in 1182 submissions. A double-blind peer review process was initiated, which ultimately resulted in 784 papers that were chosen for presentation at the conference (66% conversion rate). These papers were presented in a combination of oral or poster presentations over the course of the conference.

All accepted papers presented at TRA 2024 are published in a topical collection of the journal European Transport Research Review (ETRR) or within these proceedings. Both are published in a fully open access format.

TRA is a multi-modal conference that draws on the support of key stakeholders. These include the European Commission, ACARE (Advisory Council for Aviation Research and Innovation in Europe), ALICE (Alliance for Logistics Innovation through Collaboration in Europe), CEDR (Conference of European Road Directorates), ECTP (European Construction Technology Platform), ERRAC (European Rail Research Advisory Council), ERTRAC (European Road Transport Research Advisory Council), ETRA (European Transport Research Alliance), and the Waterborne technology platform. Key Irish supporters of the event were Transport Infrastructure Ireland, Enterprise and Ireland and the Irish Government's Department of Transport.

The editors would like to express their thanks to the presenters, authors, reviewers, session chairs, committee members and sponsors for helping deliver such a successful event. TRA 2026 will take place in Budapest, Hungary.

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Beatriz Martinez Pastor
Bidisha Ghosh
Marina Efthymiou
Nikolaos Valantasis Kanellos
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# Digital Transition

# Boosting Public Transport Through Innovative IT Solutions that Match the Needs and Expectations of All Stakeholders

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**Abstract.** Considering the significant growth rate of population in the urban area, public transport has become vital to urban living. It has become unavoidable to promote the culture of using Mobility as a Service (MaaS) among travellers to address climatic challenges, especially the global warming phenomenon. To encourage the use of public transport, It is important to introduce innovative IT solutions to the ecosystem of TSPs (Transport Service Providers) backed by an in-depth impact analysis to meet the expectations and the needs of the TSPs and the travellers. This work introduces an assessment methodology to calculate the "Effectiveness" of the innovative IT solutions for TSPs and travellers through a series of data analysis methods using the Bayesian Network, Regression analysis, and ANOVA tests. The assessment is based on two types of quantitative datasets: operational KPIs (Key Performance Indicators) and USI (User Satisfaction Index) surveys to evaluate how the expectations and needs of travellers with different socio-demographic profiles (by gender, age, income level, and impairments) are met by these IT solutions. This methodology is the foundation for the IP4MaaS Project supported by the Europe's Rail Joint Undertaking. The paper presents the results of applying this methodology to data collected in six sites (Athens, Barcelona, Liberec, Osijek, Padua, and Warsaw). The presented methodology will be helpful to the IT developers and TSPs for assessing their own IT solutions. The findings will help researchers, policymakers, and others in the transport sector to assess public transport services. This assessment methodology is scalable to other demo sites and datasets.

**Keywords:** Public Transport · Needs and expectations · IT solutions · Assessment methodology · Data analysis · MaaS

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## 1 Introduction

Nowadays, transport services, especially public transport services, play a vital role in every European society [1, 2]. Considering the drastic increase in air and noise pollution caused by GHGs (Green House Gases) and their side effects on every environment, investigating and studying traveller's behavior in making decisions and understanding their needs and expectations from one side and the other side, the capabilities and capacities of TSPs( Transport Service Providers) to answer needs as mentioned earlier and expectations, are undeniable facts for transport experts [3, 4].

It is worth mentioning that the number of passengers using public transportation in 2020 and 2021 decreased by 40% to 70% due to COVID-19, the after-effects of which continue to affect the use of public transportation systems to date. With remote working becoming a norm, daily commuting has become less frequent in many countries [5–7]. In 2020, the declining percentage number of passengers resulted in an 11% decrease in transportation service supply compared to 2019, thereby causing heavy financial losses. The drop in fare box revenue was anticipated to be 90 percent. Railways in the European Union lost twenty-four billion euros in revenue for passenger services in 2020, a 41% decrease from 2019 [8]. This paper aims to present a methodological framework to assess quantitatively how innovative technologies can respond to the needs of travellers and Transport Service Providers (TSPs) involved in the digital ecosystem for door-to-door travels in Europe, thereby increasing the attractiveness of public transport. This work uses a methodological approach to evaluate the needs of travellers with different socio-demographic profiles and TSPs (Transport Service Providers) based on rail transport. It considers social trends like reducing Greenhouse Gas (GHG) emissions and road congestion [9, 10]. The concept of the attractiveness of rail and public transport depends on complex psychological factors from a scientific and technical standpoint [11]; The methodology used in this study consolidates the concept of "user profile" and the ability of the system to respond to the needs and expectations of users, including socio-demographic-related factors such as aging, reduced mobility, and other specific conditions [12].

This work introduces an assessment methodology that considers the Effectiveness of IT (Information Technology) solutions, the Adaptability of data to the Satisfying Requirements of both Travelers and Operators, the Equity of IT Deployment in Society, and the Potential Acceptance by the Market and, in particular, by Railway Operators and their Ecosystem [13].

For the purpose of this work, the Travel Companion application has been developed to demonstrate the innovative IT solutions that are further tested and evaluated by the travellers and TSPs at the six demo sites in the IP4MaaS project. One of the key benefits of this methodological framework that distinguishes it in this field is that it provides social equality for all individuals, regardless of sex, gender, ethnicity, age, origin, income, or health, to have equal rights and access to transportation systems. This assessment methodology is part of the methodological framework developed in the first and second phases of the H2020 Shift2Rail project titled IP4MaaS (www.ip4maas.eu), which sets 6 demo sites (Barcelona, Padua, Athens, Liberec, Osijek, and Warsaw) in which this methodology is applied in a second stage [14].

## 2 Methodology

The methodology employed in this study uses the concept of "demonstration scenario"[15]. This methodology bases its innovations on a combination of operational key performance indicators and customer satisfaction surveys [15] [16]. In addition, the methodology attempts to provide a clear list of KPIs and survey questions that consider the requirements and expectations of users with varying profiles, such as the elderly, disabled people, and women, to promote equity for all individuals. These objectives will distinguish the methodology from others in the same field [17, 18]. This assessment outlines the methodology for conducting User Satisfaction Index (USI) questionnaires, which are used to evaluate the satisfaction of users with the IP4 (Innovation Programme 4) solutions, and explains in detail how the effectiveness is calculated for each user profile. The data from USIs and operational KPIs in phase II are an input for the IP4 toolbox [19]. This assessment provides a comprehensive framework for setting the final results and outcomes of the methodological framework to evaluate the IP4MaaS tool in each of the IP4MaaS 6 demonstration sites [19]. Three main inputs fed to the Travel Companion application are [20]:

1. Collected data from USI (User Satisfaction Index) travellers from online surveys;
2. Collected data from USI (User Satisfaction Index) TSPs (Transport Service Providers) from online surveys;
3. Collected data from Operational KPIs (Key Performance Indicators) from CFMs (Call For Members) (Travel Companion /IP4 ecosystem developers).

The assessment alongside the general user profile also considers 4 other specific (sensitive) profiles (the definition of the profile variable "r" is reported):

General profiles (r=1), unemployed people, low-income people, retired people, and students (r=2), disabled or impaired people, people with physical or mental illnesses, people in wheelchairs, people with reduced mobility, people with visual impairment, and hearing impairment (r=3), elderly (r=4) and women (r=5).

The methodology uses the data collected from *Operational KPIs* and *USIs surveys* during the execution of the demo sites.

The following steps illustrate this assessment methodology:

**Step 1: Definition of the User journeys "i".**

A User Journey "i" is a travel solution from an Origin to a Destination in which a traveller may interact with an IP4 innovation offered by one or more Transport Service Providers (TSPs). The assessment is carried out on one or several User Journeys.

**Step 2: Definition of the Demonstration Scenario "JK" (identification of TSPs "k" and functionalities "j") and sensitive profiles ("r").**

A Demonstration scenario (Demo) is the intersection of a new IP4 innovation "j" offered to travellers and a Transport Service Provider "k" that is offering it. On the other hand, the identification of sensitive profiles is done through a conversational survey and sentiment analysis.

**Step 3: Identification of operational KPIs ("KPIs") and benefits provided by functionalities ("j") to these sensitive profiles ("Br").**

Only those operational KPIs that can be measured during the execution of these IP4 functionalities will be considered, and benefits provided by these functionalities to these sensitive profiles will be identified.

For this identification of benefits, Focus Groups, workshops, or other brainstorming data collection methods can be used.

**Step 4: Data collection of operational KPIs and satisfaction regarding benefits through USI surveys.**

If in the case study, the operational KPIs are quantifiable, they should be collected during the execution of each demo site. On the other hand, USI surveys are used to assess the benefits provided by each functionality "j" to each sensitive profile "Br."

**Step 5: Calculation of the Effectiveness and comparisons among TSPs ("k"), Functionalities ("J"), and Profiles ("r").**

If the operational KPIs are measurable, alongside USIs data, they are inserted as input into an "Effectiveness" calculation, which is a metric on how IP4 solutions match the needs and expectations of travellers and TSPs, from the perspective of an aggregated analysis, by taking into account general profiles and specific profiles (low-income people, people with disabilities, elderly, and women) and per each group of travellers in intersectional analysis.

**Step 6: Further data analysis.**

To accurately analyze and assess the performance of the Travel Companion application, an in-depth analysis using AHP, Bayesian network, Regression, and ANOVA test is conducted on the collected data of USI surveys and operational KPIs. This methodological approach can be applied to any other projects that require the assessment and evaluation of IP4 functionalities [19] (Fig. 1).

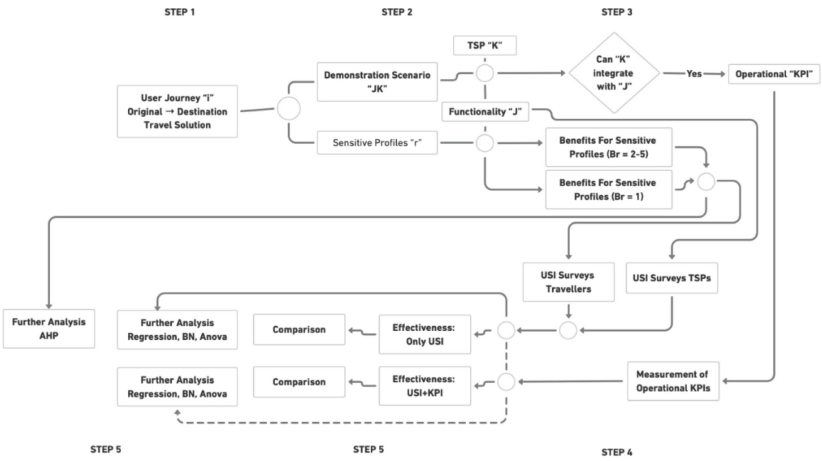



**Fig. 1.** General lighthouse methodology for the assessment of IP4 innovations.

### 2.1 The Concept of Effectiveness

The definition of each variable that is used in the calculation of the Effectiveness is: "r" the type of profile of respondents in this study (already introduced in Sect. 2), "J" the name of innovative technology or functionality, "K" the name of TSP (Transport Service Provider) which is providing that specific functionality and "q" associated question linked to that specific functionality.

The User Satisfaction Index (USI) for travellers belonging to a profile vector "r" with the functionality "j" offered by the TSP "k" is calculated as [21]:

$$USI_{Traveller_{rjk}} = \frac{\sum_{w=1}^{m_{rjk}} \sum_{v=1}^{n_{1jk}+n_{2jk}^{r}} Score\ question_{wv}}{m_{rjk} \cdot \left(n_{1jk} + n_{2jk}^{r}\right) \cdot 5} \tag{1}$$

The satisfaction index for a TSP "k" regarding a functionality "j" is calculated as:

$$USI_{TSP_{jK}} = \frac{\sum_{v=1}^{n_j} Scorequestion_v}{m_{jk} \cdot n_j \cdot 5} \tag{2}$$

All this quantitative data (operational KPIs and USIs) is managed together within the concept of "Effectiveness". The Effectiveness of a functionality "j" offered by a TSP "k" for a specific profile "r" in a demonstration scenario "D" is calculated through the following Equation. To avoid producing several equations for effectiveness per each group identified aforementioned section, a unique formula Eq. (3) has been prepared and it is implemented for all the groups in this study:

$$Effectiveness_{rjk} = \frac{\sum_{n=1}^{N} KPI_{n_{jk}} + USI_{Traveler_{rjk}} + USI_{TSP_{jk}}}{N + \delta_{Traveller} + \delta_{TSP}} \tag{3}$$

Being:

$$\begin{cases} \delta_{Traveller} = 0\ if\ \ USI_{Traveler_{rjk}} = 0 \\ \delta_{Traveller} = 1\ if\ \ USI_{Traveler_{rjk}} \neq 0 \end{cases} \quad \begin{cases} \delta_{TSP} = 0\ if\ \ USI_{TSP_{jk}} = 0 \\ \delta_{TSP}0\ if\ \ USI_{TSP_{jk}} \neq 0 \end{cases}$$

The definition of the variables in Eqs. 1, 2, and 3 may be consulted in "A Methodological Framework Based on a Quantitative Assessment of New Technologies to Boost the Interoperability of Railways Services," [21]. Given that the Effectiveness is dimensionless with a value between 0 and 1, the higher, the better, and different demonstration scenarios "D" can be compared to analyze how the needs of travellers in other locations or demo sites are matched by the same innovative technology "j" offered by different TSPs [21]. The effectiveness comparison can only be done after grouping based on what parameters are considered in the Effectiveness formula: KPIs, USI Travellers, USI TSPs, or combinations among them. All these formulations have been prepared, documented, and calculated in Julia's programming language (V 1.7.0) [22].

### 2.2 Extension of the Methodology

This assessment methodology was extended by applying the next analysis methods:

**AHP analysis**: This analysis is done to define a weighted hierarchy of factors with an influence on two following goals defined for the users of the Travel Companion APP including two parts: 1 - A Hierarchical model, and 2 - A pairwise comparison matrix (filled by the expert panel[1]). The AHP analysis has the following two main goals[2] [22]:

1. For Travellers: To encourage people to use more intermodal solutions on public transport, especially railways, by making it more attractive to users.
2. For TSPs: To encourage TSPs to use the solution Travel Companion (APP)

**Regression Analysis:** The regression analysis is done as a primary step to identify Second-level Benefits[3] highly correlated in a way that the heuristic process followed by the Bayesian Network Analysis (Module 3) already starts from learned networks, achieving better results in less time. The p-value in the two pair variables is less than 0.05 (p-value $< 0.05$), which means there is a high correlation between them.

The output from regression analysis is introduced as a forced connection into the BN analysis so that the correlations established in both processes do not contradict each other [22].

**BN (Bayesian Network) Analysis, Bellman Shortest Path, and Impact Assessment** (prediction simulation): The output of BN analysis from all six demo sites indicates what is the most influent second-level benefits[3] for the acceptance by users of IP4 functionalities offered by TSPs considered in each demo site, taking into consideration the Bayes score and cumulative weights [22–24].

**Impact Assessment Analysis:** The main reason for identifying and analysing correlations among various factors associated with respective demo sites is to carry out an impact assessment of these variables individually through predictive simulations. These simulations give us an insight into assessing the overall impact of an investment made on improving a certain factor at a demo site. The study through these simulations becomes the basis of decision-making [25] at a high level for various stakeholders involved in the project. The methodology has been designed to work with changing and scaling datasets in the future. The design of simulations makes them easily replicable to new demo sites and new factors as they get introduced in the future. A detailed description of the methodology may be found in the journal paper: "A Methodological Framework Based on a Quantitative Assessment of New Technologies to Boost the Interoperability of Railways Services," [21–25].

**ANOVA Test (Analysis of Variance)** for Travellers is applied in this analysis to determine if some socio-demographic profiles (per age, gender, incomes level, residential area, travelling with a dependent person, professional status, disability, familiarity with

[1] The **expert panel** was consisting of TSPs experts in each demo site, two experts from associations in IP4MaasS project (UITP and UNIFE) and two members of Travel Companion /IP4 ecosystem developers (HACON and INDRA).

[2] These goals were in the mind of experts during the building process of the hierarchical model and the process of filling the pairwise comparison matrix.

[3] **Second level benefits** are more detailed factors, clustered inside each of the first level benefits or factors level 1, with an influence on the usage of IP4 functionalities.

technology) show significant differences regarding the satisfaction with second level benefits based on the data gathered through the USI travellers survey[22].

### 2.3 Making the Knowledge Actionable Through an Assessment Toolbox

The performance assessment methodology of this study was made actionable through a Toolbox based on the mathematical data analysis operations explained above. The toolbox presents the results obtained from the mathematical models, in a readable and actionable manner. For instance, presenting data on the most effective features for various profiles, and the most impacted socio-demographic profiles [26]. This Toolbox aims to figure out which benefits of an innovative IT solution are more relevant for the users (TOP 10 benefits) (Modules 1 to 3), which ones show significant differences regarding socio-demographic profiles (Module 4), and which functionalities of an innovative IT solution have the highest Effectiveness based on satisfaction and operational KPIs for all kinds of profiles and specific profiles (Module 5) [27]. This Toolbox was validated in six Demo sites: Athens, Padua, Warsaw, Liberec, Osijek, and Barcelona between March and June 2023. Scripts of all these five modules can be consulted in the Zenodo platform: https://zenodo.org/communities/ip4maas/

## 3 Application to a Use Case: The "Warsaw" Demo Site

The testing and execution of the Travel Companion APP in the Warsaw demo site was done from 15$^{th}$ to 19$^{th}$ May 2023. In total 4 TSPs: ZTM, MZA, TW, and SKM were assessed in this demo site and 208 responses were collected regarding USIs. The results of data analysis for this use case are shown in the following as a sample:

**Results Regarding Module 1-AHP Analysis: For TRAVELLERS**: Time-saving, reliability, and Cost-saving benefits, with the Travel Companion (TC) APP have the highest importance and weights among other criteria or first-level factors. **For TSPs**: Improving customer relationships, general satisfaction, and increased revenues through the TC APP were the most significant criteria.

**Results Regarding Module 2-Regression Analysis:** "Giving easier access to the APP for the elderly" with "Helping travellers to make appropriate journey planning decisions" and "General satisfaction with the Navigation function" with "Time-saving" had the highest correlation (p-value $< 0.5$) in this case study.

**Results Regarding Module 3-Bayesian Network Analysis and Bellman Shortest Path:** Providing safe trips, general satisfaction, and willingness to pay with trip sharing function for all profiles got the highest cumulative weight.

**Results Regarding Module 4-ANOVA Test:** According to the results, the Increase in safety with the Journey planning function for disabled profiles and providing a safe trip from a COVID-19 perspective for elderly profiles with the Journey planning function for the case of professional status and disability showed the most significant differences in ANOVA analysis.

**Results Regarding Module 5-USI Travellers, USI TSPs, and Effectiveness:** it can be concluded that the datasets (profiles, functionality, TSP) achieving the highest satisfaction belong to the Travel arrangement functionality provided by SKM and MZA

for disabled profiles (r3J21K10) and (r3J21K8) respectively for the case of travellers. However, in the case of TSPs, the highest satisfaction belongs to the Asset manager tool provided to MZA (J23K8) with a value equal to 0.61. Considering the values of USI traveller, USI TSPs, and operational KPIs in the Warsaw demo site, and applying Eq. (3), those sets (Profile, Functionality, TSP) with the highest values of the "Effectiveness" **for the case of travellers** belong to the Travel arrangement functionality provided by MZA and SKM for disabled profiles (r3J21K8) and (r3J21K10) respectively. On the other hand, taking into account the values of USI traveller, USI TSPs, and operational KPIs in the Warsaw demo site, the top 10 variables in terms of the concept of Effectiveness **for the case of TSPs**, in terms of Effectiveness, the TC functionalities that are provided to TSPs belong to, the Asset Manager tool provided to MZA with the value equal to 0.80 (J23K8).

## 4 Conclusion and Further Developments

This paper presents a methodical assessment approach to quantify how well specific novel technologies created by the IP4 Shift2Rail programme meet traveller and TSP needs. Two quantitative types of data—operational KPIs and USIs—that enable the calculation of the Effectiveness of a particular innovative technology offered by a TSP to a profile group of travellers were introduced with this goal in mind. These data types allowed for the definition of demonstration scenarios on which the assessment is conducted. An innovative technology's effectiveness is determined by how well it meets the demands and expectations of its users, travellers, and TSPs. Effectiveness is dimensionless and has a value between 0 and 1; the greater the number, the better. Comparisons between demonstration scenarios or TSPs and various traveller profiles are possible for a particular technology. To verify its advantages, move forward with the necessary improvements, and investigate its potential, this study applies quantitative assessment methodology to six demo sites with varied demonstration scenarios defined by the H2020 Shift2Rail IP4MaaS project. Furthermore, by using machine learning techniques such as Bayesian Networks, statistical correlations between operational KPIs and USIs might be identified. An assessment methodology and a 5 Modules Toolbox have been presented in this study to assess the Travel Companion APP/IP4 ecosystem more in general. This methodology and the "5-Modules Toolbox" can be applied to other Software and IT innovations; and can be also applied to the Travel Companion APP/IP4 ecosystem in other demo sites in the future.

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# Train Dispatcher in the Cloud – Digitalising Track Warrant Control for Safe Train Operations in Structurally Transforming Areas

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**Abstract.** To mitigate the adverse effects of climate change, greenhouse gas emissions need to be minimised. The *FlexiDug* project investigates sustainable transport perspectives for structurally transforming areas where coal mining phases out. This work presents a safe, economical, and extendable approach on reusing industrial railways for passenger transport. We have digitalised the *Zugleitbetrieb*, a mode of operation that requires no trackside equipment. Our Train Dispatcher in the Cloud (German *Zugleiter in der Cloud*, henceforth *ZLiC*) has been developed ontology- and model-based. It also takes a railway network model as input, e.g., for the generic interlocking logic. Speech to text, naturallanguage understanding, and text to speech recreate the established speech interface towards conductors. A state machine ensures the prescribed voice procedure. Custom voice-activated recording allows using COTS radio devices. ZLiC has been evaluated successfully in simulations and field tests. We plan further improvements, evaluations, and a risk assessment.

**Keywords:** Structural Transformation · Digitalisation · Train Operations · Control Command and Signalling (CCS) · Model-based · Ontology-based

## 1 Introduction

To reduce the adverse effects of climate change, multiple countries reduce burning of fossil fuels. Coal mining areas in Germany thus face structural transformation. Unused infrastructure need to be removed and former mining areas rehabilitated [2]. For example, open-pit mines are turned into lakes and raise the recreational attractiveness of the areas.

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Funded by the Federal Ministry for Digital and Transport (*Bundesministerium für Digitales und Verkehr*, BMDV), the research project *FlexiDug* investigates transport perspectives for structurally transforming mining areas. Example region is the German part of Lusatia. The structural transformation together with new work models and the proximity to metropolitan areas (e.g., Dresden, Berlin) lead to foreseeable changes in settlement structures. We suggest a climate-friendly take on addressing these changes and look at possibilities to extend rail transport.

In Lusatia coal is hauled by train. Almost 400 km of railway tracks are still in use, additional lines have been closed but partly still exits. FlexiDug explores possibilities for reusing those infrastructures to save and reduce emissions.

However, infrastructures of the mining railways cannot be used for passenger transport without further ado. Special circumstances, such as isolated networks and fixed connections instead of couplings between wagons, have led to technical and operational differences. Technical differences include train detection, train protection, and signalling systems of low density and custom design. Operational differences include low maximum speeds (i.e., 60 km/h) and push-pull trains operated from the end of train. The mining railways do not fulfil the strict regulations for passenger transport and rebuilding to today's standards is costly.

This paper presents an approach on enabling safe, economical, and extendable passenger transport on yet little-used industrial railway infrastructures.

We build on the German *Zugleitbetrieb* [7] (ZLB, comparable to North-American *Track Warrant Control*). In this mode of operation, train movements are controlled by a *Zugleiter* (train dispatcher special to *Zugleitbetrieb*, henceforth *dispatcher* for readability). The dispatcher notes track occupations in a *Belegblatt* (graphical occupation sheet special to *Zugleitbetrieb*, henceforth *occupation sheet* for readability). On each train, operational duties are with a *Zugführer* (train conductor special to *Zugleitbetrieb*, henceforth *conductor* for readability). Conductors and the dispatcher communicate via radio and a prescribed voice procedure. Trackside equipment is optional but can increase performance.

## 2 Approach

We propose the digitalisation of the *Zugleitbetrieb* by introducing the Train Dispatcher in the Cloud (German *Zugleiter in der Cloud*, henceforth *ZLiC*). While ZLiC implements the dispatcher in software, the speech communication for the human conductors remains the same. The digitalisation addresses the shortage of skilled workers in all areas of railway transport and also allows for future scalability. Due to existing experiences among personnel (including approval[1], bodies) and little trackside requirements, we assume economical realisation.

We currently justify safety by the approval of the non-digitalised *Zugleitbetrieb*. In perspective, the introduction of components requires a safety re-analysis.

[1] In this work, *approval*, *authorisation*, *admission*, *certification*, and, in that sense, *assessment* are not distinguished and can thus be used interchangeably.

Given a safe ZLiC, eliminating chances for human error can also increase overall safety.

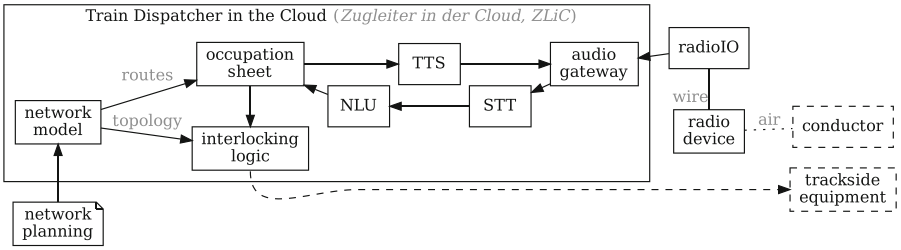



**Fig. 1.** ZLiC central (large box), distributed, input, and related (dashed) components.

Figure 1 depicts the software architecture of the ZLiC. The core of the system are components for an interlocking logic, the voice procedure, speech input, and speech output. A digital rail *network planning* is initially required to derive the internal *network model*. Once created, the network *topology* is extracted to be used by the *interlocking logic*. Extracted *routes* are required by the *state machine* to adapt the generic voice procedure for the particular network. Incoming communication is converted from speech to text (STT) and then interpreted using natural-language understanding (NLU). Outgoing communication is converted from text to speech (TTS). An *audio gateway* implements the interface to the trackside. For communicating with *conductors*, the system interacts with commercial off-the-shelf (COTS) *radio devices* via the *radioIO* component. In contrast to other components, the two radio components might need to be spatially close to the rail network. Depending on the radio technology used and the area to cover, it can be necessary to deploy radio components multiple times.

Our design and implementation have been guided by **ontology-based engineering**. Figure 2 shows excerpted and simplified example models and artefacts. We have first defined ontology models for each concept, such as software components, domain-specific data models, and generic artefact models. Because we utilise the widely used Resource Description Framework (RDF), we are able to reuse models, e.g., for state machines [11]. Using these concepts, we modelled the system itself, e.g., the voice procedure, occupation sheet, and final artefacts.

The component model and the modelled *Zugleitbetrieb* were discussed and revised with domain experts. Because the component model also describes the data flow, we are able to add the component interfaces and a connecting middleware programmatically. We also define domain-specific data models, e.g., for railway vocabulary and infrastructure models. The infrastructure model refers to digital network planning documents, e.g., PlanPro [10], which contain information about a specific railway network. Data models can contain supplementary data, such as hypothetical train routes and hypothetical train stations.

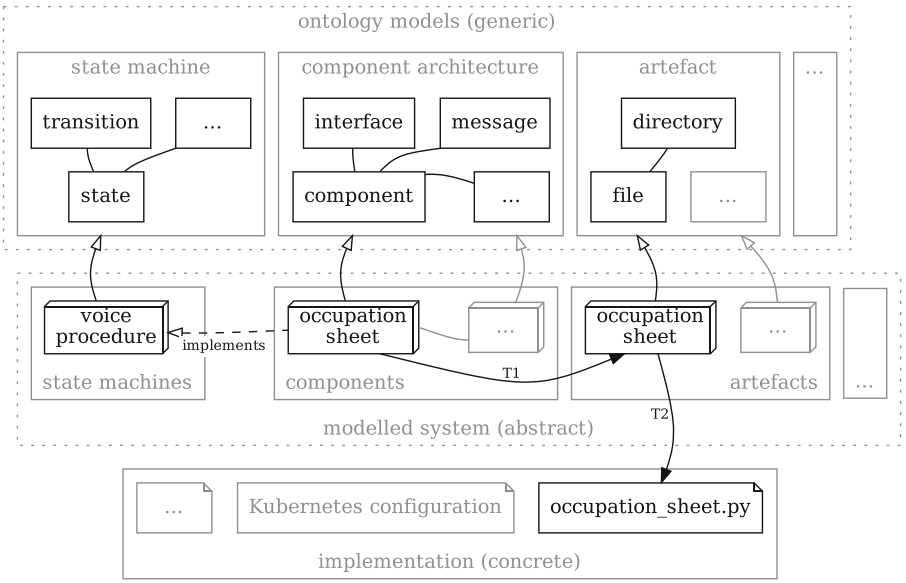



**Fig. 2.** Exemplified and simplified path from the modelled system to the implementation. All models relate to the ontology. `T*` represent some implemented transformations.

Artefacts, such as source code, are generated in two steps. First, we implemented transformations that create artefact models from the modelled system. Second, further transformations create the artefacts from the artefact models. The second step also uses information from the overall modelled system, e.g., from the component model for Docker and Kubernetes configurations.

The indirections in the modelling, generation, and implementation can only be briefly outlined here. The thereby achieved modularity allows modifying concepts (e.g., domain-specific semantics), models (e.g., processes), their interaction (e.g., communication patterns), inputs (e.g., infrastructure models), and artefacts. For example, implementations currently relying on Python could be replaced with SPARK [6], an Ada subset for safety-critical programming, prior to approval.

## 3 Implementation

From the conductors' spoken language, intentions are recognised and converted to parameterised events using STT and NLU. For STT we use OpenAI Whisper off-the-shelf which performs well in our scenarios. For NLU we use Rasa, which needs to be trained per network using a small text model. TTS is done with SVOX via Pico. We use EclipseDDS as middleware. For auditability and customisability, the chosen third-party components and ZLiC itself [1] are open-source. For, e.g., availability, ZLiC works without an Internet connection.

The voice procedure of the *Zugleitbetrieb* is used to define the state machine that interacts with the interlocking logic and the occupation sheet. As Sect. 2 describes, we use the state machine's model for its transformation to source code.

We have designed central components to be able run on both, Infrastructure as a Service (IaaS) platforms and COTS computers. Compared to specialised hardware, this reduces costs and eases procurement. The design decisions made, however, require external mechanisms for dependability. Especially IaaS platforms usually offer fault tolerance mechanisms. Since we consider the component model during artefact generation, redundancy structures can be derived systematically.

Our implementation currently allows trackside equipment to be mocked (e.g., for development), simulated (e.g., for evaluations), or compatible to *EULYNX* [3] and the Rail Safe Transport Application network protocol (RaSTA) [8].

For interfacing between the ZLiC's audio gateway and COTS radio devices, we implemented the program *radioIO*. Because no suited framework could be identified, we have implemented custom digital signal processing (DSP).

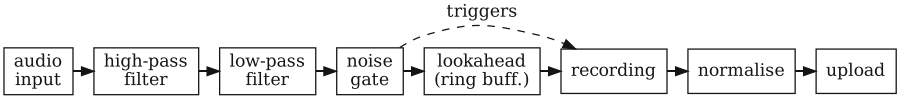



**Fig. 3.** Processing chain for automatically forwarding audio from the radio to the ZLiC.

Figure 3 shows the audio input processing we implemented. After a band-pass filter removed frequencies irrelevant for voice, a peak-tracking gate triggers the recording based on a threshold. A ring buffer between the gate and the recording implements a lookahead, so the beginning of the speech is captured completely. After no detected voice for the duration of the gate's hold time, the recording is stopped, normalised, and sent to the audio gateway (WebSocket). Audio received from the gateway is normalised and a remotely inaudible audio signal is prepended to trigger the voice-operated transmission feature (VOX) of radio devices.

Our DSP design requires analogue audio wiring only. Because no control connections etc. are needed, virtually any COTS radio device can be used.

For execution efficiency, our implementation of *radioIO* pre-allocates required memory and processes data zero-copy as far as possible. We chose the Nim programming language, which proved to be a well-working compromise between development efficiency, effortless interfacing with C libraries, runtime efficiency, and predictable timing due to deterministic memory management.

## 4 Evaluation

Our evaluations examine the feasibility of our proof of concept. In a next step, the feedback gathered from practitioners can be included in a also more formalised implementation. Both would support potential approval activities.

The evaluation is done in several tiers, each adding complexity. As the first tier, we realised simulations (e.g., [5,9]) and discussed them with railway experts. The verdict has been, that our approach is generally feasible but needs to be more specific to match with regulations. We implemented changes accordingly. As the second tier, we tested a first prototype with real trains as part of a demonstration in the Ore Mountains. Here, we focused on occupation tracking (monitored via the occupation sheet), speech communication in a field environment, and varying qualities of the radio signal. The third tier will be the deployment of the ZLiC on a model railway. Following the idea of *serious gaming* [4], we will then ask railway personnel to perform realistic railway operations using our system. We hope to obtain detailed feedback on the overall experience to identify room for improvement, such as fallback scenarios. The last tier will demonstrate the revised ZLiC implementation in Lusatia with real trains (but no passengers).

## 5 Conclusion

Due to the challenges related to climate change, there is a demand to increase rail transport. In Germany, nonetheless, there are hardly any solutions that allow for an economical reuse and operation of industrial railway infrastructures for passenger transport. Compared to the requirements for main lines, the presented concept *ZLiC* requires minimal trackside infrastructure and human resources. Additionally, the system can be upgraded gradually for increased reach and performance. The concept of ZLiC cannot be applied to routes that are part of the European corridor as defined in the Technical Specifications for Interoperability (TSIs). However, this is unlikely to be a relevant issue in rural areas.

New approaches in the railway sector only have prospects for approval if they consider regulations from the beginning on. The focus on model support and automation not only supports development efficiency but also the approval process, as it embodies structured design and well-defined processes. Small-scale projects like ZLiC can be helpful prototypes to familiarise approval bodies with concepts new to the domain. Such projects also help to gather feedback and experiences with the general approach of interweaving computer science and other domain-specific practices and cultures. With FlexiDug and ZLiC, we demonstrate that interdisciplinary research can bridge gaps and solve problems efficiently.

Besides technical improvements and more evaluations, future work includes a risk assessment to derive safety and functional requirements. As necessary for approval, the results can then guide a compliant re-engineering of ZLiC.

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# The Missing Piece to the Puzzle: Advancing Train Planning for a Digital Great British Railway

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**Abstract.** Along with much of Europe and the global trend towards in-cab signalling, Great Britain (GB) rail is transitioning to Radio-based European Train Control System (ETCS). In collaboration with several universities and research partners, Network Rail have undertaken a programme of R&D to build on the opportunities that Radio-based ETCS offers, including the move towards automatic train operation (ATO), and integrated, centralised traffic management systems that maximise the potential in capacity, performance and energy efficiency for passenger and freight customers. Bringing the train planning and timetabling capabilities into the modernised, data driven, information rich world is a significant puzzle piece of turning opportunities offered by the signalling and control technologies into the day-to-day operations of the railway. This paper covers the research carried out into the characteristics of a radio-based ETCS railway that can be analysed for a goal-based state of the art train planning capability. It considers the advancement of tools, techniques, processes and skills that are required to plan, operate and regulate the railway through automatic train operations and future traffic management systems, ultimately harmonising planning, real-time operations and post-operations performance analysis.

**Keywords:** Train planning · traffic management · ETCS · timetabling · energy efficiency · railway operations

## 1 Introduction

Train planning for GB rail is designed around the existing lineside multi-aspect signalling systems and is delivered by processes that originated prior to privatisation of the railways in the 1990s.

The GB rail industry, alongside many other global railways, is migrating to radio-based European Train Control System (ETCS) to increase capacity, reduce delays,

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enhance safety and drive down cost, thereby transforming the rail network for passengers, business and freight operators. ETCS is a key enabler for automatic train operations (ATO) and integrated, centralised traffic management systems (TMS). Together, these are referred to as Future Command, Control and Signalling (FCCS) systems [3].

Achieving the full potential of ETCS necessitates the upgrade of train planning and timetabling to take advantage of ETCS capabilities. ETCS improves precision and allows planners to remove some buffer and extra running time that conventional processes require, which can allow more train services to be planned or allow better access for maintenance activities. Generating information-rich, precise, accurate and validated timetables will support better regulation decisions and performance through TMS.

Network Rail (NR), in collaboration with several universities and research partners, has specifically investigated:

"How must we modernise train planning to unlock the full benefits of FCCS?"

Drawing on experience from academia, international practitioners and GB practitioners, the project has resulted in a roadmap containing a comprehensive set of 21 recommendations leading to 7 tangible project outputs to meet the train planning development needed to unlock FCCS benefits. Table 1 provides a high-level view.

**Table 1.** Timetabling development needed to meet FCCS expected benefits.

| FCCS benefits | Timetabling development needed |
|---|---|
| In-cab signalling (no lineside signals) means: | |
| • Higher speed limits permitted<br>• Block section layout optimisation | Use the best block layout for the intended rolling stock and service pattern |
| Supervision characteristics of ETCS mean: | |
| • Trains can pass closer at junctions<br>• Flexible use of track<br>• Overtaking is more feasible, assisted by trains running closer together | Allocate buffer time and extra running time where needed, squeeze trains together where possible<br>Case specific calculations for every train<br>Use the flexible working opportunity |
| Automated operational control means: | |
| • ATO precisely controls train's trajectory<br>• TMS could optimally resolve conflicts | Give the right type and quality of information to the control systems, drivers and operators |

The project has shown that the benefits of FCCS will be limited if the relationship between the timetable and FCCS scheme is not considered, and conventional timetabling methods applied. Installing digital technologies alone will not transform the railway – the whole through-lifecycle process must be updated, supported by appropriate data, tools and upskilled people.

## 2 Methods

This paper provides an overview of a large-scale research project. Whilst it is not possible to present all findings here, Fig. 1 (overleaf) details the key project stages and mechanisms for gathering evidence. Each box represents an activity that has been completed. Timetabling Requirements were developed through the activities on the left, including a review of state of the art in the timetabling domain [1]. These requirements formed the basis of the timetabling roadmap described in this paper, supported by an additional desktop review of blocking time methods and interviews with expert practitioners on the GB state of train planning for FCCS. The project will conclude with a demonstration of various timetabling tools to assess the maturity of the market against the timetabling requirements.

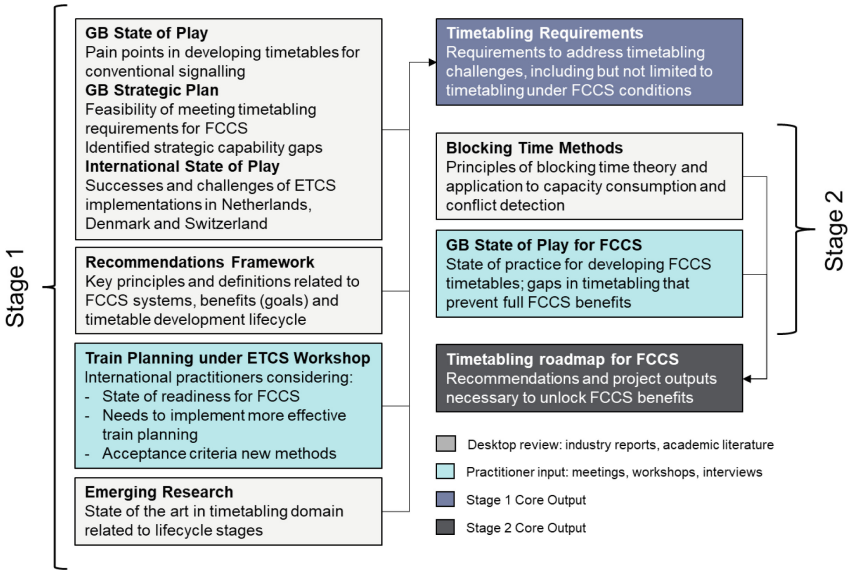



**Fig. 1.** Summary of Timetabling Project

## 3 Overarching Principles

To answer the question of how to modernise train planning to unlock the full benefits of FCCS, it is crucial to define what is meant by 'FCCS systems', 'benefits', and 'train planning', and how they should relate to each other. Development of the definitions resulted in three overarching principles necessary to realise advanced train planning and timetabling. These principles are the foundation of the project outputs (Fig. 4).

**Principle 1**: a timetable is tailored for its operational environment.

To create an improved timetable for FCCS systems, timetable planning tools must be adapted to incorporate ETCS specific characteristics and be sufficiently representative of the operational conditions. FCCS systems consist of:

- Baseline environment: the ETCS specifications (for GB Level 2 and Hybrid train detection)
- Operation automation and optimisation: ATO, including Driver Advisory Systems (DASs) for lower grades of automation, and Traffic Management Systems (TMS)

**Principle 2**: timetables developed for an FCCS renewal are optimised towards specific, measurable goals (Fig. 2).

To fully realise the benefits from the timetable of an FCCS renewal, it is essential to set goals at the outset for what the renewal is to achieve and assess performance against these goals throughout the timetable development lifecycle. A fundamental goal for all timetables is feasibility; others may target improved capability and differ depending on the needs of the part of the network. An updated timetabling process for FCCS could also improve flexibility and reduce risk.

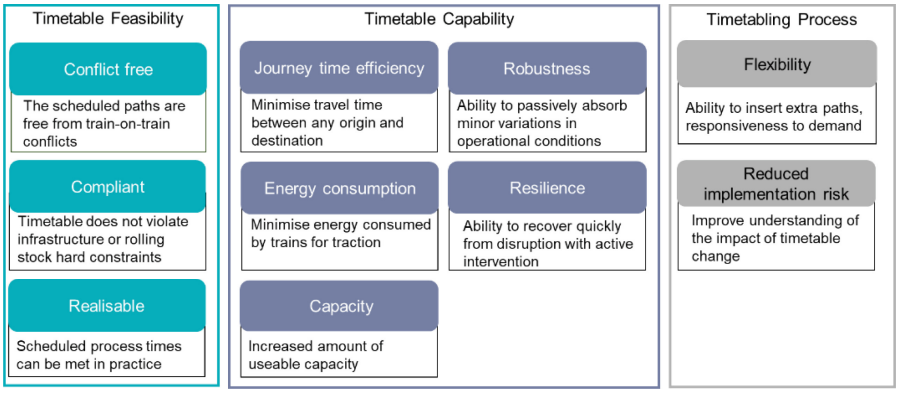



**Fig. 2.** Timetabling goals, their definitions and categorisations

**Principle 3**: the interaction between timetable and achievable performance is considered through the full lifecycle of an FCCS scheme renewal.

'Train planning' covers the whole process from the development of schemes through timetable production into operation of the timetable. Figure 3 shows the consecutive **timetable development lifecycle** stages. Goals are set at the scheme redesign phase. The design and optimisation stages are iterative with performance assessed against the goals. There are mechanisms for feedback and adjustment through the lifecycle, taking in data from real operations. Following through these stages completes the proposed high-level process for developing a timetable optimised for operation under FCCS.

## 4 Project Outputs

The enablers to effectively measure and improve realisation of the timetabling goals are shown in (Fig. 4). The roadmap [4] developed in this project gives further detail on how to procure, develop or use an output. Figure 5 summarises some detailed recommendations related to the train planning development needed, as first described in Table 1.

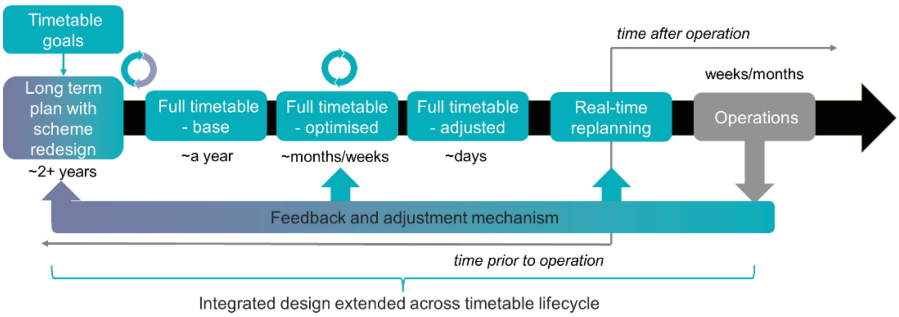



**Fig. 3.** Future Timetabling lifecycle

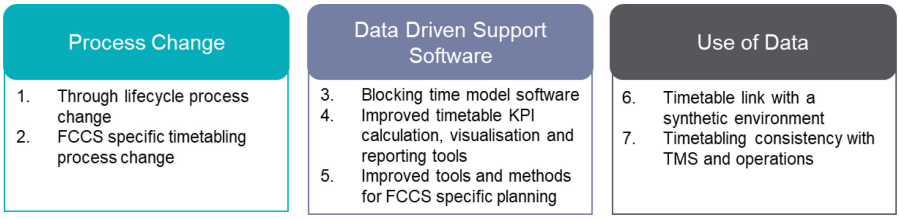



**Fig. 4.** Outputs from the project recommendations

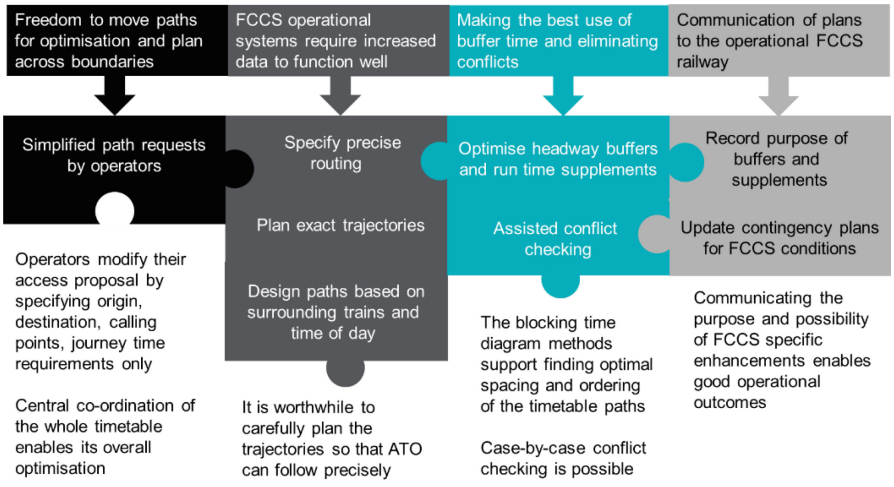



**Fig. 5.** Making effective use of FCCS data for train planning

In this paper we have highlighted three key areas from our work which are critical to achieving effective timetabling for F-CCS systems:

*1. Evaluate Timetable Options or Precursors at Key Lifecycle Stages Against the Timetable Feasibility and Capability Goals Using Generic Tools.*

To implement the principles of goal setting and consistent evaluation throughout the lifecycle of the timetable requires advancements in timetable KPI calculation, visualisation, and reporting tools, as well as a mindset of targeted evaluation and improvement.

*2. Procure a Tool to Automatically Generate Blocking Time Diagrams for a) Quantitative Capacity Evaluations and B) Conflict Identification.*

A tool to automatically generate blocking time diagrams [2] can increase understanding of capacity consumption, identifying bottlenecks at node, corridor, and network levels for planning improvements. Network capacity assessments should be given more focus, as they can incorporate all interactions in a timetable. FCCS systems can increase the availability and accuracy of infrastructure data, making capacity assessment more valuable for infrastructure managers. Proposing the most attractive and beneficial infrastructure projects based on capacity assessment is particularly valuable to infrastructure managers in using funds effectively.

*3. Provide a Single, Centrally Accessible Environment to All Stakeholder that Hosts the Timetable, Its Targets, Data, Models, and Decision Support Tools Throughout the Lifecycle.*

Design and validation processes for FCCS renewals should be supported by an integrated data driven design environment that improves the efficiency of each process step enabling iteration and optimisation. Integrating timetable development through the process will all up-to-date assessments of the expected and actual performance. NR envisage this will be done through the Synthetic Environment.

## 5 Conclusion

FCCS benefits including better performance, more train paths and energy efficiency will be reduced if the relationship between timetabling and scheme development are not considered. Current research is evaluating the capabilities of available software to meet the requirements, with the ambition of trialling and transitioning to new tools and ways of working.

Working with stakeholders involved in the design and operation of the renewed railway, NR are now taking the roadmap forward towards implementation. A successful transition to FCCS systems depends on fit-for-purpose train planning. When scheme and timetable are iteratively designed and improved together, more trains per hour can be scheduled and better performance will be safely unlocked.

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# A Real Time Decision-Support Tool for Traffic Management

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**Abstract.** SNCF Voyageurs/TGV-Intercités operates over 800 high-speed trains (TGVs) per day in France. The system can be highly tense during peaks with up to 13 trains per hour on the same track section. Thus, minor delays can affect operations, especially for long-distance trains. Supervision of the system and real-time rescheduling are difficult tasks given the complexity of the rail network and the cohabitation of different train services.

In this work, we present a real-time decision-support tool providing estimations on the arrival time of trains at each station and at destination and helping comparisons between rescheduling choices.

The estimations of future delays have a focus on explainability, with information on the causes of the delay and on the possibility to recover the delay. The operators can use the tool to test different rescheduling choices and see the impact of each scenario on the traffic, helping them deciding the actions to take to minimize delays. The predictions of arrival times of trains are based on a macroscopic discrete event simulator, coupling the theoretical timetabling with real-time information on the trains' positions.

Arrival times are displayed on the interface of the developed web application, where the user can interact with the simulation by adding information and comparing different disruption management scenarios.

The tool has been tested with success in an operational environment. The operators gave positive feedback on the tool, underlying its capacity to give them more insight on the expected delay evaluations and on potential conflicts. The information displayed was judged relevant and reliable. This is confirmed by our analysis of the quality of the simulation.

## 1 Introduction

Within SNCF Voyageurs, the main French passenger rail company, TGV-Intercités operates every day 800 long-distance trains in France and Europe under the brands TGV Inoui and OuiGo. Five operation centers assure the supervision of trains and staff. The operators take actions in case of disruptions on the train lines in order to minimize delay propagation, ensure the resource management, inform the passengers and organize their take-over if their journey is disrupted.

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Operators can take several actions to reduce the consequences of a perturbation: cancelling a train, changing its path to an alternative route, changing the scheduled order at a junction, changing a scheduled coupling. These actions are taken with specific goals in mind in terms of minimizing passengers delays and maximizing the efficiency of resource management.

When a disruption occurs, operators have a high cognitive load and must take complex decisions in a short time. Today, they lack the tools to predict the future train circulation and plan the operations, which would help them in the decision-making process.

In this paper, we present a decision-support tool, named Allié Supervision, which is based on a railway simulator and aims at giving the operator support in the supervision and the decision-making process.

The paper is organized as follows: Sect. 2 presents a brief state of the art of railway simulators for real-time applications; Sect. 3 describes the main features of the decision-help application that we propose to the operators; Sect. 4 details the experimentation we conducted in an operational center, where the tool was given to operators for real-life tests, and Sect. 5 provides conclusions and perspectives.

## 2 State of the Art

Many railway simulators exist in literature, both commercial or open source. An extensive review of railway simulators can be found in [3].

Microscopic models, like OpenTrack [1] or Denfert [2], propose a detailed modelling of the infrastructure and of the trains circulations. These models provide accurate simulations, on condition that all the necessary parameters are available with sufficient precision. The accuracy comes at the cost of higher computations times, which makes these kind of simulator unsuitable for a real-time application, like the one we are presenting in this paper.

In comparison, macroscopic simulators offer faster computation times, at the expenses of a loss in certain details of the infrastructure or of the train path. An example of such simulators is Prism [6], which provides a Monte-Carlo approach, and [5], which provide an accurate comparison between a macroscopic and a microscopic approach.

Machine-learning based models also exist, such as Transformers [4] which uses the homonyms deep-learning architecture.

Our approach is novel in which it provides a focus on real-time applications in case of disruptions, giving the operators the ability to interact with the simulator and compare different operation scenarios. It also focuses on the explainability of the forecasts.

## 3 Allié Supervision

### 3.1 Simulation Model

The main feature of Allié Supervision is its use of a deterministic, macroscopic discrete-event railway simulator to forecast current delays and actions injected

by the users. We used a simulator developed internally, whose main advantages are as follows:

- its convenience when deploying on new perimeters
- its mechanism to monitor the causality between delays,
- its modular design in regards to simulation rules.

In Allié Supervision, the simulation rules include headway constraints, delay catch-up on running and stopping times, and a heuristic to schedule delayed trains at junctions and on station departure. These rules are mostly parameterized and are calibrated ahead of time in order to maximize the forecasting accuracy of the simulation. These rules can either prepone or postpone the planned time of events, reducing or increasing simulated delay respectively.

In our model, the simulated events are departures, passings and arrivals of all simulated trains. In order to reduce computation times, these simulated trains are usually a subset of all the trains running daily in France. This subset is parameterized to include most trains running in the geographical area of interest.

At each run of the simulation, the first simulated event of each train is the one matching its latest observation. Trains that have not yet departed or been observed are initialized at their originating station and are supposed to leave on time. For all these trains, all successive events are simulated. Hence, in a real-time context, we simulate all events that will occur between the current time and the end of the operating day.

From the simulation are retrieved simulated times for each event and the causes of variation delay between consecutive events.

### 3.2 Developed Solution

A tailored application has been developed to present the simulation results to the operators, and to allow them to interact with the simulation in a simple way. The ergonomics of the application are crucial in a real-time context, where the cognitive load of operators is high and increases in case of disruptions.

The software architecture is presented in Fig. 1. The entry data are the theoretical timetable and the real-time positions of trains. A new simulation is launched every time a train position update is received. The simulation outputs are used to present to the operator with relevant information on the traffic:

- Global KPIs on the number and types of delayed trains for different time ranges are shown to give the operator an overview of the current and forecast system status
- A detailed view of each train circulation presents the estimated arrival times at each stop and includes explanation on the causes of variation of the delays: for example, the delay of a train could be reduced by using the running time supplement, or could increase as a consequence of other trains circulations (scheduling at junctions, spacing)

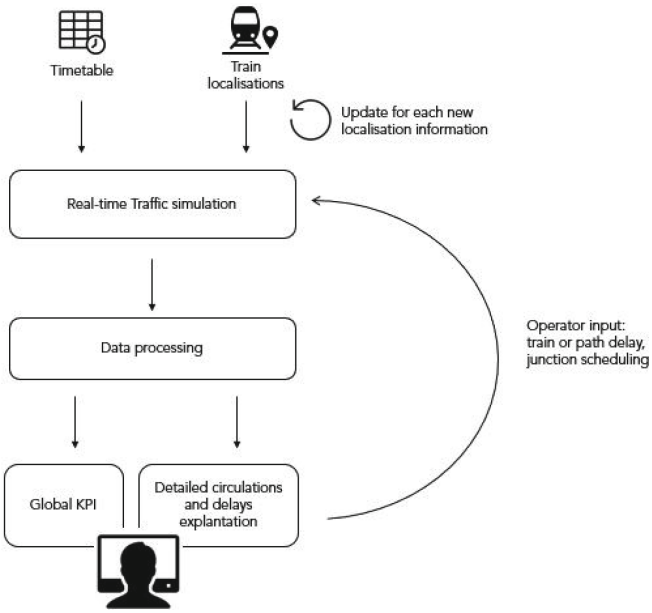



**Fig. 1.** Software architecture

The operator can interact with the simulation by adding information on a future disruption, such as a delay on a train or on a train path or the rescheduling at a junction. The simulator will integrate this new information and allow the operator to see the consequences on the circulations and to compare different scenarios. A notification function is also available to alert operators when needed, thus minimizing additional cognitive charge.

## 4 Experiment Phases

### 4.1 Experiment Perimeter

Experiments have been recently conducted with the COS Sud-Est, the operating center monitoring TGV operations in the south-eastern part of France. The simulation perimeter includes other high-speed trains running in that region (Ouigo, Trenitalia), intercity trains, regional trains and freight trains. These trains add up to about 2500 trains daily, among which about 270 are supervised at the COS.

### 4.2 Simulation Performance

Figure 2 presents the distribution of running times for the simulator depending on different time-ranges across the day. It can be seen that computation times

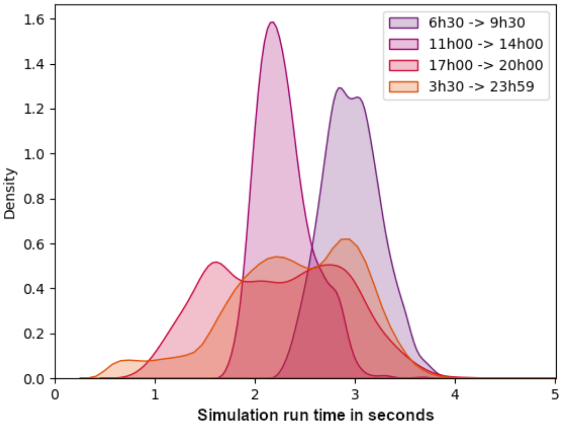



**Fig. 2.** Computation times of Allié Supervision on the COS SE perimeter by specific hour ranges

are in the order of a second. They decrease throughout the day because we do not simulate events preceding the latest observation for each train.

Ahead of user experiments, we also measured the accuracy of our simulations to propagate delay hypotheses injected by the users. We used one week of past observation and timetables to extract past incidents to base our simulations on. We extracted from this dataset occurrences of delay increases higher than 5 min, that we interpreted as primary delays. Each of these delays was injected in the simulation after which were retrieved simulated arrival times at all the following stops of the impacted train. From 400 primary delays collected, we obtained a set of 1000 simulated arrivals.

We compared our predictions to "translation", a dummy predictor that predicts that the delay of a given train to its future stop will be its current delay. The metrics that are used are

- MAE: mean absolute error
- Fiability: rate of predictions whose errors are below 5 min (indicator used in operations to evaluate passenger information accuracy)

Table 1 presents an evaluation of the predictions of our simulator to this set of primary delays. The fiability of TGV operators falls between 60% and 65%. However, the actual score cannot be directly compared to our results since they were obtained on a different time period, but we expect Allié Supervision to improve it.

### 4.3 Results

Six weeks of experiments took place at the COS Sud-Est to evaluate the relevance of our solution and retrieve user insights from the operators. The users appreciated our solution in addition to their current environment, noting that

**Table 1.** Prediction accuracy of our simulation compared to "constant prediction"

| Metric | Our simulation | Translation |
|---|---|---|
| MAE | 324″ | 461″ |
| Fiabilité | 71,3% | 57,3% |

Allié Supervision helped them to better anticipate delays propagation and future potential conflicts. Longer experiments would be required to measure how much our solution improves the operators' performance.

The possibility to inject information in the simulation was less tested by the operators, but was found helpful to sharpen the delay estimations in specific situations, for instance when maintaining connections with delayed trains.

Initially developed as an aid to passenger information, the tool revealed other uses when put in the hands of the operators. Usually, when a delayed train is bound to attach a train on time, the operators can cancel the attach operation to save the train on time. However, on such an occasion, Allie Supervision predicted that a train with 20 min of delay could reduce it to 10 by the coupling station. The coupling was maintained and the two trains arrived on time, allowing a better use of resources and hence a financial gain.

## 5 Conclusion and Perspectives

In this paper, we presented a novel solution for monitoring railway traffic based on real-time macroscopic simulation. Our proof of concept was tested in TGV operating centers and validated by our users.

Our interpretation of simulation outputs as explained delay forecasts yielded good accuracy, better than the simplistic rule currently used, and facilitated the acceptation of the predictions by the users.

The functionality to inject hypotheses to the simulation was positively perceived by the users but noted that the UX could be improved. We also plan to integrate and test new types of hypotheses, such as rerouting and train scheduling on double-way tracks.

Future perspectives are to include the simulator in a simulation-based optimization framework to add recommendation functions to our tool, and explore stochastic simulation to strengthen its delay estimations.

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# Motorway Traffic Flow Optimization: From Theory to Practice

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**Abstract.** Variable speed limits (VSL) are currently being introduced on Ireland's M50 motorway on a phased basis. To manage general everyday congestion associated with peak-period traffic, proactive speed management plans have been developed to allow control room operators to initiate speed reductions to optimize traffic flows and reduce the impact of traffic flow breakdown. The national roads authority in Ireland, Transport Infrastructure Ireland (TII), collects significant levels of data from the M50, and this paper outlines how the application of traffic-flow theory to the measured data has been used to identify when certain sections of the road are approaching capacity. This has enabled the provision of real-time data-driven alerts to control room operators, to identify when proactive speed management plans should be initiated. The measured data is then used to assess the effectiveness of the VSL plans, and it is shown that improvements in throughput are being achieved, along with a reduction in congestion and shockwave behavior. The findings of this study will ultimately inform the automation of proactive speed management plans on the M50.

**Keywords:** Motorway Operations · Traffic Flow Theory · Flow Optimization · Variable Speed Limits · Data-Driven · Congestion Management

## 1 Introduction

As part of Transport Infrastructure Ireland's (TII's) enhancing Motorway Operation Services (eMOS) programme, variable speed limits (VSL) and lane control signaling (LCS) functionality are being introduced on the M50 motorway in Dublin. The M50 is Ireland's busiest motorway, with over 180,000 vehicles recorded on the busiest day in 2022 at the most heavily trafficked section [1]. The eMOS programme has been ongoing since 2017 and in addition to the introduction of VSL; a new state of the art Motorway Operations Control Centre has been constructed; and a new Network Intelligence and Management System (NIMS) has been introduced. NIMS provides control room operators with an integrated system to enhance operational capabilities and to allow VSL to be displayed to drivers using the newly installed overhead digital display panels [2]. The introduction of VSL has been rolled-out on a phased basis, both in terms of geographical extent and in complexity of the operational response. Reduced speeds and warning messages are displayed to assist with incident management and also to proactively manage general congestion in the morning and evening peak periods.

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In the coming months, proactive speed management plans will be displayed automatically by the system, in response to real-time traffic data. However, at the time of writing, these plans are manually set by control room operators to manage morning and evening peak-period traffic. TII's extensive ITS equipment on the M50 motorway allows a comprehensive understanding of the traffic behavior to be gained. Through detailed data analytics and the application of traffic-flow theory, data-driven triggers have been developed, and incorporated into NIMS, to identify when certain sections of the road are approaching capacity. The triggers alert operators of traffic conditions which are approaching traffic flow breakdown, allowing them to implement appropriate response strategies before the congestion materializes. This paper outlines how the data has been utilized to develop guidance for operators, and also to assess the effectiveness of the response strategies, which will ultimately inform the processes of automating the implementation of proactive speed management plans.

## 2 Developing Motorway Traffic Flow Optimization Responses

### 2.1 Overview of Measured Data Sources

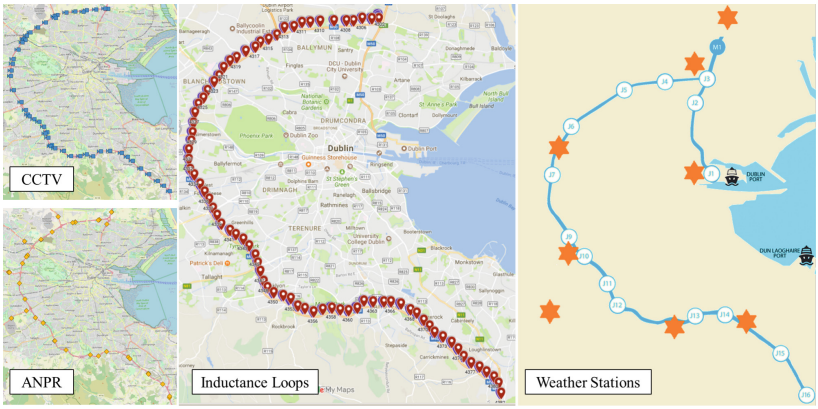



**Fig. 1.** Examples of some of the data sources recorded on the M50 motorway. Image produced using Microsoft PowerPoint [3] (background maps from OpenStreetMap [4], an open map database).

TII collects significant quantities of data which can be used to understand traffic patterns and driver behavior on the M50 motorway. Figure 1 provides an overview of some of the ITS equipment measuring data on the M50. This data includes speed, flow, occupancy, headway, and vehicle lengths recorded every 20 s from inductance loops located at 500m intervals along the full 40 km length of the motorway. In addition to this, there are a number of weather stations recording real-time weather information related to the road conditions. Camera technologies provide both CCTV and Automatic Number Plate Recognition (ANPR) capabilities covering the whole length of the M50 and provide detailed information on traffic conditions and journey times. Detailed logs

of the displayed speed limits are also recorded along with details of incidents on the motorway, or any ongoing or planned roadworks.

### 2.2 Identification of Congestion Seed Points

In order to develop appropriate response strategies to mitigate the effects of congestion caused by general traffic flow breakdown, it is important to understand the locations at which the congestion typically initiates [5]. A software tool was developed to allow the loop data to be processed and plotted on a time-space heatmap. This visual representation of traffic data allowed congestion patterns on individual days to be examined, and also allowed other influences such as incidents, or adverse weather conditions to be overlaid to identify external causes of congestion. Figure 2 illustrates how the heatmaps can be used to visually identify the typical congestion seed points (Fig. 2(a)), and the congestion associated with incidents (Fig. 2(b)). Days where congestion is caused by incidents or extreme weather can then be separated from days where general congestion occurred due to excess demand causing flow breakdown.

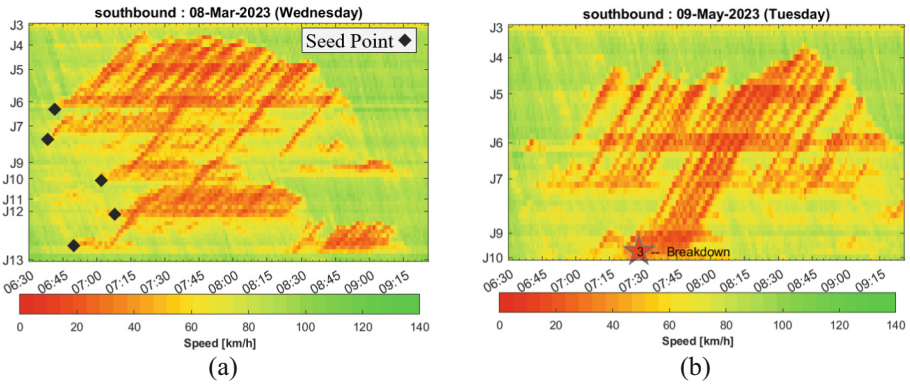



**Fig. 2.** Heatmaps of traffic speeds showing (a) general congestion patterns for a typical morning and (b) congestion caused by an incident near junction 10. Image produced using MATLAB [6].

While Fig. 2 shows congestion patterns on two single individual days, when examining recurrent congestion seed points it was necessary to combine the data from multiple days. Generating heatmaps of the average speeds for specific days of the week (with incidents, holidays and adverse weather removed), allowed recurring seed points to be clearly identified so that further investigation of the causes of congestion could be carried out. Detailed reviews of each seed point, using a combination of traffic data from inductance loops and CCTV footage allowed the source of congestion to be identified. Typically, flow breakdown initiated near junctions, where merging traffic, driver behavior or road geometry resulted in a localized capacity reduction. Understanding the nature and source of congestion build-up at each seed point, allowed appropriate speed management plans to be developed to optimize traffic flows and to mitigate the effects of congestion on the M50.

### 2.3 Data-Driven Triggers for Initiating Proactive Speed Management

In order to optimize traffic flows through the application of VSL in a proactive manner, speed limits must be reduced in advance of flow breakdown occurring. Control room operators have traditionally relied on visual interpretation of the data feeds, along with CCTV footage. However, given the dynamic nature of traffic conditions, it was found that visual observation alone was not sufficient to allow operators to accurately identify the onset of congestion before flow breakdown occurred, meaning that without additional guidance, speed plans would often be implemented after congestion had already started to form, in a more reactive manner. In order to identify the traffic conditions which are likely to initiate the onset of congestion and facilitate a proactive response, historical loop data was leveraged to establish the fundamental relationships between speed, flow and density/occupancy along the motorway. This provided a measure of the capacity being achieved at each seed point, and an understanding of the traffic conditions being experienced directly in advance of flow-breakdown. Figure 3(a) illustrates the flow-occupancy relationship for one location near junction 6, based on 5 years of data from 1st January 2017 to 31st December 2022. It can be seen that typically, a capacity of approximately 1,600 veh/hr/lane is achieved, however there is a large spread in the data points. This is indicative of the various factors which influence traffic behavior and hence the achieved capacity (e.g. time of day, weather conditions, time of year, traffic lanes). More details on establishing the fundamental diagrams using measured traffic data can be found in [7].

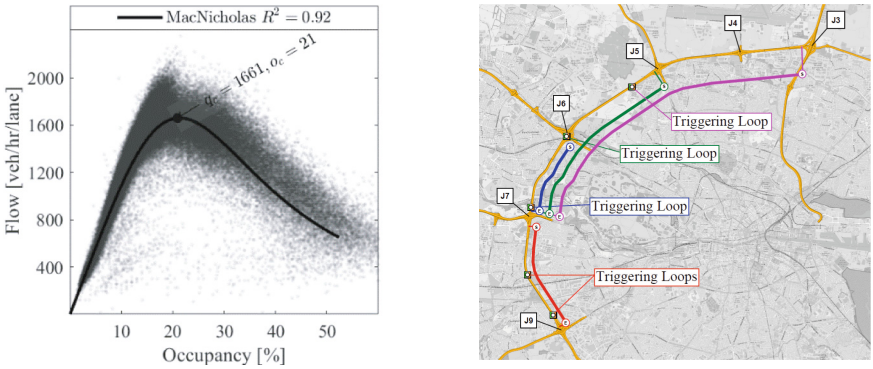



**Fig. 3.** Development of data-driven triggers and speed management plans: (a) flow-occupancy relationship to estimate capacity and (b) locations of triggers and associated speed plan extents. Images produced using (a) MATLAB and (b) Microsoft PowerPoint [3] (background map from OpenStreetMap [4], an open map database).

The application of traffic flow theory to establish the fundamental diagrams for each seed point provided a general understanding of the capacity being achieved, and the various factors influencing capacity. However, in order to develop suitable alerts to assist operators with the implementation of proactive speed management plans, a detailed study was carried out to examine the traffic parameters directly in the lead

up to flow breakdown occurring. A number of metrics were studied, and it was found that the 5-min rolling average speed was a reliable indicator of the onset of congestion. Suitable trigger locations and threshold values for the 5-min rolling average speeds were identified for each seed point and audible alerts were configured in NIMS to warn control room operators of traffic conditions when the thresholds were breached. Upon receiving an alert from one of the trigger locations, operators implement reduced speed limits along the relevant section of the M50, following pre-defined plans. Figure 3(b) shows the trigger locations and geographical extent of the speed reductions implemented by operators for each trigger during the morning peak, for a portion of the Southbound carriageway. It is noted that the speed limit of this part of the motorway is 100km/h, and the operators reduce the speeds to 80km/h following a trigger, and further reduce the speeds to 60km/h when the data indicates that flow breakdown has occurred.

## 3 Assessing the Impact of Proactive Speed Management

Following a 6-month period where operators implemented the plans shown in Fig. 3(b) in response to the real-time alerts in NIMS, the data was analyzed to examine the impact of proactive speed management on traffic conditions. Baseline traffic conditions were established using historical data from days without any speed restrictions. This allowed the influence of the speed plans on any particular day to be assessed by comparing the traffic data during times when proactive speed management was in place, to the equivalent times and locations from the baseline data set. Due to the many factors which can influence traffic conditions, days with incidents, adverse weather, holidays etc. were removed from the baseline data set. When evaluating the impact of a speed plan which was active on a particular day, the baseline for that day was generated by averaging the top 5 most statistically similar days where no speed management was in place from 4 years of historical data. This ensured a fair comparison by minimizing the potential effect of other variables which could have influenced the development of congestion.

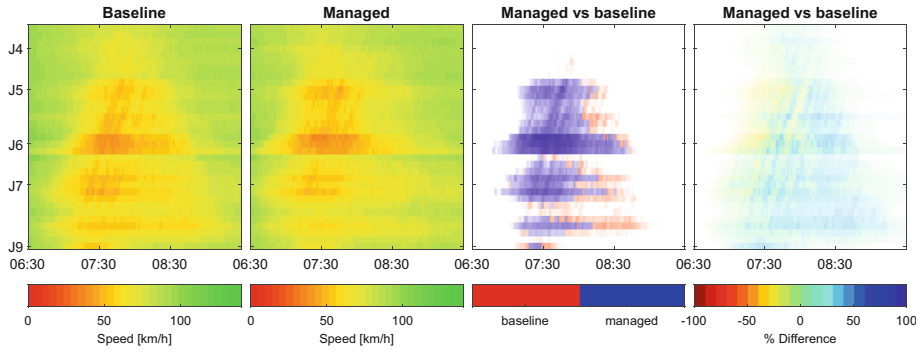



**Fig. 4.** Heatmaps showing changes in congestion patterns when proactive speed management plans ('Managed') were active compared to 'Baseline' traffic conditions. Image produced using MATLAB [6].

Figure 4 shows traffic speed heatmaps which depict the average baseline congestion pattern (i.e. when no speed plans were displayed) along with the average congestion patterns for the 6 month period where proactive speed management plans were implemented. Although, the overall assessment of the benefits was evaluated on a day-by-day basis, the average patterns are displayed here to provide a general visual overview of the effect of proactive speed management. It can be seen that when comparing the two patterns, the traffic speeds at the beginning of the morning peak tended to be slightly lower, due to the lower posted speed limits, however, the length and duration of queuing can clearly be seen to have reduced, particularly between junction 7–9.

Aside from the general congestion patterns, the analysis of the data provided a number of important insights into the effectiveness of the proactive speed management responses for managing congestion during the morning peak period. The main findings are summarized below:

- The duration and extent of queueing traffic in the morning peak was reduced.
- A 5–10% increase in vehicle throughput was observed.
- A reduction of in the number of shockwaves of 10–50% was observed.
- Speed plans were most effective when initiated within 2 min of trigger activation.
- Benefits were most evident at the fringes of the peak period (i.e. directly before and after morning peak congestion materialized).

## 4 Conclusions

This paper presents an overview of how traffic flow theory and data analytics have been utilized to understand traffic behaviour on Ireland's M50 motorway. As part of the introduction of variable speed limits on the M50, operational procedures have been developed to allow control room operators to activate proactive speed management plans. These plans are switched on by operators in response to real-time triggers which have been developed from the analysis of historical traffic data. Results from a 6-month assessment are presented, and it is shown that the implementation of proactive speed management during the morning peak period has resulted in increased throughput, a reduction in shockwave behaviour and a reduction in the extent and duration of queuing.

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# Achievements and Future Priorities of Artificial Intelligence in Transport Systems

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**Abstract.** This paper aims at defining future research priorities for artificial intelligence (AI) in transport systems. The point of the departure is the state of the art regarding the application of AI in transport combined with the EU policy needs and the assessment of the recent European projects. The paper presents an overview of the potential benefits that the deployment of AI has for transport. Special focus is put on results of European projects funded within Horizon 2020 Framework Programme. The main achievements of the research have shown that AI can help in the optimisation of applications within the transport means. It can also aid public authorities in improving the overall infrastructure thanks to data gathering and first screening. Further, the deployment of AI is a source of profitable opportunities for various sectors like automotive, software, waterborne, aviation, passenger and freight transport. The final aim of these projects is to boost efficiency, sustainability, and safety by having a human centric AI, aware of every situation it is facing and able of taking prompt decisions. The paper concludes by discussing selected cross-cutting concerns regarding the application of AI in the transport sector. They include definition of software updates for autonomous vehicles' algorithms, the need for liability regimes and the issue of data scarcity.

**Keywords:** Artificial intelligence · Research and innovation · Infrastructure · Autonomous vehicles

## 1 Introduction

Artificial intelligence (AI) is pivotal for the modernization and optimisation of the transport sector. Its deployment shows improvements, from traffic management to enhancing vehicle safety and security. The Horizon Europe (HE) and Horizon 2020 (H2020) programmes are the EU's flagship projects for research and innovation (R&I). They include several calls for actions related to the progress of the use of AI in the transport sector to boost efficiency, sustainability, and safety. In this context, the deployment of AI in transport is one of the main tools for achieving the targets set by the European Grean Deal and the Vision Zero. Hence, acknowledging both past and present R&I activities is key for the development of new technologies and strategies.

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## 2 Background

The EU priorities regarding the application of AI technologies to transport modes have evolved throughout the past years. In 2021 the European Commission (EC) started the process for the enactment of a Regulation dealing with AI horizontally. In the specific case of transport, it tackles its critical role for citizens' health [1]. R&I projects are supported by political, and legislatives aims and objectives. Thus, funding programmes for R&I are fundamental for reaching EC's goals. H2020 had an overall budget of nearly €80 billion for the period of 2014 to 2020. A new round of projects has been launched by HE for the 2021–2027 period. Most of the calls from H2020 and HE deal with the application of AI on road transport. However, increasing considerations are given to aviation and waterborne projects.

Additionally, the Joint Research Centre (JRC) of the European Commission has also been active in assessment of the deployment of AI technologies in the transport sector. Most of the JRC works looked at AI applied to road transport, where it can potentially oversee vehicles' safety, robustness, and security [2]. This includes, for instance, safety and security of AI technologies, particularly related to malicious action and cybersecurity risks in automated vehicles (AV) [3].

Moreover, the need emerged for the establishment of testing strategies accounting for the inherent flaws of AI systems [4]. Indeed, AI algorithms are ultimately responsible for the driving actions at high levels of automation [5]. Thus, a harmonised legal definition of software updates for AV algorithms is needed. However, some researchers believe that applying AI to AV could increase uncertainty and have undesirable consequences due to the complexity of the road transport system [6]. In essence, the review of the existing research studies carried out by JRC demonstrates the gap between technology and regulation and the overall need for furthering the existing knowledge for road transport and AI.

## 3 Methods and Data

In the next two sections we provide a review and assessment of the EU funded AI R&I projects with a focus on AI application to transport. Community Research and Development Information Service (CORDIS) (Fig. 1) contains a constantly updated database of H2020, and HE funded programmes and projects on transport R&I. This study focuses on 88 projects (38 for HE and 50 for H2020) that deal or dealt with AI in the transport sector. We reviewed identified projects to define main themes within AI transport research and to categorize projects according to these themes. The themes are related to application of AI for particular transport mode, and they include:

- Road: research projects that investigate AI technologies employed for predictive maintenance, automated vehicles, traffic optimisation, fleet management and reduction of environmental impacts.
- Waterborne: projects that research the improvement of shipbuilding and maintenance.
- Aviation: research on AI technologies for enabling new digital aviation technologies for new aircraft business models and services, as well as minimise the risk from emerging threats to aviation such as extreme weather phenomena, cybersecurity, and communicable diseases.

- Rail: methods to optimise automation and recognition of obstacle detection.
- Cross modal: projects that investigate the application of AI holistically to the transport sector, regardless of the type of the transport in which the technology is applied to.

We categorised the relevant R&I projects into the macro categories by identifying the relevant keywords for each category, followed by a review of project objectives and results.

# 4 Results

## 4.1 Overview of the Projects

The data analysed show an increasing interest for R&I on the application of AI to road transport. Road transport projects on AI went from 42% of the overall projects under H2020 to 64% under HE. This anticipates an implied interest for automated vehicles and their implications. At the same time, some of these technologies are cross-cutting among transport sectors.

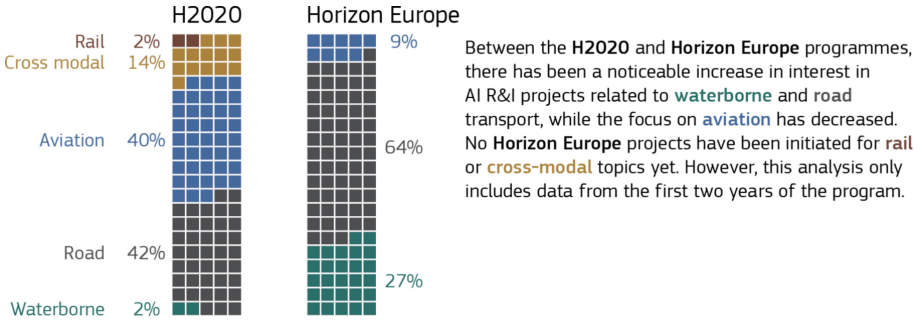



**Fig. 1.** R&I projects implementing AI in modes of transport in H2020 and HE

## 4.2 Key Achievements and Results of H2020 Projects

- **Road.** The major concern for public safety is human error as it plays a significant role in 94% of accidents [7]. Although AI appears to be a promising technology for monitoring the driver's state and behaviour [7], it lacks public acceptance of AVs [8]. One project suggested commercial campaigns as a mean to gain people's trust [9]. Another project suggested for AI to be coupled with 5G and mobile edge computing for reaching the most efficient cross-modal communication [10].
- **Waterborne.** The project BugWright2 is ongoing, however it showed promising initial results in using autonomous robotic solutions for underwater hull cleaning. This type of technologies can significantly decrease the consumption of fuels in merchant vessels.
- **Aviation.** AI has effectively tackled disruptions to air communications networks by predicting and thus preventing hazards [11]. AI was also used to facilitate airlines commercial activities by ensuring a secure digital marketplace [12]. However, AICHAIN, SIMBAD and SlotMachine projects showed the most promising results for passengers as they seek to predict, avoid, and alleviate delays for users [12].

- **Rail.** Collision with obstacles is still very relevant for rail transport. SMART2 has showed great results in designing a system that enhances the obstacle detection of the train.
- **Cross modal.** Research demonstrated that the creation of cooperative transport ecosystems connecting users and infrastructures can aid in making road transport systems safer, more sustainable and efficient [13, 14].

### 4.3 Current and Future Research Priorities: HE Projects

The future HE calls mirror R&I priorities, focusing on Vision Zero[1], environmental sustainability and boost of competitiveness. By looking at the background analysis of this paper and the topics of the HE calls it is possible to see a continuation between what should be done and what it is intended.

- **Road.** The priorities shifted from safety to optimisation of the road recharging systems, advancing environmental sustainability, and improvement of connected, cooperative, and automated mobility. AVs' systems must be technically robust and safe, resilient to attacks, respect privacy and data governance, be transparent in its operations, apply non-discriminative behaviours, ensuring societal and environmental well-being [15].
- **Waterborne.** Most projects focus on improving safer navigation and detection of viruses on board.
- **Aviation.** New projects will focus on AI application for reducing the environmental impact of aviation, facilitate business models and enhance aviation safety.

Overall, future priorities will require for further research as it is necessary for ensuring that the proper liability regimes are put in place [4]. The level of uncertainty given by human logical mechanisms can lead AI to behave unexpectedly [4]. AI technologies are key for the development of a new generation of vehicle safety systems that can better protect drivers and pedestrians by handling situations where human capabilities fail [4]. For instance, AI deployment is essential updating traffic management systems. Some of the papers reviewed by this study suggest further research on multimodality and transport infrastructure projects, sensors, and detection systems [16]. This would facilitate ongoing communication among 3 modes of transport and enable the transport system to reach and please as many users as possible. Moreover, future research should focus on the integration of such on shore automated systems with smart scheduling and potentially automated ships, integrating logistic chains and benefiting operational measures to reduce GHG emissions such as lower cruising speeds [17].

At a societal level, the application of AI technologies to transport could bring important safety and productivity gains. Nevertheless, some important concerns exist, such as users' acceptance, ethics, social inclusion, and labour. AI applied to transport systems can provide profitable opportunities for many sectors, namely automotive, software and digital media [18]. On the other hand, sectors like insurance and maintenance and repair are identified as businesses that might experience important decreases in revenues in the future due to a decrease of accidents [18].

[1] "Vision Zero" is the long-term strategic goal of having no deaths and serious injuries on European roads by 2050.

## 5 Conclusion

R&I projects are fundamental for highlighting the advantages that AI can bring and more importantly for individuating and preventing the risks associated to it. AI can potentially be the main solution to many transport challenges, despite people's scepticism. The projects reviewed for this paper represent a step forward towards an optimised, sustainable and high-functioning transport environment. R&I is necessary for cost-effective smart mobility, safer infrastructures, and for increasing the deployment of AI in support of the operation of the network. Making more data available means more deployment of data-driven services and technologies such as AI. AVs have the potential of reducing energy consumption and emissions from transport. Although AVs can enhance road safety, they do not increase road capacity. Hence, AI technologies are making the transport sector smarter, with enormous advantages in relation to safety and efficiency. Overall, the existing projects focused on pre-empting disaster and enhancing safety of all modes of transport. Thus, the essence of AI is to increase efficiency in a secure and safe manner.

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# Gamification of Early-Stage Planning, Participation and Education in Urban Mobility: The MobileCityGame

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**Abstract.** Strategic planning is of utmost importance for cities to achieve climate targets, while maintaining citizen satisfaction and meeting financial constraints. However, large assessment models are often costly and too complex for smaller cities. Thus, we designed a simplified, intuitive and dynamic transport simulation tool and serious game MobileCity to run on mobile devices for strategy processes, participation and teaching. A real transportation model running on local devices allows the free combination of different mobility interventions and shows dynamic indicators for climate, finances and livability, while offering an intuitive interface with supporting information. We currently extend the free iOS and Android demonstrator for Karlsruhe (Germany) and transfer it to European cities within the DUT project "CarGoNE-City". In this paper, we present its core functionalities and features, before assessing scenarios and concluding on lessons learned and applications. Our main messages from applying the MobileCity-App are: the timing of interventions matters for all output indicators and a sound combination of push and pull measures helps meeting climate, livability and financial targets without going into extremes.

**Keywords:** Urban mobility · roadmapping · impact assessment · serious gaming

## 1 Motivation and Objectives

Cities and regions receive increasing pressure to meet climate targets by EU and national law [1, 2], while financial limits get tighter and differing expectations on good living standards impede policy decisions more and more. Well-developed planning tools like the SUMP methodology [3] or detailed transportation models are complex and expensive to run and partly hard to understand for non-experts or public administrations. At the same time, they miss out core policy indicators like citizens' satisfaction, livability or communal finances.

In front of this point of departure, a team of Fraunhofer, KIT and takomat GmbH have contemplated the possibility of simplifying the core functions of larger transportation

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and sustainability models, make them dynamic, enrich them by information for non-experts and by additional outputs on social and financial issues and present them in an easily accessible form. The resulting tool should enable higher-level city planners to test and broadly assess various pathways towards future mobility without issuing expensive consultancy contracts in early stage planning. Second, the tool shall support public information and participation processes, and finally shall support teaching of future mobility and sustainability experts in universities.

This aspiration led to the three-year research project MobileCityGame, co-funded by the German Ministry for Education and Science (BMBF). We created a freely available serious game for iOS and Android at the example of Karlsruhe (Germany, 300,000 inhabitants) with a simple but fully functional transportation and assessment model running on local devices and an intuitive user interface. In this paper, we present its core functionalities (Sect. 2) and features (Sect. 3) before assessing scenarios (Sect. 4) and concluding on lessons learned and applications (Sect. 5).

## 2 Method and Data - the Game Engine

### 2.1 The Model Structure

MobileCity follows the logic of a system dynamics model and a geographical output interface. Time steps for computation is one year from 2023 to 2050, but monthly steps allow starting or stopping measures more precisely. Modes considered are cars as driver and passenger, carshare, public transport by tram/light rail and bus, cycling and walking. Fleet models split car and transit into electric and fossil propulsion. Population by city district and age classes (0–19, 20–64 and $\geq$ 65 years) is assigned to trip purposes (education, work, errands and leisure). In the demonstrator for Karlsruhe, the model operates on the level of 27 city and 15 peripheral districts, which are linked by hyper-networks for car, transit and bike with main and district access links.

The model structures into seven computational and three output modules. Population (BEV), Regional Structure (REG), Infrastructure (INF) and Behavior (SOZ) determine Mode Choice (MOD), which communicates with Technology (TEC). Energy (ENG), INF and SOZ again drive TEC. These modules and their sub-modules communicate dynamically via stock and flow variables, and finally deliver data for the three assessment modules Climate (ENV), Livability (LEQ) and Finances (FIN) (see Fig. 1).

The modules are defined and calibrated using local and national statistics in combination with scenario runs of the agent-based model mobiTopp of KIT [4]. The system dynamics models ASTRA and ALADIN developed by Fraunhofer and partners [5, 6] provided further data in the fields of long-term economics, sustainability and vehicle fleets. A literature review on impact mechanisms accompanied these [e.g. 7, 8]. Results were discussed with the Karlsruhe city administration and in three stakeholder workshops in the Period January to June 2023.

### 2.2 User Interface and Outputs

The results of MobileCity are of a didactic nature rather than providing exact values for indicators from now to 2050. Nevertheless, the three groups of output indicators are

computed with data from the analytical modules and are assessed by reviews of impacts e.g. on emission factors (modules ENV and LEQ) and cost rates (module FIN). As MobileCity is a serious game, a scoring system was developed, summing up the annual performance in the three impact categories. This allowed e.g. to judge not only meeting the climate target in 2050, but also emission budgets on the way. Table 1 provides an overview of impact categories, sub-indicators and scoring principles.

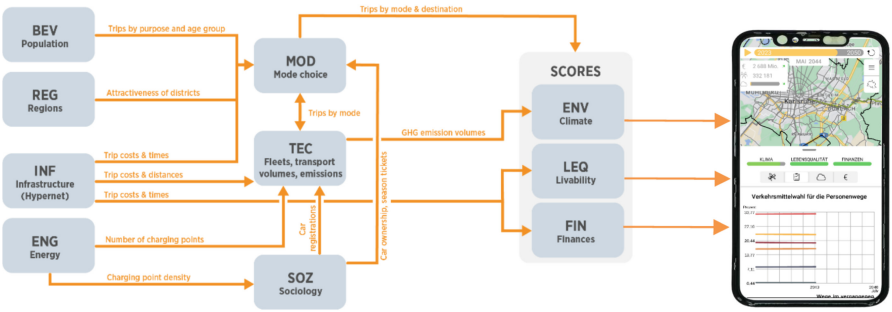



**Fig. 1.** MobileCity module and data structure

**Table 1.** Output-Indicators in the MobileCity demo version.

| Module | Output unit | Scoring principle | Sub-indicators |
|---|---|---|---|
| ENV | t $CO_2$e per capita | Range around a linear reduction path towards climate neutrality in 2045 | Emissions per main mode of transport |
| LEQ | Social benefits (€ p.c.) | Range from zero to double 2023 social benefits with progressing scores towards the extreme ends. | Mobility costs, accessibility, transit quality, air pollution, noise, safety, acceptability |
| FIN | Annual balance (mill. €) | Range from + 50 to -10 mill. € annual balance, linear | Sub-accounts for car, bike, transit and urban development; details by budget, expense and revenue types |

To quantify the acceptability of measures among the population a representative survey on the 25 largest German cities with 2660 responses was launched in summer 2023 [7]. Along the four measures Parking Fees of 20€, construction of Cycling Highways, Reallocation of Street Space and Free Public Transport people were asked to rate their consent before introduction with little information and after completion with full details including before-after-illustrations. Each measure in the MobileCity-App was labeled with acceptance values between −50 (complete opposition) to + 50 (full consent).

## 3 Features and Measures

In MobileCity, the player takes the role of the all-mighty mayor. As we look into pathways towards 2050, we deliberately ignore details on administrative, legal or technical processes. Measures are described by planning/building times, costs, acceptability and detailed impacts to individual district, hypernet or other parameters. The current demo version of MobileCity has 11 individual measures built-in, which cover various intervention categories, modes and geographical details, and which were discussed with Karlsruhe city authorities (Table 2). For real world applications this selections shall give an impression on MobileCity's capabilities.

**Table 2.** Measures in the current MobileCity demo version.

| Category | Mode | Measure | Description |
|---|---|---|---|
| Building | Bike | Cycle highways | 6 pre-defined investment projects |
| | Car | E-charging stations | Setting new stations by district & year |
| | Transit | Subway tunnel | Completed 2021: project in city center |
| | Transit | E-buses | Fix 2030: replace diesel buses by e-buses |
| Pricing | Car | Parking fees | 4 schemes, varying extents and e-car rebates |
| | Transit | PT Tariff reforms | 4 levels, monthly pass & single ticket price |
| Regulation | Car | Speed limits | 3 levels, 30 km/h incl. / excl. Federal roads |
| | Bike/Walk | Road redesign | Inner city/suburbs, 30%/70% removed parking |
| Incentives | Carshare | E-car vouchers | Acceptance through free rides via carshare |
| | Car | Street labs for e-cars | Acceptance through showcase projects |

Some, but not all of the measures are displayed geographically by respective layers (e.g. e-charging stations or parking fees). Further layers show travel times by mode between districts, population and $CO_2$-emissions per capita. The progress of modal splits, $CO_2$-Emissions. Livability and finances can be tracked during the model run via detailed graphs. After a model run, taking between 15 and 20 min, a final report is generated and can be shared with others.

## 4 Scenarios and Results

With the MobileCity App the effect of combining measures to bundles and of delaying action can be assessed quickly. To demonstrate this we have defined six bundles, each starting early (2024) or late (2030) plus the reference case. The bundles are:

- Reference: only automated actions, i.e. electric charging station provision 50% compared to Norway, market entry of e-cars and full bus electrification in 2030.
- Electrification: maximum of 130% charging stations each year, free parking, incentive programs for e-car use like vouchers for free rides and street labs.

- Cycling city: all cycling highways, street redesign (30% less parking, all districts).
- Parking & speed: parking fees of 10€ in the inner city with 50% rebate for e-cars, 75% of former free parking is charged plus 30 km/h speed limit on all streets.
- Transit tariffs moderate: monthly pass 29€ with reductions in single ticket prices.
- Climate package: bundles Cycling city, Parking & speed and PT tariffs combined. Emergency break: Cycling city, 70% of public parking removed, 20€ fees in center for all parking spaces and all cars, 9€ monthly PT pass; 130% e-charging-stations.

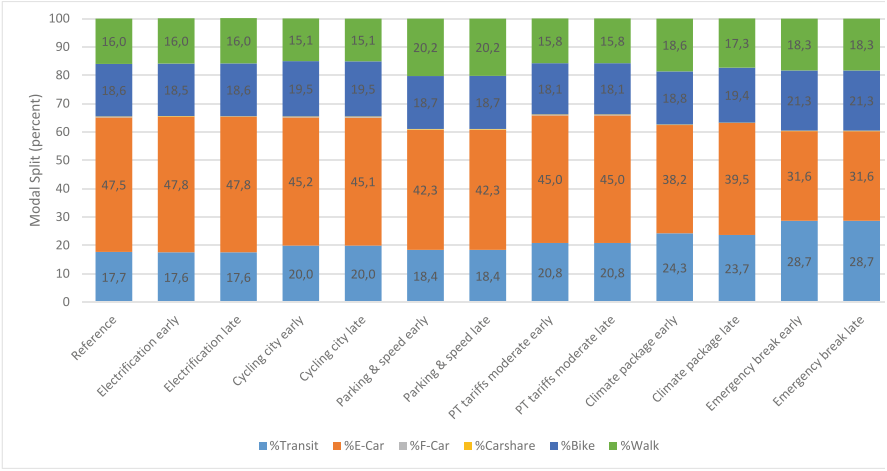



**Fig. 2.** Modal shares at trips 2050 by bundle

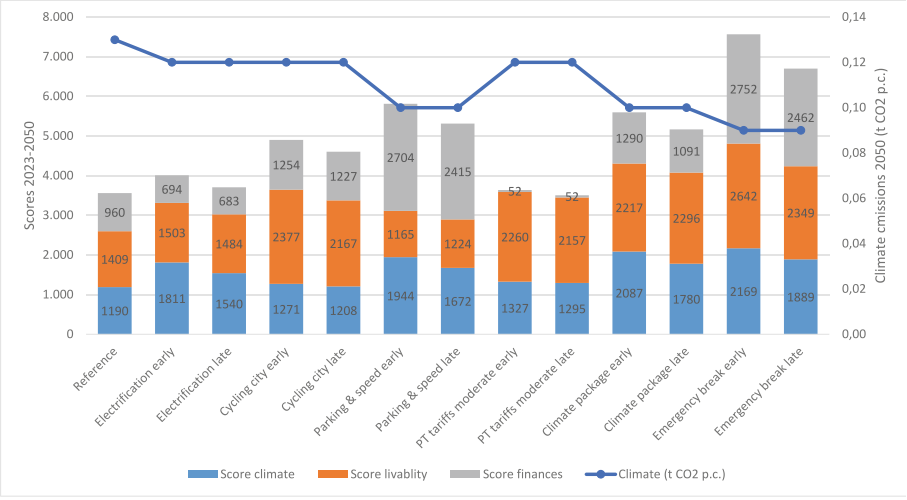



**Fig. 3.** A Scores 2023–2050 and climate emissions 2050 by bundle

For the 13 variants, Fig. 3 shows the cumulated scores 2023–2050 and the climate emissions per capita 2050. Already in the reference case, the likely checkless market uptake of e-cars reduce GHG emissions 2023–2050 by 83% from 0.75 to 0.13 t $CO_2$ p.c. Achieving further reductions is difficult, except for push measures like high parking fees. But: timing matters, as is indicated by the higher climate scores for bundles introduced early. Climate neutrality, however, fails in all cases as measures to curb grid emissions are missing. Livability and climate scores go hand in hand if push and pull measures are combined. Finally, high parking fees can re-fund practically free transit.

Figure 2 shows the modal splits at trips in 2050. According to the currently implemented model and measures, modal splits even towards 2050 appear to be resistant to major changes. Even the harsh measures under Emergency Break only manage car modal share to decline from 48% to 32%. Transit here evolves from 18% to 29%. Measures for expanding transit capacity, however, are missing in the current MobileCity version. Cycling and walking under these conditions rise form 35% to 41% while carshare does not play a significant role in either bundle or variant.

## 5 Conclusions and Discussion

The MobileCity-App allows users without any modelling experiences or analytical skills to play with the combination, intensity and timing of commonly discussed interventions for the mobility transition. Dynamic and detailed outputs for the numerous sub-indicators shall fuel discussions among policy-makers, citizens and students. Real-life tests of these potential application areas are part of the follow-up project CarGoNE-City. An extended App supporting more modes (including freight), more measures and a channel to communicate with users will be applied in participation processes.

With a number of additional functions and features added, we see the potential of MobileCity to emerge to a commonly accepted early-stage planning tool for preparing SUMPs, for workshops, public dialogues and teaching. Now we enter the stage of practice proof in particular for the diverse European cities. Features in preparation include more measures, urban logistics, shared and automated mobility services, user communication options and the largely automated transfer to other cities.

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# Can European Shipyards Be Smarter? A Proposal from the SEUS Project

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**Abstract.** Improving the efficiency and competitiveness of European Shipyards is one of the priorities of the HORIZON program, funded by the European Commission. The proper use of computational tools can accelerate this improvement, given that the shipbuilding industry faces a digitalization gap compared to other manufacturing industries. Our proposal is based on the ongoing Smart European Shipyard (SEUS) project, which aims to bridge the digital gap, focusing on integrating available computational tools, and converging into a new platform that enables faster engineering and technical management. This platform intends to provide a holistic approach to product lifecycle management (PLM) for shipbuilding, integrating existing and proven solutions in CAD/CAE with new data-driven technologies to handle shipbuilding knowledge efficiently. The paper presents a link between current challenges and possible ways to tackle them and a summary of the possible impacts this platform can achieve if adequately implemented. The paper closes with a call for peers to contribute to the discussion.

**Keywords:** shipbuilding · PLM · CAD/CAE · digital transformation

## 1 European Shipbuilding and the Need for a Digital Thread

The European shipbuilding industry faces many challenges, including increased competition from Asia, economic uncertainty, and a growing demand for more sustainable vessels, Brett and Ulstein (2012). However, despite these obstacles, the industry remains an essential player in the global maritime sector.

A vast and increasing amount of data is generated during the shipbuilding life cycle, Seppälä (2019). There is considerable scope to use this data more effectively across the shipbuilding network value chain, Gaspar (2018). Digitalization and computational tools have great potential to generate value for stakeholders in the form of cyber-physical systems or digital twins, Diaz et al. (2023). It requires a significant reshaping of existing tools and practices to be exploited successfully by the European shipbuilding industry. The gains come in the form of increased quality and reduced time required for design,

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virtual prototyping, estimations of impacts for the use of greening innovative technologies, modularization, flexible data management, interoperability across proprietary tools, cyber security, efficient support for modern robotized fabrication and openness for integration with operational platforms.

To achieve these gains, a digital thread needs to be facilitated to enable data use and management to support the life cycle of complex engineering systems effectively, focusing on the shipyard as the core of the value chain as it converges the tasks of design, engineering, construction, and maintenance. By establishing a single source of truth for ship data, the digital thread facilitates data fusion for CAE/CAD/CAM/PDM systems, which can improve the organizing, managing, and contextualizing of shipbuilding data. It has the potential to provide virtual prototypes, enhance consistency and compliance with technical standards, use AI and ML, and NLP technology to assist and evaluate technological innovations, enable iterative learning, and significantly enhance communication and access to data for all stakeholders.

However, much of the productivity gain to be achieved during the early stages of ship design is constrained by the many different CAE/CAD/PLM/PDM/ERP tools and models used to create, combine, and evaluate each of the modules that a ship consists of. Consequently, the design of a modularized and standardized work system (enabling reuse of design models and drawings), or even a new design approach configuration, lacks an effective and agile common evaluation framework that can combine standard (traditional) and customized (innovative) solutions through the ship design, engineering, and fabrication processes. A successful smart framework should consider the detailed balance of these elements, especially regarding effective documentation towards clients and third-party partners, including activities beyond the design/delivery process, such as maintenance and repair, retrofit, operation, and scrapping, Fonseca et al. (2022).

## 2 Being Smart: Challenges and Opportunities in Digitalization

Typically, ship design, engineering, and fabrication in Europe follow fairly traditional approaches, not keeping the same pace of development observed in the automotive, discrete manufacturing, and aerospace industries. Current shipbuilding approaches are partly fragmented, discontinuous, time-consuming, and laborious. The rationalization of business and work processes (e.g., PLM, PDM, modularization, parameterization, and other data-based techniques) have so far only been tested and implemented successfully in the daily tasks of yards to a limited extent.

Moreover, ship design, class approval, and maintenance include many documents managed over extended life cycles. The digital downstream to operations phase is challenging as 2D, 3D, and simulations contain a vast amount of model elements. A typical vessel model of only one design project may contain up to 2–3 million model elements or parts. The approach is significantly different from a mechanical CAD model, as shipbuilding uses high levels of topological connections between parts to make it possible for fast modifications, such as the rearrangement of equipment and piping or changes to hull structures.

The SEUS project aims to address these topics, making a step toward a data-assisted method to support early ship design. While each of the pitfalls listed above can significantly slow down or improve the overall process, having a holistic view of shipbuilding is

a prerequisite. This view, with suggested room for improvements via process innovation, is illustrated in Fig. 1.

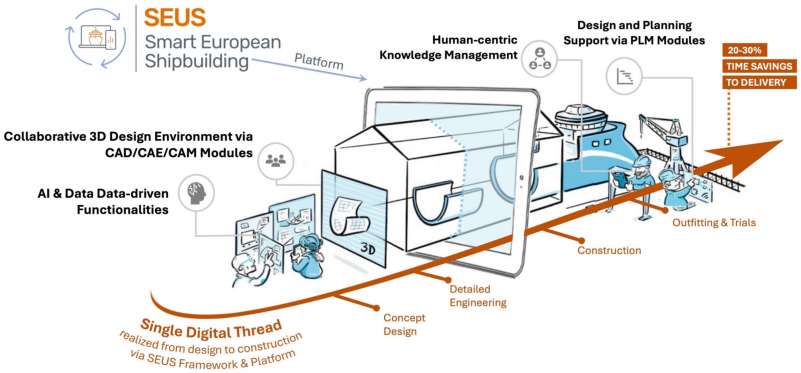



**Fig. 1.** Potential for lead time reduction in the upstream maritime value chain. Collage produced using Microsoft PowerPoint based on an illustration by Scribey Sense.

In this context, we summarize seven challenges for enhancing the current status of European Shipbuilding:

1. Facilitate rapid early-stage design to support lower-risk bid development, particularly when integrating innovative new technologies.
2. Provide better capital cost estimations and performance predictions, particularly showing the improvements expected from the inclusion of new technologies.
3. Tools to be integrated with ship construction and production and to consider supply chain management and future maintenance and repair of vessels.
4. Address and quantify the competitiveness gains provided by the tool(s) in the context of the wider European shipbuilding sector.
5. Ensure that the tool is robust and resilient against cyber threats.
6. Identify and address the development of the necessary skills needed to achieve the maximum benefit from innovative advanced computational shipbuilding tools.
7. Develop business cases to quantify the added value from the developed tool to the shipbuilder concerned and within the context of the wider European shipbuilding sector.

## 3 Being Smart: Challenges and Opportunities in Digitalization

### 3.1 SEUS Methodology Objectives

The main ambition of the Smart European Shipbuilding project (SEUS) is to tackle the mentioned challenges, by developing a smart platform dedicated to shipbuilding and its downstream and upstream lifecycle phases. This will be achieved by architecting an integrated platform for a combined and open solution incorporating CAE, CAD, CAM, and PDM software and testing it at shipyards. The new platform solution will

be built with state-of-the-art European shipbuilding expertise provided by academic and industrial consortium participants. It intends to develop novel practices for human-centric knowledge management in shipbuilding, the use of NLP, and data-driven AI design elements in the current consensus or intelligent technologies and Industry 5.0, EU (2021).

The SEUS project will develop, implement, test, and qualify software solutions with an Industry 5.0 mindset for the European shipbuilding market. We have set up seven objectives towards a stepwise progress over 4 years:

1. Create workflow activity map and use cases applying smart technology and Industry 5.0 concept, specific to European shipbuilding
2. Enhance the human-centric competitiveness of shipbuilding and reflect diverse values of stakeholders, including shipyard workers, ship-owners, operators, users/passengers, and shipbuilders in general
3. Build a shipbuilding-specific PLM platform comprising defined data models and the selected elements of CAE/CAD/CAM and PDM solutions
4. Develop a flexible platform that supports multiple instances of workflows to facilitate rapid early designs, and is fit to support AI tools and virtual prototyping
5. Ensure openness and interoperability of the platform while keeping it cyber secure
6. Test and implement in an industrial environment – developing the concept of the digital shipyard.
7. Quantify added value gains provided by the developed platform, creating a business model of exploitation, and dissemination of project results

The SEUS project's platform connects high-end solutions in shipbuilding, integrating data handling across life stages and disciplines. It challenges the traditional CAD-centric and PDM-centric approaches, which rely heavily on CAD models for production data and data management, by emphasizing expertise in shipbuilding scenarios and effective project management. Fundamental to the SEUS approach is that the current toolbox for shipbuilding can be more efficient if properly integrated into a human-centered environment, including Industry 5.0 aspects. The SEUS methodology is focused on developing a smart platform for CAD/CAE/CAM in shipbuilding based on the industrial and academic experience of its consortium members.

The SEUS approach revolves around the fulfillment of the seven mentioned objectives. It consists of four main steps, represented in Fig. 2, namely: Shipbuilding Best Practices; Smart Shipbuilding PLM Platform; Shipyard Implementation; Business and Innovation.

The SEUS approach starts by evaluating the current European shipbuilding landscape, focusing on the potential to integrate digital tools and smart technologies. A human-centered approach aligned with Industry 5.0 principles will be explored, balancing cyber-physical systems and societal needs. This study will produce best practices to inform the development of a smart platform.

The second phase centers on creating a smart PLM platform that incorporates CAD/CAM/CAE elements tailored to shipbuilding. Existing tools will be enhanced, and digital support implemented for various use cases, focusing on computational tools needed in shipbuilding.

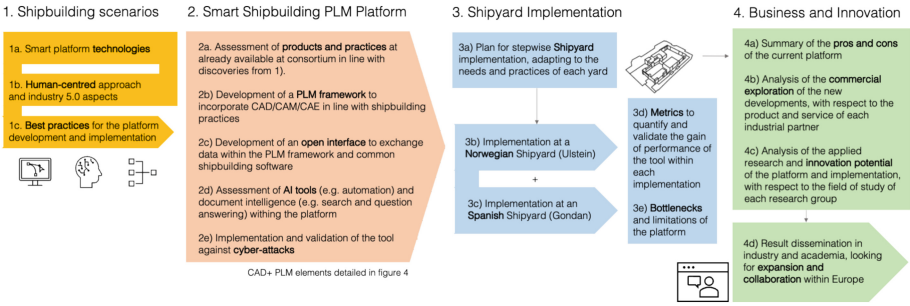



**Fig. 2.** SEUS methodology overview.

The SEUS Smart CAD + PLM platform includes CAE modules for early design, CAD/CAM tools for 3D and production design, and PDM/PLM modules for lifecycle and data management. It supports shipbuilding expertise, AI integration, and advanced cybersecurity measures. The platform aims for seamless data flow and standardization across shipyards.

Cybersecurity workshops will be held to address risks, while efforts to standardize domain knowledge will accelerate early design tasks. Integration between PLM elements and CAD/CAE applications will ensure data synchronization, visualization, and workflow management for design and production tasks.

### 3.2 Expected Impacts

The impact of SEUS is based on primarily increasing the level of digitalization in European Shipyards, facilitating the transformation of this industry towards competitiveness with a human-centric mindset. A compilation of seven key impacts is presented in as follows.

1. ***Computational Platform for PLM in Shipbuilding***: The development of a PLM-specific platform for shipbuilding will enhance the current computational tools available in Europe and worldwide. Similar to the advancements made by CAD/CAM tools three decades ago, this platform will improve digitalization through interoperability, a standardized data model, and process management tools. It aims to enhance competitiveness by shortening lead times and allowing for adaptability in design and production, ultimately reducing lifetime maintenance costs.
2. ***Facilitating Digital Transformation:*** Elevating digitalization within the shipbuilding industry will significantly enhance productivity, collaboration, flexibility, and innovation. By integrating knowledge in management and circular production, the sector can achieve resource-efficient designs and improve virtual prototyping processes, fostering a human-centric approach and upskilling shipbuilders.
3. ***Traceability and Early Design Integration:*** The EU's decarbonization targets necessitate the integration of innovative technologies in early design stages to assess alternative impacts. This platform will facilitate experimentation with hull designs and propulsion technologies while linking historical and detailed design data, ensuring traceability and simplifying workflows for naval architects, engineers, and shipyards.

4. ***Competitive Advantage through Time Savings:*** Communication challenges often hinder shipbuilding projects, Agis (2020). The SEUS platform will enhance information transfer by minimizing manual data entry and providing dynamic access to relevant information. This will streamline communication between designers and builders while involving third parties, ultimately reducing the time spent searching for information and improving design-to-production transitions.
5. ***Shipyard Engagement with Vessel Life Cycles:*** The SEUS platform will strengthen the connection between shipyards and the operational life of vessels, enabling insights from historical data and enhancing post-delivery service offerings. This collaboration will benefit both shipyards and operators, providing accurate engineering models and promoting the digital twin approach.
6. ***Human-Centric Knowledge Management:*** A customizable shipbuilding activity modeling framework will integrate expertise and data throughout the shipbuilding life cycle, fostering collaboration and skill development. This framework will enhance workforce productivity and sustainable knowledge practices while promoting integrated training programs for various stakeholders.
7. ***Development of EU Workforce Skills:*** European shipbuilders have historically been leaders in innovation. This platform will serve as a comprehensive resource for all project participants, tailored to user needs, promoting creativity and digital skills, thus maintaining the EU's leadership in shipbuilding technology.

## 4 Concluding Remarks: A Call from Peers to Join the Smart Approach

SEUS boasts a strong consortium comprised of academics, software developers, and shipbuilding partners from five European countries. This balanced partnership is dedicated to bridging knowledge gaps and facilitating the uptake of key results. The partners bring valuable experience in customer implementation, dissemination, and communication, both nationally and internationally, which will be crucial for achieving the proposed objectives. The consortium is committed to sharing SEUS's approaches and outcomes while targeting specific groups to meet development, dissemination, and exploitation goals.

Peer and stakeholder engagement is essential to SEUS's communication strategy. The consortium aims to share project findings with a wide audience and encourages external collaboration to support European shipbuilding. Joint efforts can enhance industry interests.

We invite peers to engage with the consortium by developing and sharing their insights on smart concepts such as Industry 5.0, digital threads, and PDM/PLM integration. In the medium term, we seek evaluations of the advantages and disadvantages of their approaches in comparison to ours, aiming to find beneficial combinations for European partners. The project also aims to develop an open standard for connecting commercial tools, facilitating broader interactions.

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# Smart Self-sensing Composite Marine Propeller: Increased Maintenance Efficiency Through Integrated Structural Health Monitoring Systems

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**Abstract.** CoPropel is a Horizon Europe funded project which aims to develop marine propellers for cargo vessels that are more fuel and cost efficient to operate than their more common metallic counterparts. One of the areas the project aims to tackle is the maintenance aspect of marine propellers, which can be very cost intensive. This is due to the difficulty of inspection or maintenance since the components are underwater and quite significant in size, which may lead to the need for divers or dry-dock time. The way the project aims to address this is by taking advantage of the non-monolithic construction of the composite propeller to integrate a Structural Health Monitoring (SHM) system to monitor the strain, and subsequently infer the condition, of the propeller during operation without the need to stop for inspection. This paper explores the challenges encountered in the development of the SHM system, including: 1.) inspection requirements as set out by existing guidelines and regulations, 2.) sensor integration in the composite structure, 3.) data transmission from a rotating underwater component to a data acquisition system within the ship and 4.) usage of the acquired data for maintenance decision making. Feasible alternative systems are explored including Rayleigh Backscatter based Fibre Optic Systems (FOS) for distributed strain sensing as well as a strain gauge system with wireless underwater data transmission. Preliminary small scale underwater tests are conducted to evaluate the performance of the explored concepts under simulated operational conditions. Finally, we combine the strain data acquired from the SHM system with numerical models of the propeller through a multifidelity approach. The first aim is to create a better spatial distribution of the strain measurements across the propeller by fusing data from sensors covering a limited area, with strain data from numerical models that have better distribution across the propeller. The second goal is to provide digital twinning capability through the use of the numerical model to provide extrapolated estimates (calibrated by live sensor data) of maintenance requirements (i.e. remaining life) based on current and hypothetical operational profiles to better inform operators when making future operational decisions. Through the combination of the SHM system and digital twinning capabilities we provide increased

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data driven decision making capabilities to better improve operational efficiency and maintenance costs.

**Keywords:** Marine propulsion · Composite materials · Structural health monitoring · Digital twin · Underwater sensing · Rotating machinery

## 1 Introduction

Ship propeller blades are commonly constructed as monolithic metallic parts and are designed to be rigid to maintain the optimum geometry for hydrodynamic efficiency during operation [1]. Currently, there is growing interest in applying fibre reinforced composite materials as an alternative to metals due to their controllable stiffness that allows for hydroelastic tailoring of flexible propeller blades to provide better performance and fuel efficiency [1]. However, there is one added benefit of applying composite materials that has received less attention, which is the possibility to integrate sensors for condition monitoring due to the non-monolithic construction of composite blades. CoPropel [2] is an ongoing Horizon EU funded project (Grant agreement 101056911) that aims to develop a composite propeller with integrated strain sensors to enable Structural Health Monitoring (SHM), increase operational reliability and provide better information for preventive maintenance planning. Failure of the propulsive system (and its prevention) is still a significant contributor to costs in shipping [3], thus by having an integrated SHM system it is hoped to provide additional savings from the maintenance aspect.

Currently there exists frameworks for condition-based maintenance planning (such as ISO 19030) for ships based on measured parameters of their performance and diagnostics of the machinery [3, 4]. However, these measurements are either based on indirect parameters (such as speed, engine rpm and vibration) or diagnostics of machinery within the hull (such as engine and shaft) [3, 4]. Direct measurements of the propeller remain one of the most challenging tasks due to the fact that it is rotating, fully submerged underwater and usually has strict restrictions on any disturbance to the external hydrodynamic shape. Thus, these conditions impose limitations on the size of the equipment (must rotate), where it is installed (internally) and how data is transmitted back to the hull (must handle the rotation and water medium). In this paper we present the ongoing work to develop SHM solutions to tackle these challenges and what can be done with the data provided.

## 2 SHM Solutions Developed in CoPropel

There are 2 alternative SHM strain sensing solutions being explored in the CoPropel project: 1.) a Fibre Optic Sensor system (FOS) and 2.) a wireless strain gauge system. Figure 1 provides a general schematic of the propeller blade construction and sensor installation. The propeller blade will be constructed as a sandwich with a composite laminate skin and a sand core which can be made hollow at certain sections to store electronics or pass through wires. The FOS fibre will be integrated into the dry preform of the outer composite laminate while the strain gauges will be installed between the sand core and laminate. This will be done prior to the Resin Transfer Moulding (RTM)

manufacturing process that will inject resin throughout the part and consolidate it. The strain gauges will be placed following the path of the FOS to allow for direct comparison of the train measurements as seen in Fig. 1. However, the sensor locations/topology shown in Fig. 1 are not final and serve to illustrate the concept.

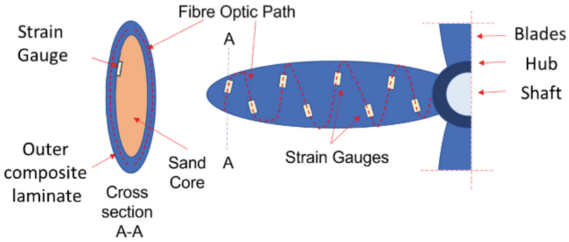



**Fig. 1.** Schematic of propeller blade construction and sensors (exact installation locations/topology is not final)

### 2.1 Fiber Optics Sensor (FOS) System for Strain Sensing

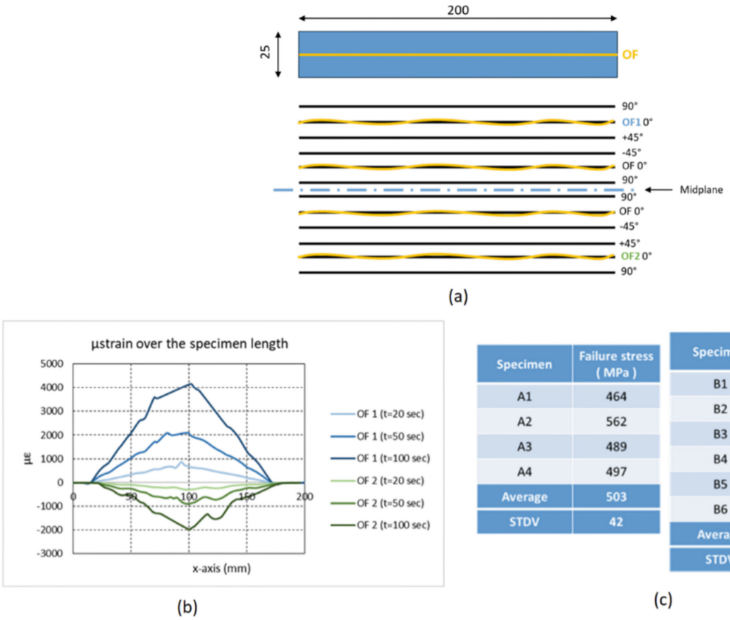
The FOS system employed in the propeller will be based on the Distributed fiber-optic sensors (DFOS) [5] that provide a continuous profile of measurements over the length of the optical fiber and thus are most suitable for large structural applications. When a light wave enters an optical fiber, the Rayleigh, Raman, and Brillouin back scattering light are simultaneously obtained. Fiber optic distributed sensing measures strain and temperature by processing spectral shift in the Rayleigh backscatter of optical fibers integrated in a structure. When the strain in the fiber changes, the spectrum of back-scattering signals will drift in terms of frequency. The amount of drift is proportional to the strain that is imposed to the optical fiber. Through relevant calculation of the measured and initial signals, the drift value can be obtained. Then, the strain value can be calculated from Eq. (1). The distributed strain information of the entire optical fiber can be obtained by scanning. [6]

$$\Delta_v = C_\varepsilon \cdot \Delta_\varepsilon, \tag{1}$$

In Eq. (1), Δv represents the value of the frequency drift of the Rayleigh spectrum, Δε is the change of strain in the optical fiber relative to the initial value, and Cεis the strain proportional coefficient of the optical fiber. The method described above is known as Optical Frequency Domain Reflectometry (OFDR). The Rayleigh system working with OFDR is the only one to offer mm range spatial resolution.

Preliminary experiments (three-point bending) have been conducted to ensure the functionality of embedded sensors and validate the minimum effect on the mechanical properties of the host material. Optical fibers were integrated to the middle of the width of each specimen at 4 different layers: 2 near the mid plane and the neutral axis of the specimen's section, 1 near the outer surface which will undergo compression and 1 near the outer surface which will undergo tension. The layup of the specimen and the

optical fiber layout are presented in Fig. 2a. The optical fiber was integrated to the fabric during manufacturing using a painter to form lines as a guide to place the optical fibers at certain positions and plastic tubes at the ingress and egress points to protect the fiber. The integrity of the OF was checked after manufacturing via a laser. The embedded sensors monitored the structural integrity of the specimens during testing (Fig. 2b). The extracted data from the optical distributed sensor interrogator indicated that the strain increased over time as expected. Furthermore, the strain profile of the optical fiber under compressive stress and the optical fiber under tensile stress were representative of the specimen's deflection. The failure stress of the specimens with and without embedded optical fibers was compared to evaluate the host material's degradation. The obtained results indicate that the optical fiber does not act as a defect to the host material (Fig. 2c).




| Specimen | Failure stress ( MPa ) |
|---|---|
| A1 | 464 |
| A2 | 562 |
| A3 | 489 |
| A4 | 497 |
| Average | 503 |
| STDV | 42 |

| Specimen | Failure stress ( MPa ) |
|---|---|
| B1 | 482 |
| B2 | 457 |
| B3 | 493 |
| B4 | 501 |
| B5 | 493 |
| B6 | 511 |
| Average | 490 |
| STDV | 19 |

**Fig. 2.** Three-point bending test results: (a) Specimen geometry and fibre optic layout, (b) strain measurements from embedded optical fibres, and (c) failure stress of specimens without (A1–4) and with (B1–6) embedded optical fibres

To transmit the optical signal transmission from a rotating underwater component to the data acquisition system within the ship, a Fiber Optic Rotary Joint (FORJ) is being tested for small scale tests.

## 2.2 Wireless Strain Gauge System

The wireless strain gauge system is being developed as an alternative to the FOS system which can provide more flexible data transmission as the options for electrical signal transmission are wider than optical signal transmission. Figure 3 provides a schematic

on the concept of the wireless strain gauge system, where the strain measurements are transmitted to the hull via magnetic coupling using thin coils on the propeller (rotating) and shaft sleeve (static). Magnetic coupling was chosen over Electromagnetic (EM) wave signal transmission (as commonly used in free air communication) as it is less affected by the water medium (where EM waves are heavily attenuated [7]) and the existence of the metallic shaft between coils provides support for the magnetic field coupling (as in electrical transformers).

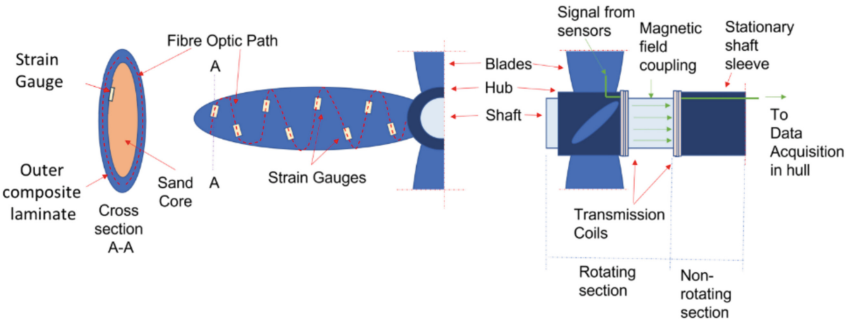



**Fig. 3.** Schematic of wireless strain gauge system

In order to achieve wireless data transmission, the strain measurements (in the form of voltage signals) need to be converted into oscillating signals [8]. This is done using a frequency modulation approach where the voltage signals of the strain measurements are transformed into a shift in a continuously oscillating sine wave. The strain measurements are then decoded at the data acquisition side by analysing the frequency component of the transmitted signal. Figure 4a shows the frequency modulation prototype that has been developed to test this concept. The frequency modulation is done using an AT microcontroller (MCU) which reads the voltage from the strain gauge and sends instructions to a DDS wave generator to generate a sine wave with the appropriate frequency. This approach was chosen as the MCU provides accurate control over the frequency modulation such that it is possible to accurately define the frequency bandwidth of each sensor to allow multiplexing of the signals. Thus, when there are multiple signals from different sensors it is possible to transmit it together on 1 line (in this case from the coils on the propeller and sleeve).

Figure 4b shows preliminary signal transmission tests done in various media (free air, water and salt water) using a 60 kHz 6Vpp signal and 1mH choke coils as transmitters and receivers. It was observed that the change in media does not significantly alter the transmitted signal strength, but it attenuates significantly with distance. Since the sleeve and propeller are usually spaced closely and in the actual case there will be a metallic shaft that can aid in signal transmission, this should not pose a significant problem.

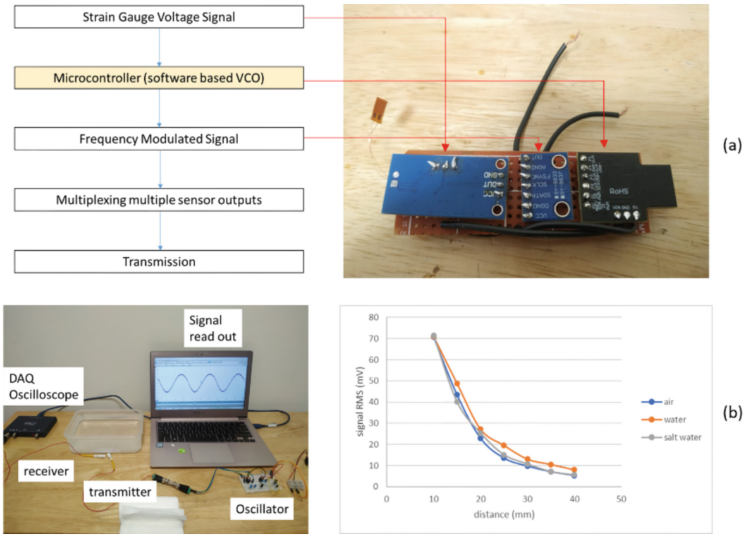



**Fig. 4.** Wireless strain gauge system: (a) prototype frequency modulation system and (b) preliminary transmission tests in different media

## 3 Data Driven Decision Making Using SHM Measurements

In order to provide better information regarding the condition of the propeller, the project will explore the use of a multifidelity approach to combine the numerical simulations conducted during the design phase (which have good spatial coverage) with the SHM measurements at discrete points/areas (which have good accuracy of the condition of the blade) to provide a more comprehensive visualisation (Fig. 5).

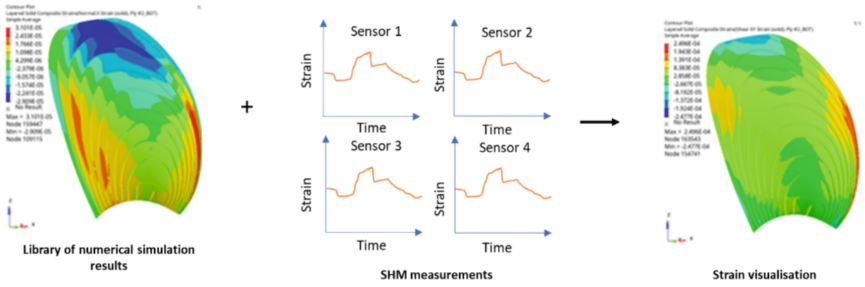



**Fig. 5.** Concept schematic of multifidelity approach for data visualisation

## 4 Conclusion and Future Work

The current work in the CoPropel project has identified 2 possible alternatives that are potentially suitable for addressing the challenge of SHM in ship propeller blades. initial prototypes and experimental tests have been presented that indicate promising results

and further development and testing will be conducted as the project moves on to the small- and large-scale testing phases.

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# MAPSIA: Automatic Pavement Distress Detection for Optimal Road Maintenance Planning

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**Abstract.** An inadequate road maintenance planning coupled with funding constraints, traffic volume rising and lack of data, results in aging pavements with increased fuel consumption and diminished user safety as well as exorbitant corrective preservation costs. Assessing road conditions for pavement distress detection currently involves two approaches: human visual inspection, which is labour intensive and time-consuming, and the use of multipurpose pavement inspection vehicles. Notwithstanding, the latter is expensive to purchase, operate and maintain, which may pose challenges for departments of transportation with limited budgets. This project automates the process of recognizing superficial road defects with an innovative solution based on Artificial Intelligence, thereby adding significant value to road rehabilitation decision-making. Our low-cost image acquisition system collects thousands of geotagged road images. Then, multiple Deep Learning (DL) algorithms belonging to the YOLOv5 family are trained to establish a functional mapping between the inputs (raw images) and the outputs (defect location and type). Also, validation metrics are calculated in order to identify the optimal DL architecture. Subsequently, a rule-based postprocessing is devised for the finest model, with the goal of mitigating false positive detections. The enhanced model outputs are utilized to engineer a pavement condition index, which is integrated in our software.

**Keywords:** Pavement Distress Detection · Computer Vision · Deep Learning

## 1 Introduction

The road infrastructure deteriorates in its physical and functional conditions due to long-term heavy traffic, aging of materials, and harsh environmental changes [1]. The abundance and level of service directly influence a country's economy, with a paved road density ranging from 40 km/M inhabitants for low economies to 8550 km/M in high economies. In the USA, 68% are poor condition, costing an extra $61B annually, yet needing $130B/year for upgrades [2]. Also, vehicle speed decreases by 55% and carbon

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emissions increase by 2.49% on very poor roads compared to excellent conditions [3]. Proactive shorter-interval pavement condition monitoring could promote small-scale repair, extending asphalt lifespan, and saving by up to 80% pavement rehabilitation [4] and lessening rehabilitation negative environmental impact, with a life cycle cost reduction of 37% [2]. Thus, a pavement management system is crucial for optimized decision-making on preservation prioritization, methods, timing and location [5].

The aforementioned precedents, combined with traditional human-based visual inspections by pavement engineers which is time-consuming and inefficient given the extensive road networks, create a knowledge gap [6]. Automation through Deep Learning-based (DL) Computer Vision (CV) systems emerges as a pivotal solution. The systems' pipeline comprises: image acquisition, DL-driven road distress recognition, surface road distress index for impact quantification, assessment through visualization tool and strategic decision conservation. State-of-the-art studies primarily focus on the design of the architecture (processing), mainly of crack-type defects, using private datasets, with no effort put into designing an index to evaluate a study area.

This full-spectrum study compiled frames of various categories (repairing, sewage, crack-type, particle detachment) using speed-agnostic acquisition device, establishing a dataset for DL model benchmarking. After approaching the problem as an object detection CV task, we compared YOLOv5 DL-architectures, evaluating detection rates per distress and computational cost to select the best model. To refine post-processing, we implemented a visual inspection-based filter method. Using the optimal model's outputs, we integrated a pavement condition index into visualization software, devising a strategic maintenance system through a case study analysis.

## 2 Methodology

### 2.1 Dataset

The dataset, annotated by pavement specialists, contains 7099 geo-tagged images ($640 \times 640 \times 3$) with 13 distress types. They have been captured under various lightning and weather conditions using a drone camera on a vehicle. The train/valid/test split is 70/15/15. The following nominal encoding has been established: D1 (block-cracking), D2 (alligator cracking), D3 (diagonal crack), D4 (longitudinal crack), D5 (irregular crack), D6 (transversal crack), D7 (D4 between lanes) D8 (patch), D9 (pothole), D10 (sewer), D11 (manhole), D12 (raveling), and D13 (sealed crack).

### 2.2 Metrics

Precision (P) is the ratio of correctly detected instances to the total predicted positives. Recall (R) is the relation between predicted positive observations to all actual positives. Mean Average Precision (mAP), the area under the P-R curve serves as our benchmarking for assessing YOLOv5 family. A higher mAP indicates a superior model performance.

### 2.3 Experimental Setup

Object detection is a CV task where multiple instances of a given class are detected and located within an image. Recent object detectors are DL-based architectures that receive raw images and output the following data per detected element: class (distress type), confidence probability (how confident the detector is that the object is in that location) and the coordinates of the bounding box.

In this research, YOLOv5 [7] (You Only Look at Once, version 5) DL-architecture was selected to automatically identify road defects from images. YOLOv5 is divided into three blocks: backbone, neck, and head. The backbone is Cross-Stage Partial Dark- net53, which performs feature extraction, enhances feature expression, and improves running speed. The neck is Path Aggregation Network which up-samples the output feature map generated from multiple convolution down-sampling from the backbone to generate new feature maps with different scales to detect small, medium, and large objects. The head, made of convolutional layers, predicts the confidence score, the class, and the bounding box. YOLOv5 was adopted for its high detection rate and swift inference, crucial for optimizing real-time image flow from acquisition camera to pavement management tool. The specifications of the dataset can be found in Sect. 2.1.

Initially, a comparative analysis will be conducted between the different YOLOv5 sub-models (n, s, m, l, x) that maintain the architecture but differ in complexity, aiming to conduct a study that balances accuracy against prediction time. All of them share the same configuration displayed in the following table (Table 1).

**Table 1.** YOLOv5 family setup. Augmentation techniques are CA -classical augmentations- (flipping, translation, rotation, scaling, shearing and perspective) and Mosaic. The loss is the weighted addition of the three terms.

| Learning rate | Optimizer | Momentum | Weight-decay | Augmentation | Epochs |
|---|---|---|---|---|---|
| 0.01 | SGD | 0.937 | 0.0005 | CA + Mosaic | 300 |
| **Classification loss** | **Objectness loss** | **Regression loss** | **Confidence threshold** | **IoU threshold** | **Early-stopping patience** |
| Focal | Focal | CIoU | 0.25 | 0.45 | 7 |

After identifying the best algorithm, a filter method was designed to minimize illogical distress detections and reduce false positives. Upon visual assessment, isolated crack (D3-D7) detections were nested within meshed cracks (D1/D2), consistent with D1/D2 being aggregates of D3-D7, potentially amplifying ambiguity. Also, child D1/D2s of bigger D1/D2s were observed. Additionally, singular cracks were occasionally detected as multiple distinct crack classes, likely due to camera perspective-induced geometric distortion. In response to these visual observations, a post-processing mechanism using Intersection over the Union and confidence scores was implemented to reduce such detections.

Based on the refined model outputs, the following area-weighted pavement condition index is proposed:

$$Index^{iimaiie} = min\left(\sum_{ii=1}^{N} A_{ii}\alpha_{ii}^{k}c_{ii}, 1\right) \quad (1)$$

For each image, the index represents the addition of the product of area ($A_i$), confidence score ($\alpha_{ii}$), and a hyperparameter emphasizing small yet critical defects ($c_i$). The index ranges from 0 to 1, where a higher value indicates poorer pavement condition. Finally, a tool was devised to analyze a road segment (case study).

## 3 Results and Discussion

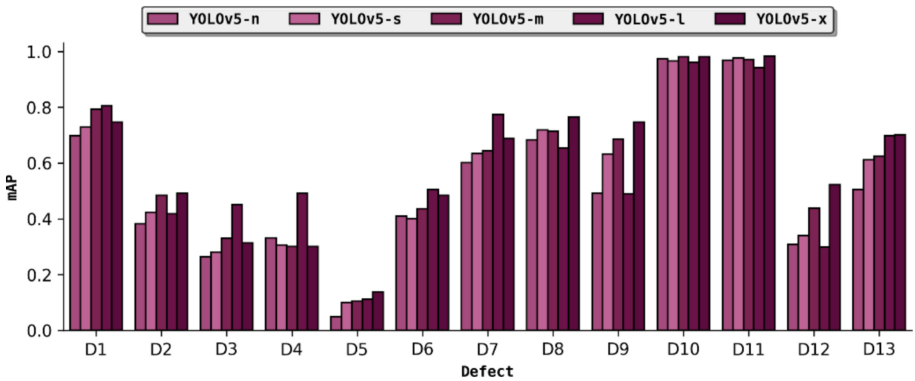



**Fig. 1.** mAP by road distress type for the different YOLOv5 sub-models.

For the isolated crack family (D3-D7), YOLOv5l approximately exhibits the best performance. These results are noteworthy since the appearance is similar, but with different geometry. The best-detected objects, regardless of the model, are D10/D11 belonging to the sewer family, likely due to their distinctive appearance compared to the pavement background. Regarding the repair block, D8 is model-agnostic, while for D13 despite being a minor defect, YOLOv5-l/x outperform the rest. Concerning the meshed crack subset, YOLOv5-l performs slightly better, and YOLOv5-x excels in D2. Simpler architectures n/m/s with inference times of 3.7–5.5 ms/image and sizes of 3.9/14.4/42.2 MB generally produce inferior results. Given YOLOv5 l/x's comparable efficiency, YOLOv5l was selected to meet the inference demands of recording at 30 frames per second at 120 km/h vehicle speed (l: 8.7ms, x: 17.3ms) (Figs. 1, 2 and 3).

A false positive is when there is a detection but no corresponding annotation. Upon applying rule-based filtering derived from visual detection inspection, defects D4/D6, with the highest false positive rates, dropped by about 27%. Meanwhile, other defects fluctuated between 20% and 45%. Then, this method enhances result reliability in the context of road defect detection as per human interpretability.

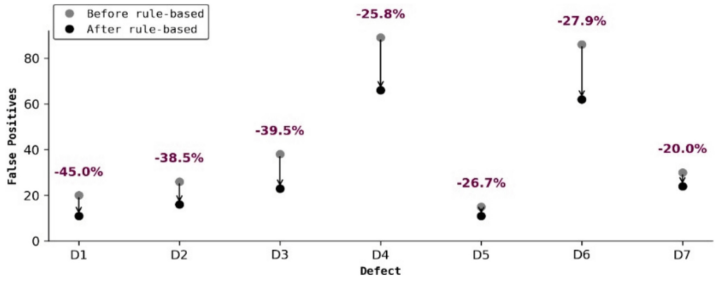



**Fig. 2.** False positives of YOLOv5-l after and before applying the rule-based filtering.

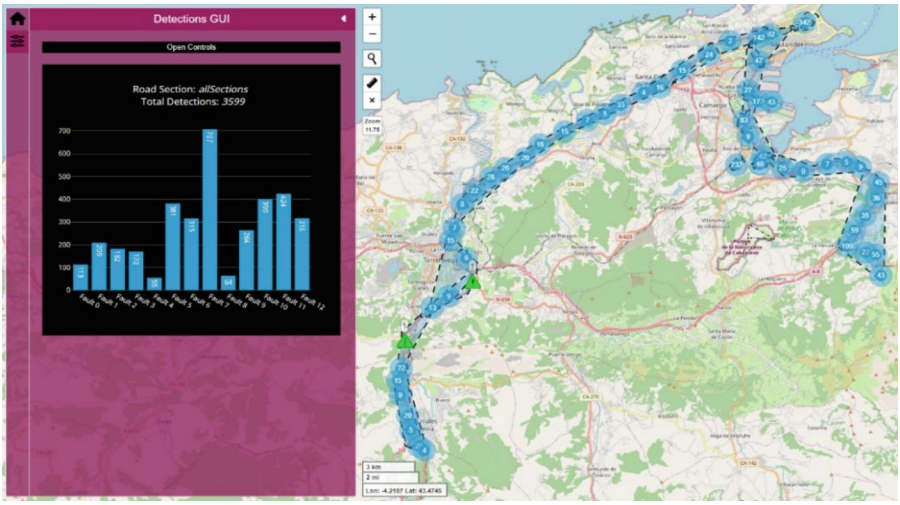



**Fig. 3.** Distribution of detections by category of defect for the case study and geospatial representation. Image produced using Leaflet.js (JavaScript), an open source software.

YOLOv5l's efficient training cost is around 2.3 h. To achieve real-time detection and reduce image storage, the trained model could be integrated into a nano AI computer and connected to the camera.

Longitudinal cracking is the most common defect (19.64%), but potholes and alligator cracking are more concerning for road maintenance (8.78% and 10.58%, respectively). The urban center of Santander, the airport area, and the Guarnizo industrial park have the highest number of pavement defects. Images with detections and color-coded index-based markers allow identifying concerning areas, such as the one in Fig. 4 with recent maintenance (3 D8s) and 2 D2s (severe damage). Thus, this pavement management tool enables strategic maintenance planning.




**Fig. 4.** Specific section with pavement distress detections by defect category, detection confidence, and contribution to distress index. Color-index equivalence: green (<0.2), blue (0.2–0.4), yellow (0.4–0.6), orange (0.6–0.8), red (>0.8). Image produced using Leaflet.js (JavaScript), an open source software.

## 4 Conclusions

A Computer Vision system has been designed to collect road images to automatically detect 13 pavement distresses. After analyzing YOLOv5 models, YOLOv5l was selected for its high recognition rate and reduced inference time. Filtering the detections with our post-processing pipeline reduced the false positives. A pavement condition index was designed to identify the most affected areas. MAPSIA is a full-scale system that will enable more efficient road management and conservation.

**Acknowledgments.** This work has received funding under grant TED2021-129749B-I00.

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# Efficient Pavement Crack Monitoring for Road Life Cycle Management

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**Abstract.** Road pavements are vital for transportation infrastructure, yet they deteriorate over time due to traffic loads and environmental factors, resulting in cracks and damage. This paper introduces an innovative method for crack detection on road pavements using digital imagery. Our approach incorporates geo-localization, annotates, characterizes, and quantifies crack severity. This empowers experts to monitor crack progression, a critical element in pavement management. The methodology allows for seamless result comparison and augments existing techniques, aiding in condition assessment and conservation strategy determination. Timely detection of cracks enables proactive maintenance, preventing structural degradation, and ensuring user safety and comfort. Leveraging deep learning and open-source frameworks like TensorFlow and QGIS, our approach automates road pavement image analysis and crack identification, providing a cost-effective, accessible solution for crack detection. This research offers significant advantages in resource efficiency and accessibility, especially in areas without regular manual inspections or dedicated vehicles, thereby enhancing road pavement monitoring and maintenance.

**Keywords:** Road Pavements · Cracks · Image Processing · Neural Networks · Convolutional Filters · Open Digital Maps

## 1 Introduction

The global road network is essential for transportation, connecting communities and facilitating economic activities. However, maintaining road pavements in optimal condition is an ongoing challenge. Over time, roads are subjected to heavy traffic loads and environmental agents, leading to the development of cracks. These pavement distresses not only compromise the safety and comfort of road users but also accelerate the structural degradation of the pavement itself. Therefore, effective monitoring and timely maintenance are critical components

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of road life cycle management. In this work we intend to study how an automatic approach, with the help of image processing, can complement this monitoring, especially in the detection, characterization and level of degradation of cracks. Automatic methods will be analyzed, which enable the detection of cracks in road pavements. Techniques to be studied include image processing techniques, using gradient filters and neural networks. It is also intended to develop a model platform that allows users to provide images of road pavements, enabling the user to provide a detailed characterization of the cracks present in them, according to the available manuals. These tools must be used and validated by experts in the field. Finally, we intend to study a way to improve this platform by adding a tool that allows the georeferencing of images uploaded to the platform.

## 2 Related Work

Several methods have been proposed for crack detection in road pavements. Traditional approaches rely on manual inspections, which are time-consuming and often impractical for large road networks [1]. Automated solutions, such as computer vision-based methods and machine learning algorithms, have shown promise results in recent years.

### 2.1 Study of Pavements

Regarding their constitution, pavements are considered structures made up several horizontal layers of finite thickness, supported on a foundation of natural pavement Fig. 1-A. The main objective of these is to support the actions induced by vehicles, transmitting them to the foundation in an attenuated form, thus providing a safe and comfortable surface for vehicles to circulate [2].

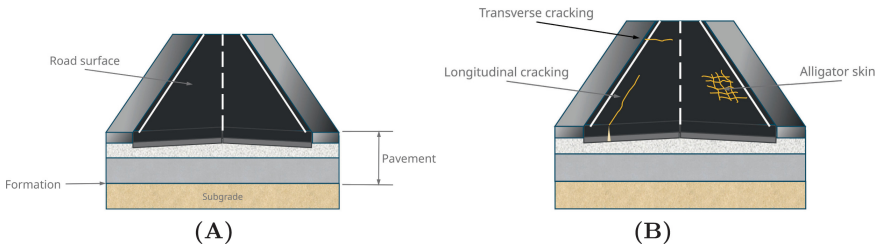



**Fig. 1.** (A) Schematic of the typical structure of road pavements and (B) different types of cracks. Both images produced using Libreoffice, an open source software.

There are several types of pavements, flexible pavement (the vast majority of pavements), rigid, and semi-rigid, each of these types, with different characteristics.

**Degradation Mechanisms, cracks.** Road pavements suffer, throughout their service, loss of load capacity, together with environmental causes (e.g. weathering and aging) which leads to the appearance of degradation. The main degradation mechanisms are the cracking of bituminous layers. There are several types of cracking, the most common is fatigue cracking. In addition to the cracks being characterized correctly, the aim is to provide more detailed information about them using the Road Pavement Degradation Catalog [9,10], which can be done, as there is a section on the various types of degradation in flexible pavements and their degradation levels. We will focus on 3 levels of degradation of longitudinal, transverse cracks and alligator skin (Fig. 1-B).

### 2.2 Image Processing

Images of road pavements can be analyzed and improved using different filters. GIMP, GNU Image Manipulation Program, is an open source image manipulation program that can includes most major image processing filters. GIMP is ideal for our use case since it can be used both manually and fully automatically from a python program. For the present study GIMP was used to highlight the cracks that were presented in the images. It can often be seen that there is a crack, but its contour is not prominent. Edge Detectors, as the name suggests, are detection filters that look for edges between different colors, thus detecting the contours of objects present in the images. Below are some relevant filters from that are considered relevant for processing these images.

**Difference of Gaussians.** This filter detects edges, this performs two *Gaussian* blurs with different radius on the image. The radius can be configured, if the radius 1 is increased, the algorithm recognizes edges that appear thicker, if the radius 2 is decreased, the algorithm detects thinner edges.

***Sobel.*** This type detects horizontal and vertical edges through the calculation of first-order derivatives, creating an intensity gradient [3]. The final result is an image with some level of transparency with black lines and some colors as can be seen in Fig. 2.

***Dilate.*** The filter *Dilate*, enlarges and perfects the dark areas of the layer. For each pixel of the image, a pixel value (brightness) will be given equal to the lowest pixel value (the darkest) of 8 neighboring pixels in a matrix. Thus, a dark pixel is added if the pixels around it are also dark. This will cause that area to be dilated in all directions, creating a "big pixel".

***Erode Noise.*** This filter is part of the GIMP generic filters, it consists of enlarging and highlighting bright areas in an image.

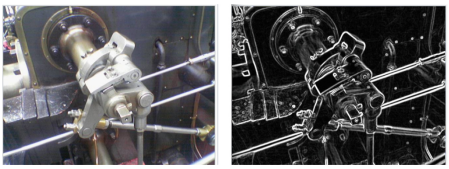


**Fig. 2.** Example of applying the *Sobel* filter in GIMP—Simpsons contributor, CC BY-SA 3.0, via Wikimedia Commons, 2025 ( Valve original (1) & Valve sobel (3)).

## 3 Methodology

Deep Convolutional Neural Networks (CNNs) have achieved innovative results over the last decade in a variety of fields related to pattern recognition, image processing and speech recognition [6]. Convolutional Neural Networks (CNNs) automatically learn convolution filters, whereas the *sobel* filter mentioned earlier serves as an example of a manually designed convolutional filter.

*VGG-16* is an architectural model of a CNN, which was developed to classify images. The "16" in *VGG-16* refers to the number of layers the network contains. The paper [7] proposed a network based on 16 convolution layers and integrates a method to predict pixel segmentation and to improve the accuracy of crack detection, avoiding the data augmentation. For this study, images of cracks collected by UAVs and images of buildings in Sydney, Australia were used. There is also another study [8] that uses *VGG-16* as a basis for developing the model for identifying cracks in concrete. This model was proposed by the *ImageNet Large Scale Visual Recognition Challenge* in 2014, and was trained on *ImageNet Dataset*, which consists of millions of images divided into thousands of categories. Cha et al. [4] developed a classic CNN to detect cracks in concrete surfaces and compared the results obtained with CNN to methods with edge detection tools, such as *Canny* and *Sobel*. The results of this study showed that the CNN had better performance in finding cracks in realistic situations [4]. Azimi, Mohsen et al. [5] state that, normally, two approaches are used to detect cracks in structures. One based on the image binarization section and the sequential image processing method.

## 4 Experimental Results

***Summary of GIMP Filter Survey and Results.*** After carrying out a study on the filters using GIMP and which of these would be appropriate for detecting cracks in images of road pavements, different images such as Fig. 3 were analysed. Another approach was attempted. Instead of detecting just one crack in the image, it aimed to detect all the cracks in an original road pavement image. After identifying all the cracks in the image, several GIMP filters, including *Erode* and *Dilate* were applied multiple times. From this study, a crack was selected from the top of the image and an attempt was made to improve the

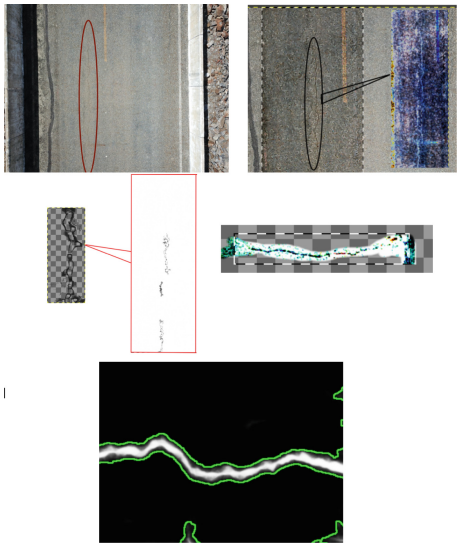


**Fig. 3.** Results obtained. The first is the crack identified on red, followed by the second imagem on the right, that was obtained by using the filters described above. On the third and fourth image is presented two isolated cracks. Finally the last imagem is the result obtained by using the VGG-16 and image processing. Images produced using GIMP and Python, both open source software. (Color figure online)

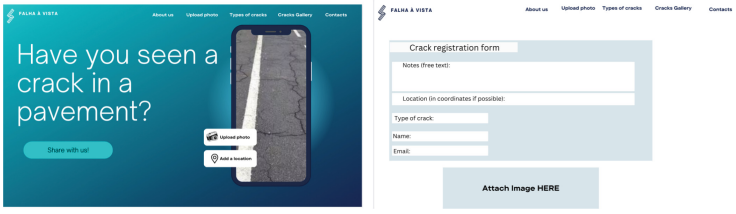



**Fig. 4.** Initial and cracks submission page of the developed website.

detection of the crack by applying more filters. However results are still far from what is needed for our goal.

***Results Using CNN and Image Processing.*** Hybrid strategies have been used to improve and increase the automatic detection of cracks in road pavements [1]. Like the approach proposed, a combination of the use of a neural network and image processing to detect cracks in road pavements Fig. 3.

***User Connection.*** In order to connect the user to this approach, a website was developed. The user is able to upload photos of road pavements taken with cameras or phones. The user can also make a brief description of the crack and evaluate the type based on the descriptions and imagens presented on the website, insert the coordinates where the photo was taken and insert the name and email. Figure 4 presents some prints of the developed website: https://falhaavista.web.app.

## 5 Conclusions and Discussion

The presented crack detection method offers significant advantages. It is highly accessible, requiring minimal resources for data collection, where standard cameras or drones can be employed, making it a cost-effective solution. Moreover, the automation of crack detection reduces the reliance on manual inspections, particularly valuable in regions where dedicated inspection campaigns are challenging.

This paper introduces an innovative approach to road pavement crack detection using digital imagery and deep learning techniques [1]. This method provides a cost-effective and accessible means of monitoring road pavements, enhancing their durability and road user safety. The development of a dedicated website for collecting images and aiding in their characterization further emphasizes the potential of this research. Future work will focus on measuring the performance of this approach in real-world crack pavment characterization to assess its practical utility and capabilities.

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# OMICRON. An Intelligent Road Asset Management Platform

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**Abstract.** The OMICRON project develops an Intelligent Road Asset Management Platform integrating a broad portfolio of area specific innovative technologies to enhance the construction, maintenance, renewal and upgrade of the European road network. The project improves the whole asset management pipeline focusing on four pillars: modular construction of bridges, road inspection digitalisation, predictive maintenance and smart execution of intervention actions.

OMICRON's Intelligent Platform enables the digitalisation and automation of a relevant portfolio of road management tasks which are still very labour intensive. Thereby, OMICRON aims to pave the way to the roads of the future, addressing the reduction of fatal accidents related to maintenance actions, the reduction of traffic disruptions, the reduction of maintenance costs, and the increase in road network capacity.

**Keywords:** Roads · Asset Management · UAS · Robotics · AI · Digital Twin

## 1 Introduction

Roads, and their integrity, are a foundation for world economic growth. According to Eurostat, 81% of passengers in Europe and 77% of inland freight were transported by road in 2020, the highest for a decade (1). Ireland (99%), Greece (97%) and Spain (96%) were at the top of this list.

This context of high-quality services and maturity has a dark side related to the ageing and necessary upgrading of road infrastructures. A large portion of Europe's road network was built between the 1960s and 1970s, and its design envisaged a lifetime of 50 years, using technologies that were not as advanced as nowadays. Consequently, significant effort is needed to monitor and maintain road condition to avoid the repercussions of an outdated system. This is not limited to an increase in accidents affecting public safety, but also threatens the welfare of road workers and increases pollution and emissions.

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Given the fact that current inspection and maintenance systems are still very labour-intensive, it is clear that the European road sector needs to improve its inspection, maintenance and management procedures. Industry 4.0, with the rise of robotisation, digitalisation and Artificial Intelligence, and Climate Change mitigation, with the aim of reducing emissions, are changing the paradigm of both the technical requirements of roads and the techniques to be used in asset management.

In summary, the sector demands technologies for the management and maintenance of road infrastructure with the following objectives:

- To improve road services in terms of safety and connectivity.
- To reduce costs derived from the high volume of maintenance activities that will be necessary in the coming years.
- To increase the capacity of the network, making a smarter use of it.
- To enable sustainable asset management, moving towards decarbonisation following the European Green Deal (2).

The OMICRON project, funded by the European Union's Horizon 2020 Research and Innovation Programme, addresses the aforementioned needs of road design, construction and maintenance, as it aims to improve road condition throughout its lifecycle, from inspection and data management to maintenance execution.

## 2 OMICRON's Intelligent Road Asset Management Platform: From Design to Maintenance Execution

The objective of OMICRON is the development of a portfolio of technologies to comprehensively address the aforementioned challenges. Thus, OMICRON proposes an **Intelligent Road Asset Management Platform** concept with the aim of automating, robotising, and optimising road management processes. The platform is based on four main pillars (Fig. 1), presented in this section, covering the whole road lifecycle.

1. **Pillar 1.** Modular Bridge Construction.
2. **Pillar 2.** Road Inspection Digitalisation.
3. **Pillar 3.** Predictive Maintenance.
4. **Pillar 4.** Smart Intervention Solutions.

### 2.1 Modular Bridge Construction

OMICRON aims to enhance the construction methodology of road overpasses. The project specifically addresses hybrid bridges consisting of a central metallic girder connected to symmetric reinforced concrete girders at the sides. The objective is to study and enhance the connections between the metallic and concrete sections in order to propose design guidelines to promote a more effective modular construction of such bridges.

OMICRON has performed a comprehensive study of road overpasses, followed by several monitoring campaigns on bridges of the same type. In a second stage of the study, laboratory tests have been carried out on 1:2 scale prototypes for three solutions designed in the project, using different prestressing, connections, and diaphragm solutions.

The study provides guidelines to improve both the mechanical behaviour of this type of overpass, as well as its manufacturing and construction compared to traditional solutions. Thereby, OMICRON aims to address key industry demands related to agile and digitalised construction, accident prevention, lifecycle management, and traffic impact reduction.

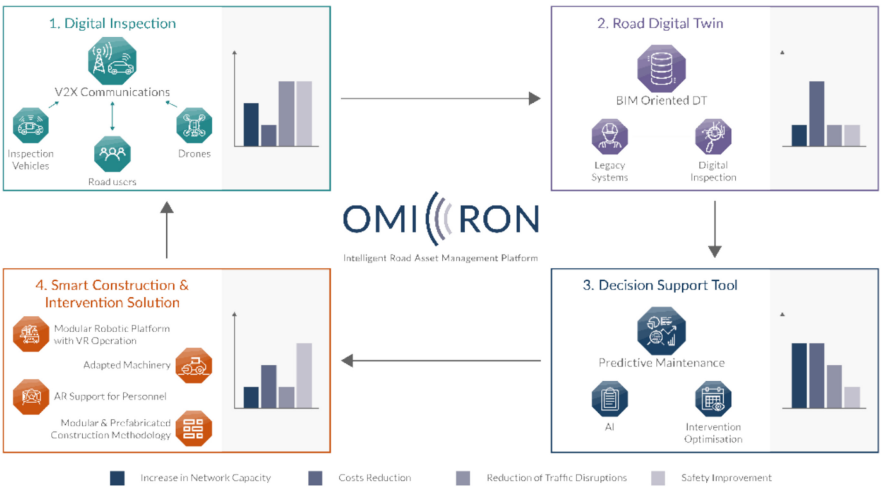



**Fig. 1.** OMICRON project concept covering modular construction, digital inspection, predictive maintenance and smart maintenance execution. Reproduced with permission from the OMICRON consortium, copyright OMICRON, 2024.

## 2.2 Road Inspection Digitalisation

OMICRON proposes advanced inspection technologies to avoid maintenance personnel exposure to traffic, enhance network availability through the automation of repetitive tasks, and reduce costs associated to road inspections.

The project develops **novel Unmanned Aerial Systems** (UAS) to improve the efficiency of current asset inspection processes. Firstly, OMICRON has created a collaborative multi-UAV inspection system. The use and coordination of UAS in inspection processes covering large areas enhances the effectiveness of inspections, increases reliability and process quality, and reduces inspection times. Furthermore, the project is developing *Detect and Avoid* technologies for drones, which serve as enablers for shared airspace use with other aircrafts (3). The key advantage of integrating these technologies into aerial inspection systems is the ability to conduct remote inspection flights over longer distances and at lower altitudes, allowing the coverage of larger areas. These aerial inspection systems are employed to capture high-quality images and generate 3D infrastructure maps.

OMICRON also develops innovative **terrestrial inspection vehicle technologies**. The project works on a system integrating a combination of sensors, including a mini laser scanner and other types of vision systems, currently under a patenting process. The

objective is to lower the costs of inspection vehicle systems to automatically capture spatial, visual and thermal data, enabling the assessment of pavement condition state.

Finally, OMICRON leverages **V2X (vehicle to everything) communications** capabilities to coordinate maintenance operations and road users. The efforts are focused on the use of C-ITS (Cooperative Intelligent Transport Systems) communication technologies and Road Side Units (RSUs) to provide short-range communications according to European ITS-G5 regulations. Thereby, the control centre gathers information from various sources, including location and maintenance work status, weather or traffic, among others. This information is transmitted to road users via the deployment of standardised C-ITS services.

### 2.3 Predictive Maintenance

The information captured by OMICRON's inspection technologies as well as all road data sources are harnessed for the creation of **OMICRON's Road Digital Twin** (DT). The DT is conceived as a digital replica of the infrastructure in an environment that combines (i) the BIM representation of singular assets, (ii) the GIS representation of linear assets, (iii) dynamic data from infrastructures, and (iv) the information and analysis conducted on this data (Fig. 2).




**Fig. 2.** Digital Twin visualisation. Analysis of modes of vibration as a step in the DST. Reproduced with permission from CEMOSA, copyright CEMOSA, 2025.

These sources of information provide large volumes of data to generate this digital representation of the infrastructure. Thereby, an innovative workflow has been created within the Digital Twin, based on a graph-oriented database, to mimic real road assets in all their relevant aspects, including geometry, condition, and all necessary information for comprehensive analysis.

The necessary processing chains (including different data management, integration, and services layers) have been defined to process and store data from inspection activities

and other sources, transforming them into information available in the Digital Twin and the various analysis streams, including the Decision Support Tool (DST).

The goal of **OMICRON's Decision Support Tool** is the optimisation of maintenance interventions and resources (4), considering various sources of uncertainty, including asset condition and other operational environmental factors. This system enhances existing intervention planning workflows and aims to establish a stable connection between data collection, information extraction, road network state awareness and automated intervention execution.

The guiding principles of this tool are infrastructure condition prediction, risk assessment, and infrastructure maintenance actions optimisation. Additionally, the system considers traffic impact and resource optimisation making use of the information from the Digital Twin.

OMICRON's DST is focused on four main interlinked use cases: (i) pavement condition prediction using historical data on road parameters such as IRI, SFC or deflexion; (ii) Structural Health Monitoring (SHM) for bridges applying Artificial Intelligence techniques; (iii) digitalised inspection processing; and (iv) planning and optimisation of maintenance activities.

### 2.4 Smart Intervention Solutions

The last innovation pillar within the project focuses on the automated and robotic execution of road maintenance activities. OMICRON has developed a **Robotic Modular Platform** to perform multiple road maintenance actions, building a robust business case for the implementation of robotic processes in labour intensive road tasks. The platform currently undertakes the following maintenance activities, although the modular design of the system enables the adaptation to other tasks in the future (Fig. 3).

1. **Emergency interventions.** The platform includes a robotic module for the automated installation or replacement of safety barriers.
2. **Rutinary interventions.** The system supports these actions from two perspectives. First of all, concerning road safety, the system enables the automated installation of signalling and cones. Additionally, a module has been developed with the objective of cleaning road and tunnel signals and lighting.
3. **Extraordinary interventions.** The platform includes modules for (i) signalling installation during construction works; (ii) laser-based removal of lane markings (avoiding the use of methods like black paint); and (iii) sealing of pavement cracks.

The robotic platform has been designed to be teleoperated using Virtual Reality (VR) or Augmented Reality (AR) systems, depending on the type of intervention. Thus, VR and AR applications have been carefully selected with the aim of reducing workers' exposure to hazardous situations while assuring maintenance action efficiency.




**Fig. 3.** Robotic Modular Platform test moving a cone. Reproduced with permission from Tekniker, copyright Tekniker, 2024.

## 3 Conclusion

The overall objective of OMICRON is to promote the digitalisation and safety of the European road network through the implementation of the Intelligent Asset Management Platform presented in this article. The demonstration and evaluation of the platform is being performed in three stages with the aim of reaching TRL 7 in various pilots in Portugal and Spain, including a final TRL 7 demonstrator at the A1 in Italy.

OMICRON aims to have a significant impact on road asset management, which can be summarised in four main areas: (i) the reduction of fatal accidents related to maintenance actions; (ii) the reduction of traffic disruptions; (iii) the reduction of maintenance costs; and (iv) the increase in road network capacity.

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# Geofencing to Accelerate Digital Transitions in Cities: Experiences and Findings from the GeoSence Project

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**Abstract.** Geofencing is a tool that offers innovative solutions to manage and control traffic, transport, and mobility. The technology enables cities to define digital zones and to create dynamic rules for mobility within these zones. Here we report on three geofencing use cases, their results and lessons learned that were conducted as part of the joint European project GeoSence. In the city of Gothenburg, the performance of a geofencing-based retro-fitted intelligent speed assistance system was tested and evaluated in 20 vehicles of publicly procured transport services to support drivers in complying with new speed regulations around schools. In Munich, geofencing was used to implement and enforce a new station-based parking regulation for shared e-scooters in the city's old town. Thirdly, in Stockholm preconditions, processes and workflow for continuous changes and updating of the underlying digital geo-data bases were analysed to better understand institutional and practical challenges to implement geofencing-based digital transitions in future. Findings from the use cases and project accompanying surveys are evaluated regarding the general topics of transport management, including issues of data sharing and management, stakeholder involvement, technical & vehicle readiness, feasibility of technical platforms, as well as institutional problems related to governance, policies, resources and the acquiring of necessary competencies.

**Keywords:** Geofencing · ISA · micro-mobility

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# 1 Introduction

## 1.1 Geofencing as a Tool for Digital Transition in Traffic

Societies are faced with many challenges that will require collaboration and innovative solutions to be solved. One of the challenges facing cities is the management - and planning of traffic, balancing between increased accessibility and availability for users while dealing with issues such as congestion, traffic accidents & incidents, and health and environmental issues. Investing in new physical infrastructure is needed but is usually very expensive and cities need to find more cost-effective ways to plan and manage traffic. New digital and connected solutions, such as geofencing, are being developed with the potential to effectively reduce these issues. Geofencing and how it is applied is shown in Fig. 1 below. Simplified, geofencing applications are based on 5 steps:

(1) **Geographically bound information**: such as traffic rules e.g. parking, no-parking, speed limits, etc.
(2) **Communication from senders to receivers**: in this case, a transport operator has created a virtual boundary for parking (green), and non-parking areas (red).
(3) **Receivers can locate themselves geographically**: i.e. vehicles/mobiles can position themselves geographically usually via satellite system, and/or via cellular, wifi-signals, Bluetooth, etc.
(4) **Receivers act on the information:** The driver is either informed or warned e.g. via a mobile phone or directly by the vehicle. The vehicle can also restrict e.g. speed, or allow/disallow the driver to park in certain areas depending on what was communicated in step 2.
(5) **Communication from receivers back to senders:** the system validates that the driver has acted correctly and is in compliance with what was communicated. The quality of the geofencing application will depend on these 5 steps and system perspectives such as user acceptance, governance, impact assessment and policy.

## 1.2 About GeoSence

GeoSence is a JPI Urban Europe project, funded by Horizon 2020, with the objective to design, trial and evaluate new geofencing concepts and solutions in cities and to propose new ways to deploy different geofencing applications. It started in 2021 and will finish in 2024 engaging partners representing research institutes, universities, and local/national public authorities from four European countries. Three cities: Stockholm, Munich and Gothenburg are involved in the project, focusing mainly on the following:

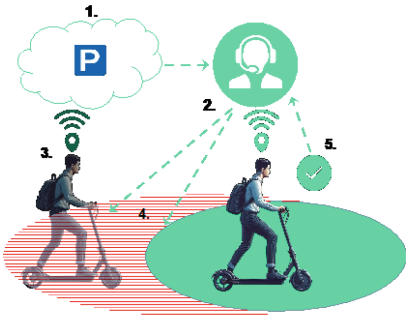



**Fig. 1.** Five steps of geofencing applications

(1) Stockholm is overviewing their role as a data provider and aims to improve their governance structure to better make use of georeferenced data such as traffic regulation data. This is an important precondition for developing new geofencing-based services.
(2) Munich is demonstrating how cities can successfully collaborate with e-scooter operators to develop safer and more accessible micro-mobility solutions. New regulations adopted in 2022 aim to prevent e-scooters from being parked where they can obstruct or endanger pedestrians, especially people with mobility impairments. The city has data-sharing agreements with e-scooter operators; the data gives insight, and a dashboard is used to monitor, create and communicate geofencing zones.
(3) Gothenburg is demonstrating lower speed limits in vulnerable areas in their special transport services. They are interested in understanding how geofencing services like speed control can aid the drivers and looking into how these services can be procured. This is an important step for cities to show that they are taking proactive measures to improve traffic safety for users such as schoolchildren and the elderly.

Complementary surveys, interviews and literature studies were conducted in the use cases. Also, surveys and interviews were conducted in 2021/2022 on the challenges and needs of European cities in using geofencing for urban traffic management [1].

## 2 Learnings

This chapter summarises key learnings from the use cases and complementary surveys, interviews and literature studies described in 1.2. The learnings focus on policy and regulation, transformation capacity, and readiness of underlying capacities, and key learnings from interviews and surveys conducted with transport and traffic experts representing the public sector, in different European countries.

### 2.1 Policy and Regulation

There is no legislation that directly prohibits geofencing. On the other hand, there is also no legislation that explicitly allows it, although there are exceptions in some countries. This means that different actors need to find their own way. However, there are rules that affect the chosen solution, such as GDPR (EU 2016/679). The GDPR governs how personal data is allowed to be collected and used, which can be particularly challenging for a city. The city often does not want personal data but only aggregated data from users. This means that the chosen geofencing solution needs to meet this need. The city may also want to procure vehicles or transportation services that are geofenced. One lesson from the GeoSence project is that the technology is not yet ready for large-scale procurement, but that more pilots are needed regarding this matter. Currently, it is possible to procure solutions based on retrofitting of vehicles from 3rd parties, but these solutions so far require personalization of vehicles for the technology to work.

### 2.2 Transformation Capacity

Access to and harmonization of data is a critical prerequisite for new applications and innovations in geofencing to emerge in the city. However, harmonized data and data availability alone are not enough for geofencing to significantly influence the city's transport and mobility ecosystem. In an analysis of the city of Stockholm, we see that another key factor is the city's ability and capacity for transformation in this area. This transformation ability is a combination of data management-, digitalisation-, and innovation capacity, combined with the city's ability to work horizontally and mitigate internal lock-ins while improving collaboration with external actors. By exploring geofencing as a technology, we see that the city can make significant progress in preparing for the sustainable mobility of the future by enhancing its ability to apply innovative geofencing solutions. If the city is in parallel and at the same pace are strengthens its overall transformation capacity.

### 2.3 Readiness of Underlying Digital Technologies

**Positioning**

Implementing geofencing requires a technical device to accurately measure a vehicle's spatial position and a digital system to process the geofences and geospatial information. Position data for geofencing is typically collected via Global Navigation Satellite System (GNSS). The spatial accuracy of modern GNSS sensors is about 1–3 m under ideal conditions but it can be affected by various factors (e.g., tall buildings, tunnels, or dense urban environments), introducing position errors of several meters.

The use cases in Gothenburg and Munich illustrated the challenges posed by GNSS inaccuracies. In Gothenburg inaccuracy led to issues with the detection performance for a geofencing-based retrofitted Intelligent Speed Assistance (ISA) system. When two roads ran closely alongside each other - one within and the other outside a geofenced area - the system sometimes triggered erroneous feedback (i.e., false positive or false negative errors, both resulting in wrong speed limit suggestions). Even though this occurred rarely, it affected the perception of effectiveness and acceptance among the participating drivers negatively. However, the collected data offers the chance to identify and analyse such issues and to adjust and improve geofences and system functions.

In Munich, parking zones for e-scooters were geofenced. The inherent limitations of GNSS accuracy together with the small dimension of the parking zones (2 x 10 m) cause a low reliability to detect an e-scooter within a parking zone. To prevent this, a tolerance range (approx. 20 m) is therefore applied to verify correct parking. Nevertheless, users experienced that e-scooters could not be returned despite standing within a parking zone, and in other cases e-scooters were returned in non-parking areas outside a parking zone. Presently, GNSS accuracy often falls short of providing reliable data to regulate e-scooter parking in urban settings. Therefore, additional sensor technologies are currently being tested worldwide to enhance the accuracy of the position signal.

The second prerequisite is a technical solution to process position and geofence information to generate feedback for drivers and/or to enable direct vehicle control functions (e.g., speed regulation or permitting/rejecting e-scooter parking). This can be achieved either by an on-board digital device using pre-installed data (e.g., maps and geofences) or

by sending the data via wireless broadband communication to a cloud-based service for processing and subsequent feedback information. The former approach demands more technically complex systems but provides more or less real-time performance. The latter method is suitable when temporal delays of several seconds between data transmission and reception are not critical for performance.

A prevailing challenge for geofencing implementations is the absence of standardized application interfaces and that few geofence solutions are available in new cars. Existing solutions are often closed systems with proprietary OEM-specific APIs for fixed functionalities. Retrofitted hardware is currently the only viable option for implementing geofencing solutions in a heterogeneous vehicle fleet, but applicability may vary. Barriers include elevated costs for retrofitted equipment and expenses for equipment installation, mobile data usage, and third-party services as well as potential issues concerning insurance and warranty rights.

**Digital Platforms**

Digital platforms are required to implement geofencing solutions in a meaningful way within an authority. The digital platforms are used to create and manage geofences and their policies in an easy and seamless manner, integrating it into existing digital processes and workflows, and processing data that enables the analysis, control and further adaptation of geofenced-based regulations (data for governance).

Our work in GeoSence revealed two ways in which authorities find appropriate digital platforms. One reported approach is that authorities develop digital solutions on their own, relying on open (source) and partly self-developed software, standards or data interfaces. The solution in this particular case was initially developed in an innovation project by a municipality in Norway and later used by other cities in the country. It provided digital maps with different layers of information for e-scooter companies including regulations for speed, access, parking and vehicle fleet size restrictions.

However, most municipalities will probably rely on procuring a commercial digital platform solution through a public tender. Especially for the micro-mobility sector (but also in the transport management sector) a number of commercial solutions have been developed in the past years. A commercial solution for geofencing in the micro-mobility sector has been implemented by Munich's mobility department. The solution allows the definition and management of geofences and their policies and provides functionalities to transfer the rules to the e-scooter providers in a standardized way. The dashboard solution also retrieves data about e-scooter usage and parking from the providers, can display them together with rules on a map, and integrates various tools for the analysis of the data. As solutions get more developed and mature with time this approach to integrate digital platforms is perhaps a more appropriate way for authorities, since it will require less expertise and human resources to handle technical and IT-related issues in the long run. Further important decision criteria for selecting a digital platform are scalability and interoperability to fit the needs of new or higher demands in future.

## 2.4 Challenges and Needs for Geofencing in European Cities

Learnings from the interviews and surveys conducted with transport and traffic experts representing the public sector, in different European countries [2] are in line with the learnings from the GeoSence use cases. Some of the key learnings are:

(1) *Potential, risks and barriers* – One of the potential things mentioned are a need of fewer signs and maintenance, leading to more efficient traffic regulation. One risk mentioned is that transport companies will use geofencing solutions mainly to buy one's way of access in the transport system. One barrier mentioned is the limited economic resources in municipalities to make this transition. (2) *Acceptance and stakeholder involvement* – Acceptance of geofencing for traffic management is easier with stepwise implementation for shared types of transport, starting with smaller pilots before scaling up. Successful implementation also requires multi-stakeholder collaboration, including private entities, the public sector, research, and the users. For instance, it is important to involve the right stakeholder with the required competencies at the right time, e.g., to set geofencing zones. It is also crucial to start with the user needs, rather than with the technological solution. (3) *Agreements and regulations* – Voluntary agreements between e.g., municipalities and mobility operators are one way to implement geofencing solutions, and if done correctly can develop the relation between the actors. The problem is that with voluntary agreements, the municipalities cannot guarantee that the operator will comply with the proposed measures. In some cases, new transport modes such as e-scooters can benefit from clearer regulations making it both clear for the operator what they need to oblige with, and also making the space of enforcement for the municipality clear e.g., to what degree they can demand that operators use solutions, such as geofencing. (4) *Data* – It is important that there is access to desired data, that it is of good quality, that the data is updated frequently and that the data format used is interoperable and standardised. In some cases, municipalities, are setting their barriers own by not providing access to the desired data. Data sharing platforms for sending and receiving data make setting up and communicating the zones more efficient.

## 3 Discussion

A basic premise for a geofence to reach its purpose is to have a marked-off area in a digital map, and this area must contain a rule or regulation differing for the area around. But to apply such a solution demands a vast set of factors for geofences to be fully implemented, A geofence use case is not only a technology or bundle of technologies but a system. Learnings from this project show us that for geofencing to accelerate the transition of urban management there is a need for a systemic approach that takes into consideration both the technology and the social context [2]. Geofencing could contribute to removing speed signs, remove parking signs – thus contributing to less infrastructure, it could make traffic more efficient and flow better, and even pollute fewer chosen areas. But a new digital system of transport management with geofencing, how can we get there? Our findings show that the main drivers and barriers can be related to the configuration of technological, institutional, and social functions. These are related to the readiness of underlying digital technologies such as for positioning and digital platforms, but also updated and shared data (technology), policies and regulation (institutional), and the transformative capacity, which means among others competence and knowledge (social). Depending on the use case of geofencing and the stage of implementation, the configuration of these three must be optimized. E.g., involve the right stakeholder with the required competencies at the right time. This example shows the need to develop

the technological & institutional functions and the technological & social functions in alignment The transformative capacity of Stockholm is a good example - combining innovation capacity together with the knowledge exchange and collaboration to move forward and accelerate the digital transition.

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# Digital Transformation in the Transportation Sector: Unleashing the Power of Data

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**Abstract.** The transportation sector is undergoing a profound transformation, utilizing digital technologies to move people and goods more efficiently. Data and analytics play a pivotal role as the core of digital transformation and insights-based decision making, as organizations are realizing the necessity of effectively leveraging their data assets. This paper discusses how advanced data analytics techniques, such as artificial intelligence, and solutions can be harnessed to embrace digital innovation and improve operations and services while respecting the transportation industry's unique requirements regarding stakeholder engagement, user needs, supply chain, legacy systems, stringent safety and security regulations, and system interoperability. This discussion is built around project examples: a Digital Engineering Information Management solution for managing large and complex road construction programs; natural language processing on traffic incident data; a telematic assessment of fuel consumption and emissions from road traffic; and the predictive maintenance of transportation infrastructure. This paper concludes with the proposal of a systematic framework that encourages best practices, clarity, efficiency, and successful outcomes and value extraction from data analytics projects for the transportation sector.

**Keywords:** Data · Artificial Intelligence · Digital Transformation

## 1 Introduction

The transportation sector is undergoing a profound digital transformation, utilizing digital technologies to move people and goods more efficiently, leading to new business models driven by changing expectations around solutions and services [1]. Data analytics plays a pivotal role as the core of digital transformation and insights-based decision making as organisations are realising the key to unlocking their full potential lies in effectively leveraging their data assets. In the meantime, digital transformation in the transportation industry also poses unique challenges as it usually operates within a more conventional framework where the infrastructure, regulations, and practices are well established [1].

Based on AECOM's global experience, this paper discusses how advanced data analytics techniques and solutions can be harnessed to embrace digital innovation and

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improve operations and services while respecting the industry's unique requirements regarding stakeholder engagement, user needs, supply chain, legacy systems, stringent safety and security regulations, and system interoperability. To prove the universality of these insights, this paper is structured around real project examples.

## 2 Discussion: Project Examples

### 2.1 Digital Engineering Information Management for Highway Authorities

AECOM's experience has been that in many cases across the transportation sector, engineering data are often owned by the delivery supply chain and only partially delivered to the sponsoring organisation. As more digital engineering software and tools emerge to the market, the ability for asset owners to manage the data across these tools gives opportunity for large efficiency savings, visualisation, and insight.

One recent road infrastructure project federated all engineering and environmental data and designs into a single system, allowing the sponsoring organisation to manage all digital information, amounting to over 2,000 layers. It was reported that time-saving efficiencies of up to 70% were recording in accessing design information, such as GIS or BIM data, photos, or survey information. Aside from efficiency and transparency, access to this data allows for innovative value-generating exercises. In this project example, 13,000 images from the photogrammetry surveys were processed into a 3D reality model of the project site, which gives engineers, surveyors, and other stakeholders a different perspective of the site and provides a backdrop to other datasets. Storing data in the cloud brings opportunities for streaming datasets to an individual's device without the need for expensive or expansive memory. 1.4 TB of data in this project are available to stream, leaving it now possible for a wider collection of project members to perform tasks such as creating dynamic cross-sections of the site, without needing to request such an action from the design team. This functionality further enhances efficiency savings. Finally, bringing digital engineering information and data into a single environment gives the managing organisation an audit trail for data access controls, interaction, and version control.

The project showcased how digital technologies can transform the conventional highway construction process by seamlessly blending with existing legacy systems and their data. This fusion of digital and legacy systems not only enhances operational efficiency but also leads to substantial cost reduction. Active stakeholder involvement played a pivotal role during this project. Engaging stakeholders ensured that their perspectives, concerns, and expertise were considered throughout the project's lifecycle. This collaborative approach fostered transparency, alignment of goals, and ultimately contributed to the project's success.

### 2.2 Natural Language Processing for Traffic Accident Analysis

The transportation industry includes many datasets with large unstructured text fields, with examples such as pdf documents, project issues or reviews, or health and safety reports. One category of artificial intelligence (AI), natural language processing (NLP),

allows large-scale analysis of text-based information that may have previously been inaccessible, as well as translation services or the extraction of specific information [2].

Data were recently processed with NLP for the purpose of classifying driving incidents, based on text descriptions captured by Traffic Officers in a mobile application. Approximately 18,000 of these records were processed, noting causes, behaviours, actions, and locations regarding the incident. Each of these were classified, with a dashboard describing the insights for each output.

A manual process of reviewing the notebooks of Traffic Officers that was previously unfeasibly expensive for analysis was therefore completed in seconds, for tens of thousands of entries. This is only possible due to the storage of the data in digital format and the advanced analytics of NLP. AECOM's transportation engineers were then able to perceive insights from the results, drawing and presenting conclusions to the client organisation that will feed forward into policy design and targeted areas for safety improvements for road transportation. This example of collaboration between subject matter experts and data professionals has become the default at AECOM, creating new opportunities for insight that were previously unfeasible.

### 2.3 Vehicle Telematics Data for Emission Analysis

One example where advanced data engineering techniques have opened new possibilities is with telematics and big-data analysis. Current methods for assessing the distribution of fuel consumption and vehicle emissions average measured vehicle speed over road links that may be kilometres long and disregard the impact of acceleration [3]. AECOM have demonstrated the use of telematic information from real road users to provide an enhanced level of granularity in fuel consumption analysis.

One example dataset encompasses over 6,000 vehicles over two months and includes 0.5 billion datapoints, describing every three seconds the motion, geolocation, and vehicle information for every active vehicle. Insights at national, regional, road, road section, or even specific geolocation therefore are all possible. Each journey was identified and assigned a unique ID, thus allowing the investigation of specific journeys or routes.

The telematic assessment of fuel consumption has three advantages to previous road-link level methodologies: 1) Data are collected at a scale orders of magnitude larger than current methods, simultaneously, and without the requiring costly equipment or roadside in-person measurements; 2) acceleration data add an extra dimension to existing standard road emission calculations in which this crucial factor is not currently considered, giving particular detail to stop/start traffic – a source that is poorly represented in current methodologies; 3) GPS locations of individual timestamps lead to a level of spatial granularity that may be tailored to the research question, rather than an assessment being limited to adhere to traditional road links.

A new scale of data provides opportunity for data science tools that enhance insight and can discover previously unidentified efficiencies. For example, driving styles may be classified with AI to reduce the impact of biases that may exist in the data. The power of this new way of considering emissions opens the potential for future investigations such as identifying, classifying, and understanding national emissions hotspots, or analysing and visualising the distribution of relative fuel consumption for different road, junction, or infrastructure types. However, as with the NLP analysis in Sect. 2.2, analysis is only

useful when coupled with the domain understanding of what brings value to organisations and end-users within the industry. It is widely understood that cutting road traffic emissions as part of sustainability is a key goal of highways authorities [4], but the input of subject matter experts allows targeting this to key roads, regions, or environments to align with more precise organisation goals.

### 2.4 Predictive Maintenance for Transportation Infrastructure

Predictive maintenance (PM) is a technique that forecasts the remaining lifespan of critical components through inspections or diagnostics, allowing these parts to be utilised up to their maximum service duration [5]. Employing maintenance scheduling based on real-time requirements, thereby lowering operational costs the technique finds extensive use in Industry 4.0 applications. Research also shows that predictive maintenance extends useful life and reduces failure rate [6]. These are illustrated in Fig. 1.

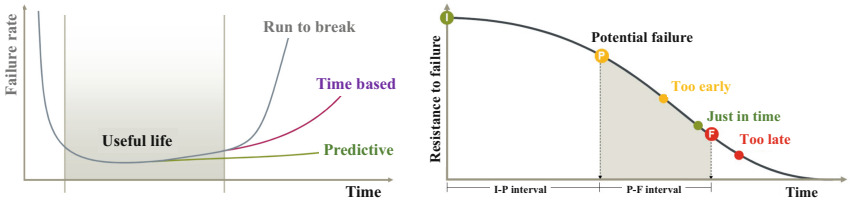



**Fig. 1.** Maintenance mode and failure rates (left). P-F curve with the PM objective (right).

Electric motors were selected as the equipment of choice for this project due to their extensive utilisation in transportation infrastructure, including applications such as baggage handling systems at airports, traction systems of rolling stock, and electric buses. The primary goal of the project was to leverage real-time sensory data acquired from these motors to determine the optimal timing for maintenance or replacement, thereby preventing substantial performance degradation and unexpected failures.

Highly sensitive vibration and temperature sensors were installed on the motors. These sensors transmitted sensory data to mini edge servers via nearby base stations. After pre-processing the data was sent through 4G communication to the cloud, where virtual models were deployed. These virtual models were created through data analytics and machine learning techniques applied to operational data, essentially representing the P-F curves or signatures of the motors. Real-time monitoring of the motors' condition against these signatures was conducted. The initial results of the tests demonstrated that the developed models could effectively offer early warnings, detect anomalies, provide short-term predictions of outages, and optimise performance.

The project highlighted the promise of applying predictive maintenance in transportation infrastructure, particularly in mission-critical sectors. Furthermore, it is instrumental in shifting the maintenance business model away from traditional time and material-based approaches towards more cost-effective performance and contract-based models. Additionally, predictive maintenance is frequently linked to the concept of digital twins,

which is a prominent focus of many governments. However, when it comes to implementing large-scale deployments, numerous challenges persist. Transportation infrastructure often operates in demanding environments characterized by high temperatures, radioactivity, water exposure, and magnetic fields, all of which can substantially affect data quality. Addressing these challenges necessitates substantial domain expertise and experience.

## 3 A Framework for Digital Transformation

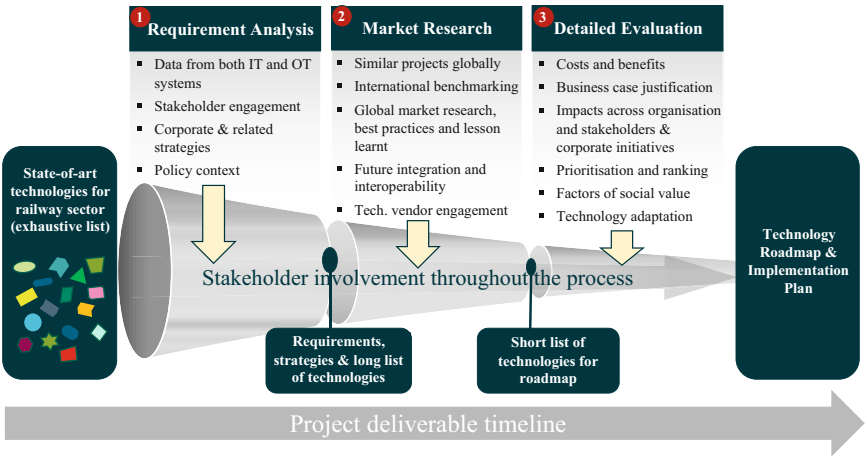



**Fig. 2.** A general framework for the execution of digital projects

Leveraging the knowledge gained from these projects and others, including their respective benefits, hurdles, and key lessons, a comprehensive framework is proposed (Fig. 2). This framework is designed to promote best practices, enhance clarity, mitigate risks, improve efficiency, and, most importantly, ensure the successful implementation of digital initiatives in the unique and challenging context of the transportation sector.

The framework places strong emphasis on evidence-based decision-making for selection of technological solutions and transparency at every stage of the project's life cycle. In the context of transportation systems, it seamlessly integrates operational technologies with information and digital technologies. Our project experience illustrates that this approach can lead to a significant enhancement in the adoption of digitalization.

## 4 Conclusions

With relevant examples from recent projects, this paper detailed some of the possibilities the digital transformation of the transportation sector has provided. By consolidating data, organizations and asset owners can leverage advanced analytical techniques to provide new levels of insight over their operations, projects, schemes, or sites. To make this

transition most effective they must be integrated into existing engineering design processes. This paper gave examples where the insight and understanding of domain experts combined with data processing and analysis techniques led to successful project delivery and to possibilities previously deemed unfeasible. As part of the digital transformation, upskilling subject matter experts has become a vital organizational goal; increasing the number of opportunities for improvements in efficiency and insight, and the ability to meet universal challenges such as climate change.

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# Collaboratively Developing Mobility as a Service as a Digital Policy-Enabler

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**Abstract.** As a new digital tool, Mobility as a Service (MaaS) provides the opportunity for novel approaches in delivering policy outcomes when led by public authorities. Harnessing the opportunity offered by MaaS requires not only a behavioural, operational and commercial transition for public bodies, but also a digital transition. Whilst complex, this transition opens up opportunities. Collaborative digitalisation means recognising that participating actors and stakeholders can often have competing motivations and objectives, reflecting the complexity of delivering MaaS as a system of digital and commercial relationships. However, with the right behaviours and frameworks, all parties can align towards a common goal. This cannot be achieved by chance, but only through concerted and considered effort to develop a culture of collaboration. This paper explores the evolving collaborative delivery model being taken by the West of England Combined Authority in its digital transition to deliver a policy led, customer focussed MaaS solution.

**Keywords:** Mobility as a Service · MaaS · collaboration · collaborative digitalisation · digital transition

## 1 Introduction

MaaS has been a point of discussion within the global transport sector for over decade [1]. Whilst the UK began investigating MaaS around the same time, MaaS in the UK remains in the trial phase. Almost all progress in the UK has been driven by the public sector, with funding largely coming from Transport Scotland's MaaS Investment Fund and the UK Department for Transport's (DfT's) Future Transport Zone (FTZ) trials.

One such FTZ funded MaaS project is that being developed by the West of England Combined Authority (CA). The CA is a city-regional level of local government covering the urban areas of Bristol and Bath, and surrounding rural areas. The vision for the project is to 'collaboratively deliver a regional journey planning, booking, ticketing, payment and information solution'. The scheme is being designed to promote active and sustainable modes, and will use marketing, incentives, and mobility credits to deliver public policy goals, aligned with elements of Level 4 of the MaaS typology [2].

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The West of England MaaS scheme is driven by internal and external collaboration, bringing together relevant stakeholders, end customers, and the wider public. The approach to deliver a highly digitalised solution through a collaborative process has not come about by chance, but through concerted effort to develop a culture of collaboration. Researchers have argued that MaaS requires collaboration between stakeholders that have not traditionally worked together, and the success of the scheme will highly depend on how all the actors work together [3] [4]. The benefits of cross-sectoral digitalisation related collaborations include information sharing, co-creating effective solutions, and pooling capabilities – all while keeping the needs of the public at heart [5]. Collaborative environments enable creative and participatory processes to solve complex problems – which are frequent when developing a MaaS scheme [6].

While the importance of stakeholder collaboration has been well documented in literature, there is much less work that considers how MaaS stakeholder networks and style of collaboration evolve over time. Against this background, this paper explores the evolution of the collaborative stakeholder ecosystem that has been involved in the design of MaaS in the West of England. We focus specifically on the period leading up to operational launch, when most of the design and key decision making takes place. By taking a real-life case study as an example, valuable lessons can be learned about the tradeoff between knowledge gained from wide stakeholder networks and the practicality and efficiency of a small (but growing) core delivery team.

## 2 Stakeholder Collaboration in the West of England MaaS

MaaS stakeholder ecosystems are complex and incorporate a large variety of actors outside of the core team [7] [8]. However, it is important to consider the feasibility of continuously engaging with so many stakeholders while also delivering a project with key milestones and deadlines. As such, at times it is important to scale up or down the involvement of certain stakeholder groups during the project lifecycle.

We define core stakeholders as strategic stakeholders that are essential for the delivery of MaaS. They are part of the decision-making process and have high levels of influence in design and delivery. Not only has the core stakeholder group expanded during the project, the way of collaborating has also evolved. Stakeholders outside the core group include the DfT, local government, customers and the general public, and wider stakeholders, such as academia and other public sector bodies not in the area.

To evaluate this evolution of stakeholder collaboration, the project has been split into stages (Table 1). These are divided by key decision points, where the aims of each stage, and thus the stakeholder collaboration, is substantially different. The nature of engagement between core and wider stakeholders is considered following Table 1, reflecting the evolving collaboration model through the staged delivery.

**Stage 0:** A fast-paced period, with a need to rapidly prepare a proposal that would meet the requirements of the funder, and local ambition. During this stage the core team was small, consisting of CA staff and external advisors. Although not in the core team, engagement with government bodies, MaaS providers, Mobility Service Providers (MSPs), and other stakeholders was undertaken to help scope the MaaS scheme.

**Table 1.** Project stages

| Stage | Details |
|---|---|
| Stage 0 | Project visioning and bidding for funding from the DfT's FTZ programme |
| Stage 1 | Objective review and validation post-funding award |
| Stage 2 | Project definition and scoping leading up to procurement of a MaaS solution |
| Stage 3 | Procurement stage with a focus appointing the MaaS solution provider |
| Stage 4 | The build and testing stage, leading to a MaaS minimum viable product |
| Stage 5 | Refining, implementing, and testing the operating model ahead of launch |

**Stage 1:** Funding was awarded in Spring 2020, coinciding with the first UK national lockdown in response to COVID-19. This necessitated a review of the project's objectives to ensure they aligned with new priorities. Additionally, consideration was given to how the project would be delivered, the nature of the resource model, the required stakeholders, and the delivery model. At this time the nature of the project was contractual, with consultants appointed to deliver review priorities.

**Stage 2:** With project objectives confirmed, project delivery commenced. There was a need to rapidly grow the capacity and capability of the core delivery team, with a significant increase in input from advisors and consultants from a range of organisations. A Collaborative Delivery Contract was developed between the CA and its consultant partners, so that the CA could access a wide range of skills and expertise from professional service providers and integrate them into the core delivery team. In part this was necessitated by the limited capacity at the CA to manage multiple commissions across a range of external providers. However, the primary objective was to ensure that collaboration was fundamental across the contracted parties, not just with the CA as client. Through this, the core delivery team began shifting to a 'one team' approach.

Although MSPs did not join the core team until Stage 4, a prioritised engagement plan was developed at Stage 2, with a 'key account manager' approach adopted to build direct 1–1 relationships with each MSP. This was critical to allow key MSPs to be ready to join the core team by Stage 4. Consideration was given to how MSPs could be encouraged to participate, with development of a negotiation playbook and use of role playing to prepare for discussions. Additionally, a market testing activity was undertaken to illicit input and feedback from MaaS providers. The intensity of activity was considerable and governed by stakeholder and market engagement plans.

**Stage 3:** Through procurement, the core delivery team grew to include other areas of the CA such as finance, commercial and procurement. The external advisor team remained consistent and the culture of collaboration continued as a unified team. External collaboration shrank significantly, as necessitated by procurement regulations.

**Stage 4:** The build and testing stage involved growing the core delivery team to its largest, with the addition of the MaaS provider, additional advisors to support with managing the provider, and addition of a marketing agency into core team activities. At this stage it was recognised that contractualising collaboration would only go so far in driving collaboration across the core team, and that in addition, a behaviour driven approach

was required. To achieve this, the core team participated in a two-day collaboration and team building workshop. The workshop involved each participant completing a Strength-Scope assessment, a technique used to understand an individual's strengths. By sharing the outputs of the assessment across the group, the team was able to understand collective and individual strengths, and any gaps/blind spots. Time was also spent discussing expectations and motivations of each individual, and preferred ways of working. The two-day activities resulted in a collaborative Team Charter being produced capturing the values, behaviours and commitments which the team agreed to work by; this charter proved a valuable reference point throughout Stage 4 and beyond.

Further effort was required to build a productive collaboration model with the appointed MaaS supply chain partners. Having a shared vision and motivations, and recognising where priorities may diverge and discussing those, has been key to identifying and overcoming potential obstacles. Regular meetings from an officer/employee level, through to CEO level, have proven fruitful for nurturing vested and shared interests.

With this expansion of the core delivery team, sub-groups emerged as project delivery was broken down into four main work areas: Customer, Scheme, Platform, and Monitoring & Evaluation. To maintain a 'one team approach', weekly all-hands Sprint meetings were held, to ensure team alignment around core objectives and milestones.

External collaboration increased with users, bodies delivering MaaS (for knowledge sharing) and business groups and trip generators (as potential partners). However, the closest external collaborators were MSPs, as we worked to integrate them. To support their involvement and extend the collaborative model further, a MaaS MSP Forum was established as a space for collaboration, and open and constructive dialogue. This forum has given opportunities for MSPs to collaborate directly together, enabling opportunities to enhance services for customers.

**Stage 5**: The scale of the core team grew with additional service providers joining the project. External collaborative activities and intensity reduced due to a focus on internal readiness and preparations for MaaS release, with the exception being user engagement to assist with service refinement.

To provide a visual representation of the levels of collaboration between stakeholders, the project team rated the level of involvement on a scale of 1–10 of each stakeholder at each project stage. This is presented in Fig. 1.

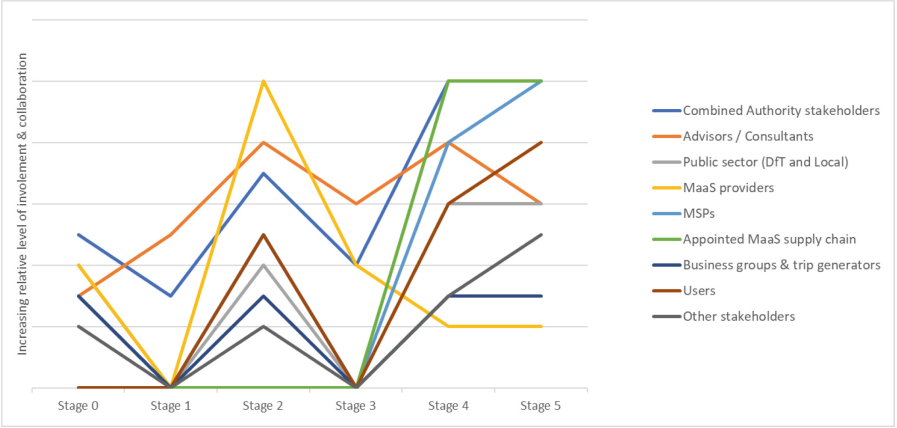



**Fig. 1.** Level of collaboration with stakeholders throughout the project stages

## 3 Discussion and Opportunities

This paper has evidenced that the scale of the stakeholder landscape associated with delivering MaaS is significant, as is the intensity of engagement associated. This reflects that MaaS is more than just a transport scheme, and more than just a digitisation programme. It is an inter-organisational, cross-functional, transformational service, which necessitates close collaboration; this is more so true when led by the public sector, where collaboration extends to include other governmental bodies, and multiple internal functions. As such, MaaS must not be seen as a singular, standalone digital transition; but rather a sectoral and organisational transition, where success is reliant on collaborative digitalisation. That MaaS is so relationship based must be understood when considering the emergence of MaaS within a UK transport market context.

This need for collaborative digitalisation across stakeholders necessitates widespread and intensive engagement. This has positives, such as capitalising on opportunities that emerge from collaboration, but the extent of effort and time required should be recognised, as this impacts delivery timescales, team capacity, and budget. As collaboration across stakeholders varies by project stage (Fig. 1), an agile, organic approach to engagement is as valuable in MaaS as having a well considered engagement plan.

For several stakeholders, their motivations and goals for involvement in MaaS may not align, or may be in competition. Competing motivations reflect the complexity of delivering MaaS as a system of digital and commercial relationships, and this should be recognised when collaborating through open dialogue. Whilst motivations may vary, with the right behaviours and frameworks, all parties can align towards a common goal.

In procuring a MaaS solution, the Authority spent significant time engaging upwards of 60 potential suppliers through market engagement. It was notable that when MaaS suppliers reference collaboration, this was seen through a technological lens. Collaboration was seen as an output (an API integration, a shared project plan, a shared risk register) rather than a behaviour for many MaaS suppliers, who struggled with understanding collaboration from a more relationship perspective, where shared goals, a common language and vision, and the right behaviours are essential.

A final reflection has been the challenge of bringing in the customer voice. At the earliest stages of delivery the customer voice was difficult to capture, given restrictions on movement during COVID-19, and natural diversion of priorities. Since then work has been undertaken to make the customer voice in the project louder, through a SuperUser group, which is involved with testing the emerging MaaS solution. However, the Authority perceives a strong risk in giving the public too much access to the testing versions of the MaaS solution, for fear of backlash on social media, and from the general media. In hindsight, an alternative approach would be to have a 'voice of the customer' represented at all key product decision and design stages.

The opportunities that emerge from the collaborative approach to digitalisation taken in delivering MaaS in the West of England are multi-faceted. MaaS itself, as a digital tool, is expected to enable more informed strategic and operational decisions, as a result of data generated; it also offers a new channel to directly engage and consult customers and the public. Realising this opportunity will require necessary systems, processes and ways of working within the CA to be updated – and often digitised for the first time. In terms of behaviours and ways of working, delivery of the MaaS collaboration can be held as an internal case study from which new ways of working, processes and systems can evolve. In this way, MaaS is a platform for business and organisational transformation, potentially improving how service delivery reaches and impacts on the general public. Finally, a considerable opportunity has emerged for the transport market within the West of England to work together more closely. With the de-regulated nature of the UK transport market outside London, MSPs typically compete, even across modes, but with MaaS the West of England offers a digital collaboration platform, a commercial environment to collaborate, and a 'safe' space via the MaaS MSP Forum for collaboration to take route. This extends as well to the Authority's own relationships with MSPs, which have grown more mature – particularly with non-bus service providers with whom local transport authorities in the UK typically have limited engagement.

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# MegaBITS: Greening Urban Mobility Through Smart Cycling

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**Abstract.** To achieve a 90% reduction in the transport sector's greenhouse gas emissions by 2050, the North Sea Region has to move (among others) from fossil fuelled vehicles to cycling, especially in urban areas. All kinds of projects are initiated to contribute to this objective, each with their own objectives and means. The MegaBITS project, and its predecessor BITS, are aiming at greening the European transport system through the use of Intelligent Transport Systems (ITS) in the cycling domain. ITS can contribute to the attractiveness of cycling, by improving cycling safety, improving speed, improve convenience and comfort and by giving the cyclist a better experience. This paper highlights the results of the BITS project, shows the first results of the MegaBITS project and sheds a light on the prospects of smart cycling.

**Keywords:** ITS · cycling · sustainability

## 1 Introduction

With an average GDP of €28.516 per capita (2002) for its 60 million inhabitants the North Sea Region is a very prosperous region. But this comes with high societal costs: fossil fuel dependence, air pollution, liveability issues. The North Sea Region, like other EU regions, should move towards a greener society, with the ultimate EU aim of at least 55% greenhouse gas reduction by 2030 and climate neutrality by 2050 [1]. For transport this implies a 90% reduction in the sector's emissions by 2050 [2]. To achieve this target, the North Sea Region has to move (among others) from fossil fuelled vehicles to cycling, especially in urban areas. This is exactly what the MegaBITS project [3] is doing: Greening urban mobility through smart cycling.

The main goal of this paper is to demonstrate that cycling policy should be more than just investing in bicycle infrastructure, bike parking, promotion and training. In the BITS project [4] over 30 ITS applications for cycling have been demonstrated and evaluated, varying from improving cycling safety to giving the cyclists a better cycling experience. In this paper a summary of the outcomes of the BITS project is given, we introduce the MegaBITS project and give an outlook on the smart cycling ecosystem.

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## 2 The Role of ITS in Cycling Policy

Derived from the Maslow's hierarchy of needs (Maslow Pyramid) and Herzberg's Two-factor theory, Mark van Hagen (Nederlandse Spoorwegen) and Bas Govers (Goudappel Coffeng) in 2019 developed a similar hierarchy of needs for cyclists, showing the factors influencing modal shift from car to bike. Firstly, cycling has to be safe and reliable, secondly it should be (relatively) fast and convenient (clear routes, easy bicycle parking, etc.). Once these levels have been matched, comfort and user experience become important.

Traditionally there are mainly four policy instrument to promote cycling: (1) building new cycling infrastructure, (2) Building bike parking facilities, (3) provide cycling education and (4) promotional campaigns for cycling. These instruments, or a combination of them, can be used to improve the cycling conditions: better safety, higher speed, more convenience, comfort and finally also a better cycling experience.

The Bicycle and ITS project (BITS) has added a new policy instrument: Intelligent Transport Systems (ITS). And coming with ITS also the provision of cycling data, either directly to the cyclist or indirectly to improve cycling policy. In fact ITS creates a digital layer on top of more traditional cycling policy instruments. ITS can influence each level of the cycling pyramid, as can be seen in Fig. 1 below.

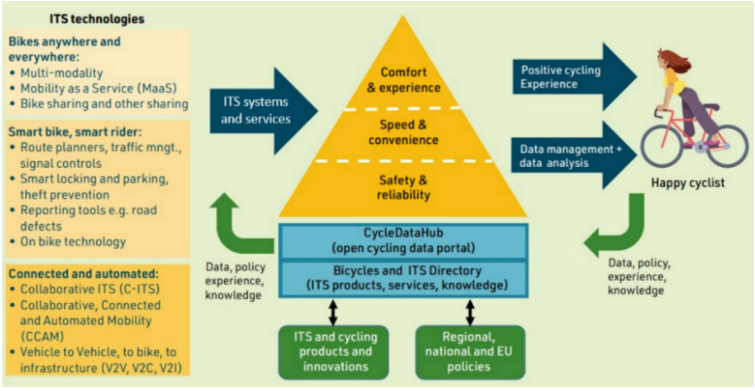



**Fig. 1.** ITS systems and services in relation to the cycling pyramid (source: MegaBITS project).

It should be noted that ITS is not a goal in itself. It should be used to fulfil the needs of the users (cyclists). The cycling pyramid forms the basis of the BITS project (2019–2022) and the MegaBITS project (2023–2026). Both projects are co-funded through the Interreg North Sea programme. In the following sections we will first present the main results of the BITS project, followed by a short description of the MegaBITS project.

## 3 The BITS Project

Table 1 summarizes a selection of cycling ITS applications and lessons learned from the BITS project. A more extensive overview can be found in the BITS legacy booklet [5] and at deliverables section of the BITS website [6].

**Table 1.** ITS applications and lessons learnt from the BITS project.

| ITS domain | ITS applications | Lessons learnt |
|---|---|---|
| Safety | • Warning cyclists for motorized traffic (Zwolle)<br>• Reducing cycling speed with dynamic signs (Amsterdam)<br>• Analysis of 3D camera images of near accidents (Bornem/Antwerp)<br>• Dynamic lighting at cycle lane (Zwolle, Aarhus) | • Projects have resulted in safer roads, less near accidents and lower speeds<br>• Installation of road safety systems often is more cumbersome than anticipated (digging, connection to electricity, privacy issues)<br>• Busy and complex traffic situations might not be suitable for additional dynamic signage<br>• Warning systems at one location might improve safety there, but reduce safety at spots without these systems |
| Bike sharing | • Bike library with sensors (East Riding)<br>• Bike sharing for tourists and citizens (Overijssel)<br>• Bike sharing for students (Zwolle) | • Each situation requires clear goals and a clear bike sharing concept tailored to the goal<br>• Shared bicycles can be equipped with additional sensors to provide useful information for policy making (dangerous spots, parking needs, pollution, frequented routes, etc.) |
| Bike parking | • Bike parking referral system (Bruges)<br>• Bike parking guidance system (Zwolle) | • Signs should be placed at strategic and visible locations<br>• Safe bike parking highly valued by cyclists (more expensive e-bikes, cargo bikes, fat bikes, etc.)<br>• Bike parking info can be used directly by cyclists, but is also useful for cycling policy (need for more parking spaces, orphan bikes, etc.) |
| Traffic lights | • Green light for cyclists and extra priority for bike couriers (Zwolle)<br>• Extended green going downhill (Aarhus)<br>• Faster green for groups of cyclists (Overijssel) | • Requires so-called ‘smart traffic lights’<br>• Faster green highly appreciated by cyclists<br>• Smart traffic lights give additional benefits with collection of cycling data (e.g. counting, green time)<br>• For cyclists it is important to know that they have received priority over cars. This should be communicated |

Apart from the ITS applications demonstrated in BITS, the project also produced the CycleDataHub [7] and the BITS Directory [8], respectively focusing on sharing data and sharing ITS applications for cycling.

## 4 MegaBITS Project

In the MegaBITS project seven cities and regions have different levels of bicycle infrastructure, bicycle use and bicycle policy, and therefore different priorities on the Bicycle Pyramid. For this reason, in the MegaBITS project each city/region promotes the digital transition of the cycling policy with a specific focus:

- Smart cycling corridor (Province of Overijssel, City of Zwolle, City of Enschede)
- Smart traffic management for cyclists (City of Copenhagen)
- Digitizing urban cycling (City of Hamburg)
- Engaging citizens (Province of Antwerp)
- Smart cycling management (Le Havre Seine Métropole).

The MegaBITS project brings the digital transition of the cycling sector to the next level. By initiating 5 ITS cycling flagships in 7 cities/regions, MegaBITS will fast track the deployment of ITS technologies to improve rider safety, comfort and convenience, thus making cycling a more attractive mode of transport. Not only will the project demonstrate smart cycling in the flagships. The project also plays a pivotal role in bringing together the various public and private stakeholders in the smart cycling ecosystem, where different parties and initiatives each have their own role in making smart cycling an integral part of the sustainable mobility policy in Europe.

## 5 The Role of Smart Cycling in Europe

### 5.1 Policy on All Public and Private Levels

Cycling is well-known as a sustainable, healthy mode of transport. Private efforts are focused on the bicycle itself. A transition is going on from "analogue" bikes towards e-bikes, speed pedelecs and cargo bikes. Meanwhile, governments are providing different kinds of bicycle infrastructure, varying from simple bike lanes to sophisticated "cycle highways". Recently, there is also more attention for the (potential) cyclists themselves, e.g. on how to initiate behavioural change. At the same time there is a transition going on towards smart cities and smart mobility to benefit from all kinds of technological solutions helping to achieve societal goals. Smart cycling is not yet part of smart mobility, but it should be. The BITS project showed the potential added value of cycling and ITS. And this will be continued in the MegaBITS project. After initial experimentation, it is now time to get smart cycling on the policy agenda at all government levels as well as on the agenda of the private smart mobility sector.

### 5.2 Bicycle Data

Smart mobility starts with data and digitalization. Data is needed for ITS solutions. The question is whether all data which is available for cars also has to become available for bicycles. Probably not, because a bicycle is not a car. So, data for automated driving is useful for cars but not for bicycles. But currently a lot of information is still missing for bicycles. That's because most bicycles, in contrast to cars, have no sensor on board to give full information about origin and destination, routing, speed and so on.

Nowadays, a lot of energy is put in combining different sources to get useful cycling data. ITS solutions like counting with cameras, smart traffic lights and cycling apps are growing and give more information than in the past, when manual counting was common. But this combination of sources never gives the complete picture, partly also because data is often owned by companies. The question is if complete and/or real time data is needed for the applications that are useful for cyclists or for cycling policy. That has to be analysed and organised. MegaBITS plays a role in demonstrating applications using floating bike data in many of its flagship projects, as well as in further developing the CycleDataHub. Alternatively, the European NAPCORE project aims at coordinating the accessibility of data, including cycling data, through the National Access Points. And additionally in proposing standards for the key cycling data categories. In this way cycling data can take their place in the European Mobility Data Space.

### 5.3 ITS Solutions

ITS solutions are useful for cycling/mobility policy. It can help to create safe cycling conditions, to prioritize cycling at intersections, to ease access to shared bicycles, and many more. Smart cycling thus is an additional instrument to promote cycling, next to good infrastructure, nice bikes and good bike parking facilities. But which ITS solutions are needed where? Here it is important to differentiate between different target groups, with different wishes and incentives. Cycling can for instance be divided into utility cycling, recreational cycling and logistic cycling. But also the cyclist as a person has different needs and wishes, depending on whether he is experienced or not, elderly person, scholars, etc. For policy implementers it is important to have access to a toolbox of useful smart cycling applications. And when there are successful projects it is important to scale them up. The BITS directory is the knowledge hub for smart cycling applications, where local and regional authorities can find a myriad of smart cycling solutions as well as best practices.

### 5.4 Smart Cycling Ecosystem

The MegaBITS project is focussed on the implementation of smart cycling solutions and cycling data at the local and regional level, especially in the North Sea Region. But the project aims at a much wider cooperation:

- With other smart cycling initiatives. Some of them are focussed on smart cycling, others only have it as a (small) part of their activities.
- At a European level, and not just in the typical cycling countries like The Netherlands, Belgium and Denmark.
- With public and private stakeholders.

This cooperation is needed in order to further boost the development of smart cycling applications and cycling data. This ecosystem of smart cycling actors and projects should work on a roadmap to enhance smart cycling in Europe, covering among others data standards, open cycling data, smart cycling use cases, best practices, governance and finance.

## 6 Recommendations on Smart Cycling

Smart Cycling and Cycling Data should be dealt with in a much more equal way as is the case with motorized traffic. We therefore recommend that more attention should be paid to the following Smart Cycling topics:

1. Cycling data:
   - ***Standardisation of bike data:*** Lack of standardisation leads to higher costs for ITS providers and also for the road operators responsible for cycling data. It also makes it more difficult to gather data and do analysis on top of it, as it is hard to compare the data without standards.
   - ***Research on Floating Bike Data (FBD):*** Further research on FBD is needed, e.g. with respect to standardisation, representativity, applicability for various use cases, business cases for service providers to provide FBD, privacy issues.
   - ***Data Collection and Harmonisation:*** Data on cycling is scattered, not accessible or representative, and not gathered in a consistent way. The EC should stimulate the collection and exchange of cycling data in a consistent and harmonised way.
   - ***Quality of data:*** Definitions should be harmonised, and there is a need for full geographic coverage. Many Smart Cycling applications are based on cycling data. The applications can be only as good as the quality of the data!
2. Smart cycling applications:
   - ***Awareness Raising:*** Smart cycling is not part of the toolbox of cycling policy makers, which means that more attention should be paid to creating awareness on the possibilities of smart cycling applications.
   - ***Cost/Benefit Evaluation:*** It is recommended to start studies focusing on the assessment of the costs and benefits of Smart Cycling, including investment costs, operating costs, benefits for the cyclists and socio-economic benefits (safety, traffic flow, environment, health, …).
   - ***Incubation and Scaling of the Smart Cycling Ecosystem:*** Authorities should financially support the implementation of Smart Cycling applications at the local and regional level. This will stimulate launching customers, help to overcome shortage of personnel and reduce risks.

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# Privacy-Preserving and Passenger-Oriented Solutions for Air-Rail Multimodal Travels

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**Abstract.** Nowadays passenger travels are more and more multimodal. Often advocated as the way to follow to strike a balance between sustainability and travel time, air-rail is a prominent example of multimodality. To accommodate the fast-growing business the travel and tourism industry is experiencing, operators are going through a continuous digital transformation including solutions based on wireless connectivity, smart-sensors, Internet of Things, and Artificial Intelligence. The goal is twofold: improving passenger processing and operations, and passenger experience. On the other hand, significant challenges to tackle and opportunities to unfold in terms of security, privacy, and optimization, are still only partially addressed. The EU H2020 E-CORRIDOR project develops a secure, collaborative, and confidential framework for information sharing and analysis. Solutions for the air-rail multimodal pilot seek to improve passenger experience, perform seamless authentication, enhance the cybersecurity posture of the transport operators, break down data silos existing among stakeholders, and better support Passenger with Reduced Mobility (PRM) and coordination among operators. This paper presents some of such solutions where privacy is the keystone.

**Keywords:** multimodal transport · identity management · privacy-enhancing technologies · smart airports · passenger experience · data sharing

## 1 Introduction

In the past, travels were considered matching the duration of a single ticket. Nowadays, this definition is limiting. Travel boundaries have now been stretched as multiple modes of transport are actually part of a single trip. *Door-to-door (D2D)* travels could start by taking local transportation or renting a car to reach the nearest train station, and then taking a flight to cover the longest segment to

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destination. The Flightpath 2050 [4] sets as a goal that 90% of travelers within Europe are able to complete their D2D journey within 4 h. Such a high-level goal requires: i) an evaluation of the entire journey rather than a single travel leg (i.e., the trip from point A to B), and ii) ease of access and cooperation between modes of transport. In Europe, two primary modes of transport for intercity travels are train and plane. Their combination is highly attractive to reach the Flightpath 2050 goal as well as to curb climate change by reducing 90% of greenhouse gas emissions in transport (as stated in the EU Green Deal), and improve connectivity while also taking into account the cost involved in a "green" transition and the impact on the environment posed by the construction of new infrastructures [2]. To better support a growing business, operators are continuously investing in the digital transformation, by means of wireless connectivity, smart-sensors, Internet of Things, and Artificial Intelligence. Indeed, in a D2D travel experience (from reservation to final destination), seamless access, personalization and availability of value-added services are identified as key factors for the future mobility [5]. Passenger experience can be improved only if accompanied with enhancements to passenger processing and operations.

*Structure of the Paper.* Firstly, we introduce the air-rail scenario highlighting current processes and needs (Sect. 2). Then, we describe the approach of the E-CORRIDOR project and a selection of its solutions for improving passenger processing, experience and operations (Sect. 3). Some remarks are in Sect. 4.

## 2 Challenges

A multimodal journey is built around services offered by multiple stakeholders. From the travel reservation, to check-in, service access, and request for added-value services. Here we focus our attention on the air-rail multimodality.

Currently, manual and reiterated procedures for identification and authentication to the services of each stakeholder (ground operators, airlines, border control, etc.) for check-in, baggage drop-off, security check, service access, custom border, and baggage claim are adopted. At each *touchpoint*[1] passenger information, often sensitive, are exchanged. Frequently this is performed with coarse granularity (i.e., all the information even if not strictly required are shared). *Challenge 1. Offer a seamless access to transport services while implementing the Self-Sovereign Identity (SSI) approach and its data minimization tenet.*

As infrastructures evolve the amount of collected data has surged. These data have the capacity of improving the performance of the transport operators, e.g., by estimating the queuing or service access time, or monitoring infrastructures and assets. As multiple stakeholders are part of the data collection, silos are built and their benefit is not fully exploited. *Challenge 2. Build a digital ecosystem able to break the data silos to analyze the collected knowledge for operations management, by means of privacy-preserving solutions.*

[1] A business jargon to define any interaction between customer and business.

The unfortunate COVID-19 pandemic exacerbated limits of transport services whose access procedures and user interaction flows were not always up-to-date and often based on manual procedures, causing increased waiting queues. Millions of requests of assistance per year are collected by the busiest airports and train stations from People with Reduced Mobility (PRM). PRM services are often sub-contracted and fragmented regulations coupled with the complexity of synchronizing the physical position of operators working for different modes of transport generates a degraded passenger experience. *Challenge 3. Improve the passenger experience (in particular for the PRM) by designing and adopting digital solutions, e.g., based on mobile devices.*

Recent sectorial initiatives have recognized important gaps and are working to find solutions. The IATA (International Air Transport Association) OneID[2] aims at offering the ability to identify and prove the passenger travel requirements before reaching the airport by means of trusted digital identities. In the joint IATA and ACI (Airports Council International) NEXTT (New Experience Travel Technologies) a vision for future travels is defined where data silos, interoperability, timely notification and big-data play a role in improving passenger experience considering expectation of both ageing and millennial populations[3].

## 3 Solutions

By placing the multimodal transport scenario at its core, E-CORRIDOR offers a secure, collaborative and confidential framework for information sharing and analysis. *Prosumers* (i.e., agents acting as producer and/or consumer) generate and share data, and are interested in extracting the contained knowledge. The E-CORRIDOR framework is built on top of two pillars: *data sharing* and *privacy*. Data sharing is achieved through the specification of *Data Sharing Agreements (DSAs)*. A DSA is a contract between data producer and the framework. It is attached to the data (with the *sticky policy* paradigm) regulating their access and usage. Properties of agents and data finely regulate the permissions. DSA are continuously enforced even during usage and can specify pre-processing operations. Privacy is ensured for all the data exchanged in the framework. While common approaches foresee data encryption for data stored and while in transit, E-CORRIDOR includes a suite of *Privacy Enhanced Technologies (PET)* to offer data protection by minimizing the amount of shared data and maximizing security during computation without losing functionalities of the offered services. Some E-CORRIDOR solutions are described in the following.

### 3.1 Mobile Enrollment with Verifiable Credentials

From reservation to destination multiple stakeholders are involved in a D2D trip. Identification and authentication need to be performed multiple times. Federated

[2] https://www.iata.org/en/programs/passenger/one-id/ [Access: Aug 2023].
[3] https://airlines.iata.org/2019/10/30/nextt-generation-travel [Access: Aug 2023].

authentication is an effective way to manage the process. The EU *eIDAS (electronic IDentification, Authentication and trust Services)*[4] is a regulation defining a framework for digital identities and electronic signatures having the legal validity of the ones in the "physical world". In the transport sector, the eIDAS identity management enables: i) interoperability and compatibility across borders (legal, operational and semantic in the EU single market), ii) error reduction in the passenger's files (as identities of European citizens are validated by the Member State). In the airport business, the potential benefit of the eIDAS identities has been estimated [3] on savings for over €650M annually. Indeed, airlines spend time in fixing and processing passengers' records containing errors, and, due to incorrect entries, receive fines and cover costs for repatriation.

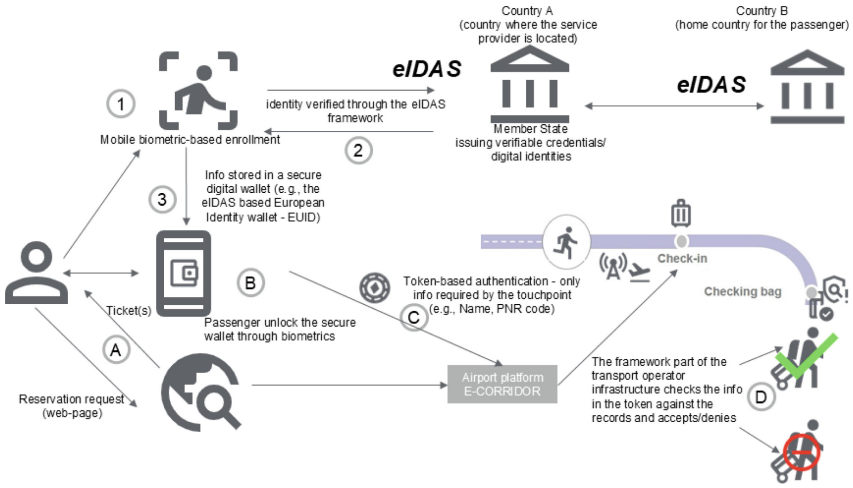



**Fig. 1.** Mobile enrollment for the transport sector based on eIDAS verifiable credentials. *Icons from* https://fonts.google.com/icons *Apache License Version 2.0.*

The solution designed for pan-European travels enables an End-to-End authentication based on eIDAS verifiable credentials and the SSI approach. The entire flow is managed through a secure mobile application as represented in Fig. 1, where steps marked with numbers are performed only once at home, and the ones with letters are specific to each trip. The passenger enrolls at home by means of: i) a biometric solution (currently face recognition comparing a video captured by the camera against a scanned identity document), ii) a digital identity from the eIDAS framework. The service provider can be hosted in any member state (country A in the figure) and interact with the home country of the passenger (country B) to retrieve the verified credentials. Information is stored in a secure wallet on the passenger's mobile phone. To reserve a trip, the passenger needs to unlock the information contained in the wallet. At each

[4] https://digital-strategy.ec.europa.eu/en/policies/discover-eidas [Access: Aug 2023].

touchpoint a token with only the minimum amount of information is created and shared (e.g., only Passenger Name Record, PNR could be enough at the bag drop desk).

### 3.2 Privacy-Preserving Service Discovery

At reservation time, during a layover, or once at destination, passengers may consider value added services. Two main examples are while planning the trip (e.g., train and flight options, hotels, local attractions) and while waiting for the next travel leg (e.g., looking for shopping and dining options). Currently, passengers have to either manually sift through the various offers or give up their data (such as constraints and preferences). Indeed, without sharing any information the passenger could wander in the train station or airport terminal ending up discovering that the queue in front of their favorite restaurant is too long considering the available time, or the favorite food is over.

We designed a privacy-preserving interest-based solution for the discovery of value added services. In such a way, the passenger can input their preferences and receive the best matches without compromising the privacy of any data. The setting foresees a *client* used by the passenger to express their preferences, and the *host* located in the premises of the transport operator. The latter is connected with the service providers which have knowledge about availability and characteristics of their services (such as the type of cuisine, distance, cost range, and estimated waiting time). Client and host exchange information through the secure Two-Party Computation (2PC) using the Yao's protocol [6]. In such a way a preference matching is performed while maintaining the confidentiality.

Two different scenarios have been considered for the air-rail project pilot: restaurants and hotels. Notably, in the second scenario our solution [1] has been connected with a testbed environment of Amadeus[5], a global distribution system. Passengers can use their own smartphone or a public totem to initiate the search. The designed solution can be applied more broadly to other scenarios where service personalization maintaining the data privacy has a pivotal role.

### 3.3 Localization and Digital Wayfinding

Due to their size, navigating in train station and/or airport terminals is not always easy. Moreover, passengers will have to go through touchpoints varying for each journey according to their reservation. The localization and digital wayfinding solution prompts passengers with real-time information tailored to their journey and guides them to their relevant touchpoints and personal points of interest, all while preserving their privacy.

The passenger position is estimated by means of signal degradation-aware trilateration models. Computations are made locally on the passenger's device and no information about the computed position is shared. To improve accuracy, Bluetooth beacons are deployed with higher density close to the points of

[5] https://developers.amadeus.com/ [Access: Aug 2023].

interest. Data about flights are gathered from FlightAware[6] (a service providing worldwide real-time flight information) and cross-referenced with the passenger reservation. When paired with the estimated position of the passenger, the optimal path and the suggested time to reach the next points are computed. Real-time information about flights (including delays) allows the tool to swiftly inform the passenger of their current schedule and suggest to extend their path with optional points of interest matching the passenger's needs (see Sect. 3.2).

The same solution can be used to facilitate the journey of PRM and the related airport staff. The airport can locate the available supporting assets (e.g., wheelchairs), and, with the PRM's consent, coordinate between operators (for a transfer between airport and train station) to offer a more efficient and dedicated assistance service[7]. The localization service can be used by the transport service provider to monitor their assets as well as to estimate service and queuing times without invading the privacy of any of the passengers.

## 4 Conclusions

With forecasts announcing a doubling of passenger numbers over the next 20 years and passengers' expectations encompassing service access, privacy, and personalization among the others, evolving the transport operator infrastructure covers a pivotal role. A reinvigorated excitement in the transport sector is paving the way to enhancement in the passenger services. The E-CORRIDOR project has designed and evaluated different solutions for passengers opting for air-rail journeys. Such solutions are aligned with the major sectorial initiatives and European efforts in the realm of digital identity, and take a step forward with the data sharing and privacy-preserving features build-in the E-CORRIDOR framework. On a technical standpoint, the framework has been designed to be compliant with the GDPR (General Data Protection Regulation) principles.

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[6] https://www.flightaware.com/ [Access: Aug 2023].
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# Spatial Density to Supplement Factors Used for a Screen Line Analysis and Travel Demand Estimation

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**Abstract.** Origin-destination (OD) matrices from floating phone data (FPD) are a valuable data source for screen line analysis. However, FPD does not contain any trip purpose information. To get additional information regarding the trip purpose distribution at a screen line, manual surveys with a huge sample size would be needed. Such surveys are very complex and expensive. Hence, they are rarely conducted in practice.

This study aims to overcome these shortcomings and presents a novel approach for assigning trip purpose distributions to OD-matrices. Based on limited but geocoded survey data, spatial structural data and routing information trip purpose distributions can be mapped on OD-matrices from readily available FPD. By using k-means based clustering techniques the spatial structure is used as a link between FPD and survey data.

The developed methodology was successfully applied to the Graz region in Austria, with approximately 300.000 residents and showed promising results. The derived trip purpose distributions were verified by utilising traditionally survey data. Therefore, this method is transferable and can be used as supplement to traffic volume screen line analysis to gain valuable planning information while keeping the survey effort and related costs to a minimum.

**Keywords:** screen line analysis · floating phone origin destination matrices · trip purpose

## 1 Introduction and Motivation

For the purpose of demand-oriented planning, transport planners require comprehensive origin-destination (OD) matrices for all trips passing through a screen line, such as a specific segment of the city boundary. This requirement can be fulfilled either by a well calibrated demand model or unbiased OD surveys with a suitable sample size. However, many metropolitan areas lack either of these data sources, yet they require such information for transport planning tasks. Utilizing passively generated Floating Phone Data (FPD) can minimize data collection efforts and improve accessibility to the required information. For instance, OD relationships, traffic volumes, and modal splits

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(the distribution of transport modes used) at the city boundary can be predominantly acquired from passively generated sources like permanent counting stations and FPD [1].

However, the distribution of trip purposes still requires manual collection, since the motivation behind a trip cannot be passively observed. Moreover, even if a traditional survey is conducted, the small sample size often hinders the usability and accuracy of such data. The proposed method aims to overcome this challenge by using multiple data sources and exploiting the known spatial dependencies associated with trip purposes. This dependencies, include among others, the different types of land use in a destination zone [2, 3] as well as the traveled time and distance to reach this zone [4].

A variety of clustering techniques for estimating trip purpose distributions from different input data can be found in the literature. Most researchers use either land use information of traffic zones as trip purpose distributions representations for destination traffic [2] or cluster travel survey data to obtain groups of passengers with similar travel behavior and enrich given OD-data with this information [5]. Most studies in this research field use OD-data for public transport, like smartcard or automated fare collection data [2, 3, 5] or trajectories from GPS supported surveys as an OD data source [6].

Different to these approaches, we use passively created OD-matrices from FPD for this study, which are easily and continuously available on a large scale while reducing the survey effort. The proposed method in this paper uses clustered spatial structural data as link between given OD-matrices and OD-geolocalized travel survey data. Therefore, we use limited structural data and travel distances between all traffic zones to generalize the information from the trip purpose survey data, which has a small sample size, and map the distributions onto the FPD OD-matrices.

The presented method was successfully applied to a screen line analysis at the Graz Region in Austria, which is a city of 292.630 residents. The screen line of interest is shown in Fig. 1. which represents the city boundary (blue), defined by several cross-sections (red). On disaggregated level we observed 20 different road cross-sections, which represent all major roads passing the screen line (Fig. 1).

## 2 Methodology

In this study we utilized four different data sources: For spatial clustering we used spatial structural data (number of working places, educational places and residents), as well as OD-routing information, like travel time and distance, between all traffic zones. The trip purpose information was derived from an OD-geocoded trip purpose survey which was conducted at 13 out of 20 different cross sections at the screen line. The survey was conducted between 6 am and 6 pm with a sample size of $n = 2377$ persons. As OD-information we used OD-matrices from FPD which were mapped to the road network. This allowed us to link each trip to a specific cross section, which are shown in Fig. 1.

We monitored only inbound traffic on roads. Furthermore FPD and survey data was weighted with available traffic and occupancy counts similar to [1]. An overview of the used data and developed methodological framework is shown in Fig. 2.

Initially, a spatial OD-dataset was created. This dataset consisted of one instance for each possible OD-relation within the study area. Every OD-relation was identified

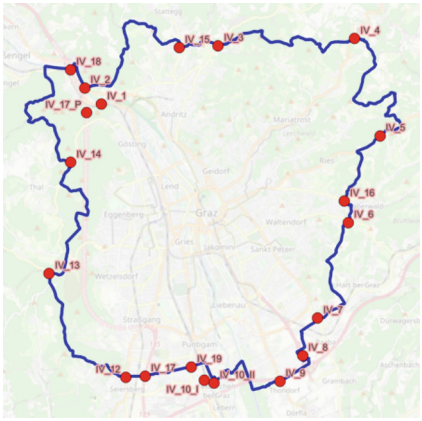



**Fig. 1.** Screen line and monitored cross sections. Background Map: © OpenStreetMap contributors, 2024 (License: ODbL), Map created using QGIS, 2024 (License: GNU GPL)

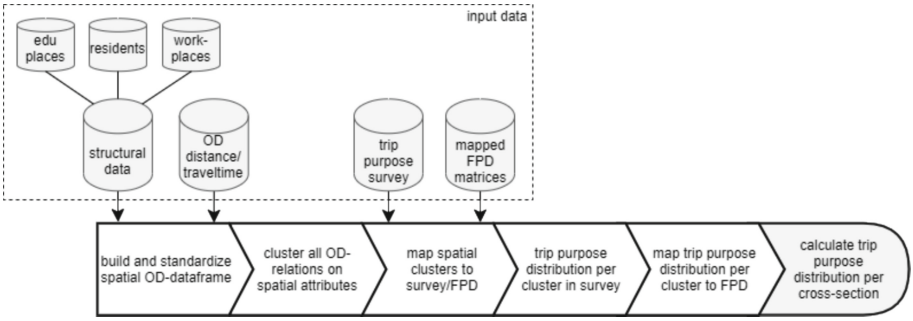



**Fig. 2.** Overview of the developed methodology.

by the ID of the origin and destination traffic zone and contains data about the number of workplaces, residents and places for educational purpose within both the origin and destination traffic zone, as well as the travel distance and duration between the two zones.

By using a k-means clustering algorithm the spatial OD-data was grouped into meaningful clusters. Before applying the algorithm on the spatial OD-data set the data needed to be standardized, meaning it had to be transformed to have a mean of 0 and a standard deviation of 1. Otherwise this could distort the results of the clustering as data attributes differ in scale [7]. The number of clusters, which is an input parameter for k-means, was determined by calculating the silhouette score. This score indicates the clustering quality based on the previously defined number of cluster [8]. Under the hypotheses that more than two clusters are needed to account for various spatial influences, we identified 9 clusters before observing a significant drop in cluster quality (see Fig. 3).

Each OD-relation in the spatial dataset was assigned to one cluster. The same clusters are transferred to the trip purpose survey and the FPD matrices by matching each OD-relation in both datasets with the corresponding OD-relation in the clustered spatial

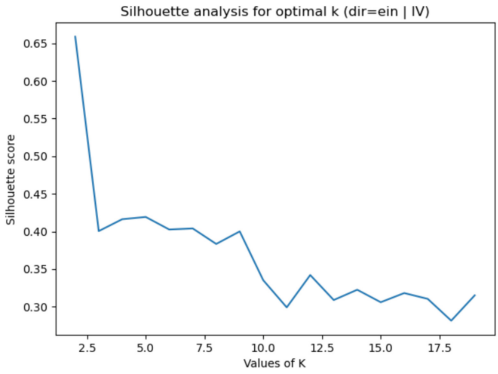



**Fig. 3.** Silhouette analysis for optimal number of clusters.

dataset. The IDs of the origin and destination traffic zones were used as link between the datasets to annotate both datasets with the corresponding cluster.

By utilising the annotated survey data, a trip purpose distribution per cluster was calculated. Each OD-relation in the FPD was assigned to a cluster and the calculated trip purpose distributions from the survey were transferred to the mapped FPD-matrices by use of the cluster annotation. This way we derived a trip purpose distribution for all existing OD-relations in the FPD.

An overview of the described data structure and dependencies is shown in Fig. 4.

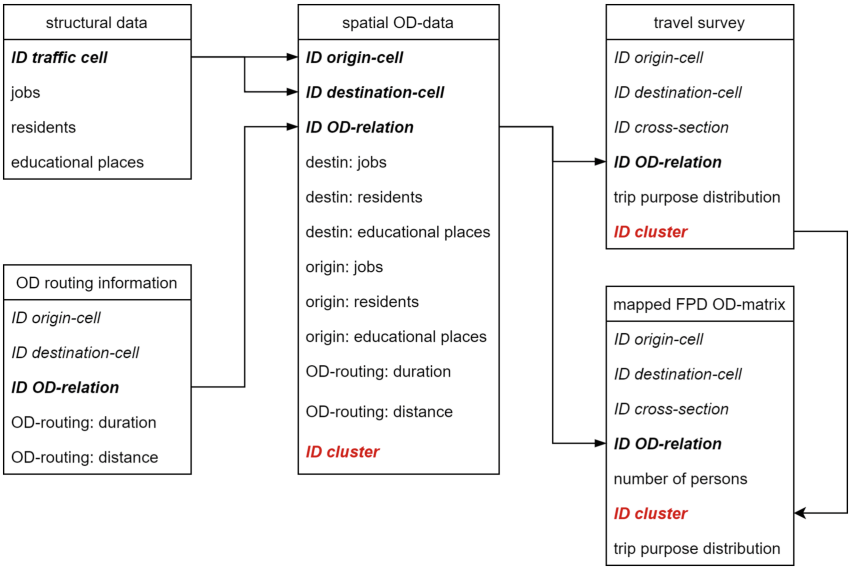



**Fig. 4.** Data structure and dependencies.

As the FPD was mapped to the road network and thus to the cross-sections, the different OD-relations could be aggregated for each cross-section and the screen line, respectively. By aggregating the mapped and annotated OD-matrices a mixed trip purpose distribution was obtained, which represents the final trip purpose distribution at the city limits.

## 3 Results and Conclusion

The developed methodology is a valuable supplement to estimate trip purpose distributions for OD-data used in screen line analysis. We managed to calculate a detailed trip purpose distribution for each cross-section of the screen line from OD-matrices derived from FPD and manual survey data with a relatively small sample size. Therefore, survey costs were reduced to a minimum. The methodology is transferrable to other regions.

Table 1 shows specific results for our use case in the region of Graz, Austria. The first column shows the aggregated trip purpose distribution for the whole screen line, while the second column shows the upper and lower boundaries of trip purpose distribution at different cross-sections. The last column lists the surveyed trip purpose distribution at the aggregated screen line.

**Table 1.** Trip purpose distribution from clustering model compared to survey data.

| Trip-purpose | cluster model (screen line) | cluster model (cross-sections) | survey data |
|---|---|---|---|
| Work | 28.7% | 25.0 – 37.7% | 31.7% |
| Education | 6.3% | 4.9 – 9.2% | 5.2% |
| Leisure | 4.6% | 3.4 – 5.0% | 4.3% |
| Shopping | 7.9% | 5.5 – 9.0% | 7.3% |
| Private | 14.5% | 13.9 – 16.0% | 15.0% |
| Home | 29.6% | 21.0 – 31.8% | 26.4% |
| Business | 3.0% | 2.5 – 3.7% | 3.0% |
| Drop off / pickup | 5.5% | 4.6 – 5.8% | 7.1% |

The result of the cluster model is comparable and similar in scale to the surveyed distribution. The largest deviation between the modelled results and survey data can be observed for trips back home. While the model shows 29.6% of all trips passing the screen line going back home, the survey only shows 26.4% on this trip purpose. The surveys were conducted between 6 am and 6 pm. Therefore, some late trips back home might be missing in the data, which would be in favour of the higher value for trips back home in the model-based approach. The interval at the different cross-sections shows boundaries from 21.0% to 31.8% of all trips going home, which includes the value of the survey (26.4%). This large dispersion can be explained by different spatial structures along the screen line. Therefore, it's an expected and desired effect of the cluster model

to capture those spatial differences, which impact the trip purpose distributions. For all other trip purposes, the distributions obtained from the model are comparable to the survey data. In most cases the results from the survey data are within the interval of the different cross sections computed by the cluster model. Only for drop off and pick up trips the survey data is outside the interval. This discrepancy could suggest that either the model or the survey fails to accurately capture this specific trip purpose.

A significant benefit of this method is its ability to depict the distribution of trip purposes across all cross-sections with the same level of detail as found in the survey (covering eight distinct trip purposes), despite the constraints of a small sample size. For the method's further refinement, it is advisable to undertake a quantitative validation, on cross-section level, through a comprehensive control survey. For further improvements of the spatial cluster model, we would recommend using additional structural data which can represent the shopping and leisure potential of a traffic zone. These data sources are not always easily available in a good quality. Therefore, this framework and its transferability would benefit from a supplementary method to calculate these potentials from open data.

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# Collaborative Digitalisation and the Future of Networked Production: Exploring Decentralised Technical Intelligence in Supply Chains

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**Abstract.** Networked production, supported by advanced logistics and supply chain processes, is crucial for companies to stay competitive and foster cooperation and integration of production resources. It replaces sequential processes with dynamic arrangements, presenting challenges like managing product variants, short life cycles, and process optimisation. Agility is vital for adapting to changes and natural disasters. Decentralised Technical Intelligence (DTI) is an approach that manages complexity and incentivises integrating new technologies in planning and manufacturing.

DTI involves distributed and autonomous intelligence embedded in interconnected systems, where humans and machines collaborate to achieve common goals. Humans bring unique skills like creativity and intuition, complementing AI's capabilities. DTI relies on a multi-agent architecture, enabling trust, interoperability, and data sharing for better decision-making and efficiency. The EU knowlEdge project exemplifies this by providing AI solutions that are distributed, secure, standardised, and collaborative, integrating cognitive technologies, data analytics, IoT and more.

DTI's human-centric design fosters a different quality of intelligence, leading to greater autonomy within multi-agent systems. To realise advanced networked production, a roadmap must be implemented, focusing on a vision, value promise, and development pathway. Europe can maintain its leadership in future networked production through this approach.

**Keywords:** Decentralised technical intelligence (DTI) · networked production · supply chain management · multi-agent system · roadmap · collaborative digitalisation

## 1 Introduction

In today's rapidly evolving global marketplace, networked production has risen to the forefront as a critical factor in maintaining competitiveness [1]. Initially driven by the pursuit of profitability, manufacturers have strategically focused on their core competencies, outsourcing non-core functions to specialised suppliers

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[2]. This transformation has led to increased fragmentation within the industry, necessitating a heightened focus on collaborative digitalisation.

Integrating state-of-the-art technologies and digital platforms enables companies to build robust connections between manufacturing operations and a diverse stakeholder network with local and global reach. This interconnectedness underpins competitive advantage by promoting broader supplier-customer engagement, cost efficiencies, operational improvements and higher product standards [3]. It also enables agility, rapid response to market changes and resilience [4,5]. Partnerships further accelerate innovation and align with technical paradigms such as collaborative design. [6]. This dynamic supports scalability through collaboration to manage peaks in demand and disruptions , while innovative management addresses increasing complexity [7] and contests traditional hierarchical norms.

In meeting these challenges, future-oriented companies adopt advanced technologies like AI and data analytics to devise new management strategies [8]. Decentralised Technical Intelligence (DTI) emerges as a transformative solution, merging human and machine intelligence in decision-making. DTI forges a decentralised network of systems, devices and agents, fostering collaboration that reduces hierarchical reliance. [9] Here, the workforce plays a key part, contributing a unique human dimension to the integrated system.

The article provides insights into the concept of DTI as a form of collaborative digitalisation, where distributed activities and expertise strengthen production processes. It introduces the European *knowlEdge* project, which provides a platform that enables DTI and collaboration and shows how pooling expertise and resources improves problem solving, ideation and product development. Finally, the article looks at the building blocks for a roadmap of DTI and collaboration platforms, highlighting core features such as technology fusion, intelligent control, seamless collaboration, co-creation, sustainability and resilience.

## 2 Decentralised Technical Intelligence

Decentralised Technical Intelligence (DTI) is an innovative concept that will revolutionise production by leveraging technologies for collaborative digitalisation. In response to the demands of networked production, DTI aims to empower decentralised, autonomous systems with embedded intelligence. This concept was born out of the European Technology Platform ManuFuture's call to increase productivity and efficiency in future manufacturing [9,10].

DTI utilises advanced technologies and coordination methods to drive significant improvements. It integrates multi-sensor networks, AI, machine learning, simulation and more to optimise processes, enhance performance and ensure sustainability. DTI empowers systems to self-optimise, adapt in real time and collaborate seamlessly between human and AI agents. Its objectives encompass high productivity, quality, efficiency, flexibility and resilience, contributing to a holistic improvement in manufacturing. Additionally, DTI strives for sustainability by setting zero-impact goals, including zero emission, zero defect, zero waste and zero downtime, ensuring both efficiency and responsibility. [9,10]

Building on earlier advances, DTI's interdisciplinary approach marks a next step towards more sophisticated production systems and contributes to a comprehensive transformation. By combining human expertise and advanced technologies, DTI creates an adaptable, intelligent production ecosystem capable of responding quickly to changing conditions. This convergence recognises the unique strengths of humans and machines and envisions a multi-agent architecture in which all stakeholders work towards common goals. [9] In this sense, collaborative digitalisation is the channel through which insights, decisions and actions flow, ensuring efficient interaction and seamless coordination within the production network. [11]

## 3 The KnowlEdge Platform and Its Implications

The European project *knowlEdge - Towards Artificial Intelligence powered manufacturing services, processes, and products in an edge-to-cloud-knowledge continuum for humans [in-the-loop]* (2021 – 2023) embodies principles of DTI and aligns with the concept of collaborative digitalisation [12]. The knowlEdge project (www.knowledge-project.eu) offers AI solutions that are distributed, scalable, secure, standardised and collaborative. The project's platform is designed to support the management of distributed data and knowledge sharing, thereby enhancing collaboration across the network (Fig. 1).

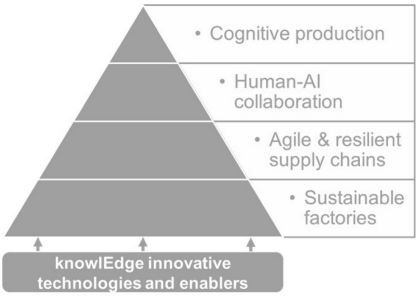



**Fig. 1.** knowlEdge response to the needs of industrial supply chains

The integration of various cognitive technologies such as data analytics, IoT, digital twin and edge-to-cloud computing further amplifies collaboration. These technologies enable real-time data collection, analysis and dissemination, ensuring that relevant information is accessible to all stakeholders in the network. This interconnectedness optimises decision-making, sustainable resource allocation and overall operational efficiency.

Moreover, human-centric design and human-computer interaction signify the project's commitment to involving human intelligence and expertise within the digital ecosystem. This aligns with the essence of DTI and collaborative digitalisation, which aim to combine the collective intelligence of humans and tools to achieve synergistic results and create a cognitive, continuously learning production system.

A pilot study exemplifies the platform's functionality, focusing on production scheduling. The use case encompasses supply chain optimisation, demand projection and production batch refinement within an industrial setting, with DTI technologies playing a pivotal role. Real-time data from production facilities

becomes usable via sensors and edge-based interfaces, integrating monitoring, analysis, and informed decision-making. Machine learning algorithms analyse historical and current data for demand forecasting, production schedule optimisation and bottleneck identification. Digital twins anticipate and simulate future scenarios, enabling proactive production plan adjustments. [13]

The fusion of AI and data analytics forms the basis for effective decision-making, error avoidance and time saving. The AI system consistently learns and broadens its knowledge base through documented anomalies, errors, and their resolutions. This positively impacts various performance metrics like scheduling hours, response time, productivity and forecasting accuracy [14]. User interfaces are pivotal in this interaction, prioritising human-centric engagement and real-time monitoring. They facilitate process adjustments and edge coordination, accelerating proactive decision-making and reinforcing synergy between humans and AI agents. This holistic approach creates a viable production system.

Essentially, DTI's multifaceted impacts accelerate the evolution of networked production. Firstly, it enhances collaboration among humans and AI agents, boosting decision-making in the collaborative supply network. Secondly, it expedites knowledge sharing, leveraging digital connectivity and standardised data exchange. Thirdly, DTI enables dynamic, autonomous operations, bolstering responsiveness and resilience. Fourthly, it drives innovation through enhanced collaboration, fostering adaptability. Lastly, DTI promotes standardisation for cohesive data exchange, benefiting from its decentralised nature.

## 4 Building Blocks of a Roadmap

A roadmap for advancing networked production through DTI can leverage collaborative digitalisation to drive Europe's production future [10]. Its foundation envisions integrated human-machine intelligence, seamless collaboration, and agile production networks. Within the frame of this article, the roadmap encompasses a number of building blocks, each contributing with a value proposition and based on various technological and organisational specifications, including:

- Integrating multiple technologies, such as AI, IoT, data analytics and cyber-physical systems, to create a holistic digital ecosystem
- Establishing standardised interfaces for seamless interactions
- Ensuring robust data governance and security
- Designing for human-centric collaboration
- Encouraging real-time knowledge sharing for continuous learning
- Empowering DTI agents for agile decision-making
- Promoting decentralised operations and resilience
- Fostering partnerships to accelerate innovation

The outlined specifications serve as a foundation for the roadmap's building blocks, which propel networked production through the implementation of DTI (Fig. 2). Additionally, the roadmap could also function as a dynamic research agenda, guiding ongoing innovation efforts [15]. The following five building blocks

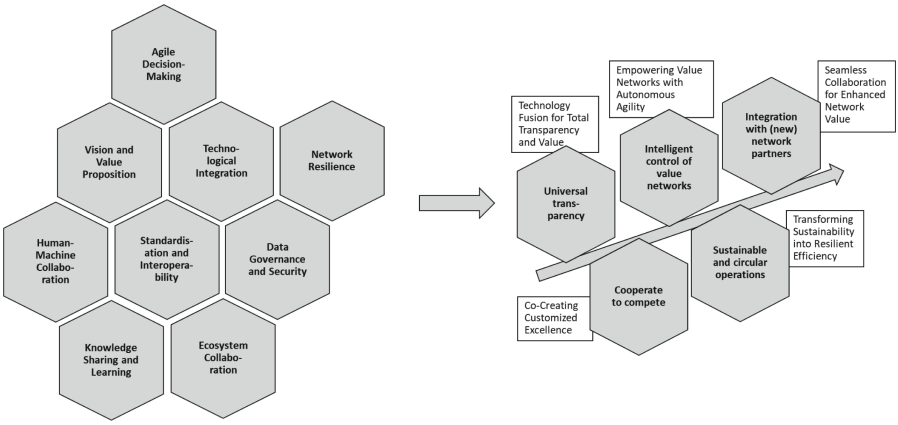



**Fig. 2.** Specifications forming the roadmap building blocks

of the roadmap exemplify how collaborative digitalisation plays a pivotal role in shaping the future of networked production.

1. Universal Transparency: Aims to achieve comprehensive end-to-end transparency across value networks, fostering collaboration, efficiency, and trust through real-time monitoring and information availability.
2. Cooperate to Compete: Focuses on collaborative innovation through co-design, co-engineering, and co-production, resulting in customised products and services while leveraging the benefits of shared knowledge and resources.
3. Sustainable and Circular Operations: Optimises resource efficiency, minimises waste and adopts circular economy principles to achieve extended machine operation and secure new resources, ultimately enhancing sustainability and reducing environmental impact.
4. Intelligent Control of Value Networks: Focuses on decentralised and autonomous management of value networks, leveraging both human and artificial agents to enhance anticipation, agility and overall performance.
5. Integration with (New) Network Partners: Concerned with dynamic integration, separation and collaboration with partners, fostering overall network performance, efficiency and customer satisfaction.

## 5 Conclusion

DTI is a catalyst for rapid networked production development that goes beyond incremental progress. Integrating work into a multi-agent system and merging human expertise with AI insights adds a unique dimension to intelligence and improves processes and autonomy. For example, in a supply chain context, multiple DTI agents work autonomously together across a decentralised network.

The roadmap for networked production is a strategic plan that embodies Europe's future potential. The holistic approach of DTI synergy with production illustrates the strengthening of competitiveness, innovation and sustainability. This approach extends to supply chains, logistics and mobility, triggering a cascading effect that increases resilience, efficiency and adaptability. Consistent use of DTI strengthens industrial performance and permeates supply chains and mobility systems, reinforcing the foundation of networked systems.

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# Processing Digital Railway Planning Documents for Early-Stage Simulations of Railway Networks

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**Abstract.** The digitalization of the railway domain is a key enabler for more efficient railway operations matching the future needs of society. One part of this process is the digitalization of planning processes, replacing the use of paper-based plans with digital formats. Digital planning documents also open new possibilities, e.g., deriving representative simulation in early project stages. A commonly used simulator for such purposes is the Simulation of Urban Mobility (SUMO). To use the capabilities of SUMO, we are presenting a tool chain for unifying planning documents and generating simulation configurations from them. The core of this tool chain is the *yaramo* model, covering mainly the topology, geography, and the control command and signaling (CCS) infrastructure of the railway network. The tool chain consists of three major layers: Importers to support multiple data sources (such as PlanPro or OpenRailwayMap), processors to enrich the model, and exporters to support various consumers of the model. This leads to several applications, such as rail network performance evaluations and test automation for CSS infrastructure. Ultimately, our work aims to support the digitalization process of the railway domain, especially the digital planning and development of railway networks.

**Keywords:** Railway Simulation · Digital Railway Planning Document · PlanPro · SUMO · Test Automation · Generic Interlocking Logic

## 1 Introduction

A more efficient and reliable railway system is widely requested by society. Besides this, there is a shift in politics towards more passenger and freight traffic on the rails to reduce the emission of carbon dioxide. To reach these goals, one of the key enablers is the digitalization of the railway domain. This already widely affects the control command and signaling (CCS) infrastructure with open standards, like the EULYNX standard [5] and IP-based communications.

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The new standards also call for digitalized planning processes. Among other things, these planning processes replace paper-based media with machine-readable documents, which ease data exchange and processing. This change leads to the advantages of digitally exchangeable documents, reduced transmission errors during scanning of paper-based plans, and better validation of the planned documents [3]. Besides these advantages, there are also several challenges with digital planning processes, like the lack of extensive tool support, version control of the files, and multiple versions of the formats themselves.

Additionally to the planning process itself, digital planning documents are also usable for other applications. This paper focuses on taking the digital planning document as input to traffic simulations. Converting digital planning documents to traffic simulations combines the capabilities of both worlds. Digital planning documents, on the first side, have a precise model of the planned railway network which is a detailed input to the simulation. This includes the topology and details about the CCS infrastructure. The traffic simulation, on the other side, can operate the planned railway network in the early stages of the planning process. Together they support our three main use cases:

**Early-Stage Simulations of Railway Plannings**. The evaluation of the railway network regarding criteria, such as bottlenecks, performance, and others.

**Test Automation of CCS Infrastructure**. The testing of hardware under development by using a generic interlocking logic and hardware-in-the-loop (HiL) capabilities to trigger state changes of the hardware.

**Support Railway Research Projects**. Operating newly developed railway systems in research projects in traffic simulations.

The following paper presents a tool chain for converting digital planning documents to traffic simulations. It has the central *yaramo* model and three layers of software components: *Importers*, *processors*, and *exporters*. Besides converting the planned network to a simulation model, yaramo has more capabilities, like the conversion of formats and the lightweight creation of planning documents.

## 2 Railway Planning Formats

The industry and communities, such as the OpenStreetMap community, developed formats to plan and describe railway networks and the CCS infrastructure. These formats have detailed information about the topology (e.g., points, signals, and rails) and geography (e.g., locations of components) of the system.

One of the first developed formats is the PlanPro format – introduced by Deutsche Bahn. Development started in 2009 [1] and it is capable of planning an electronic interlocking (ESTW) [2]. It is an XML-based data format that represents the topology of the railway network with a network graph, connecting topological nodes (e.g., points) with tracks. Additional objects are available to describe the CCS equipment, such as signals or train detection systems. Deutsche

Bahn offers a tool to visualize and check plannings while two commercial products are available that allow for such plannings to be created. Besides this format specific to Germany, European formats are also under development.

Digital planning formats have been designed to allow for the full planning process of the CCS equipment of a line. In contrast, data about railway infrastructure has been collected by volunteers as part of the OpenRailwayMap (ORM) [6] project. The underlying data model is also a graph, whose nodes can be enriched with arbitrary key-value pairs. For a lot of domains, conventions to represent the data have developed. This data can be queried with a query language and is accessible to the general public [4]. The data quality varies widely, but in a lot of places, there is accurate information about the topology and geography of railway lines as well as signals and other trackside devices.

## 3 The yaramo Pipeline

The tool chain presented in this paper uses railway network data from the mentioned formats to support the digitalization process of the railway domain. The key idea is to use digitally represented railway network models to create simulation models, perform conversions to other formats, or use the central model for data processing and parametrizing further logic.

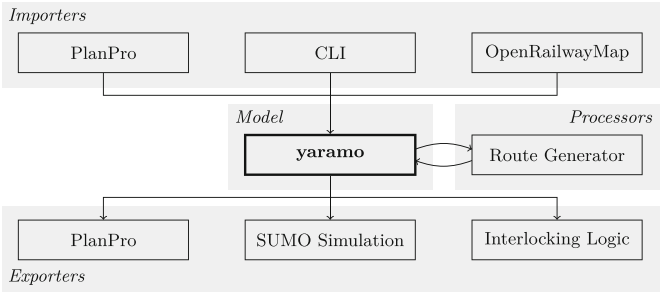



**Fig. 1.** The yaramo environment. It consists of the yaramo model and three tool chain layers: importers, processors, and exporters.

The core of the tool chain is the yaramo model, storing the topology and geography, as well as details about the CCS infrastructure. Besides the model, the tool chain is generally structured in three different layers, as also illustrated in Fig. 1: The importers read digital railway network models to create yaramo instances, processors modify these instances, and exporters write them in another format or use them as input for further tools. All these different components are implemented as separate software components as Python libraries, available on GitHub [8]. A simple example of the tool chain can be found in the repository [9]. In that code example, a PlanPro file is read by the PlanPro importer. The railway route generator, as an example of a processor, generates all possible

routes through the railway network. In the end, the result is exported to a SUMO simulation model [7]. At the moment, only one importer can be used at the same time, but multiple processing engines and exporters can be applied.

### 3.1 The yaramo Model

The digital planning formats describe the real-world objects precisely, their focus is an interchange format that can be stored and transferred easily. However, this format is not well-suited for processing. When operating on the topology graph used by those models, common graph algorithms like DFS are useful, e.g., to find routes in the railway network. XML-based formats need further processing to allow these operations. As there is not a single model that has reached widespread adoption yet, data from multiple sources is of interest and therefore each software would need to exist in multiple flavors to allow that.

We introduce yaramo to overcome the presented issues. The model consists of a graph topology with edges and nodes as well as additional classes to represent concepts like signals and routes. Because these concepts can be found in all of the existing models, a conversion to and from them is feasible. The model is easily extensible to cover other use cases and the objects and attributes needed therefore. The yaramo model is implemented as a Python library. An extra topology class works as a wrapper class for all objects in a single yaramo instance. This topology can then be passed to other components of the pipeline.

### 3.2 Pipeline

This section describes the abovementioned three layers of the pipeline.

*Importers.* Since the yaramo model is a Python library, it is possible to create instances of the model by hand through creating the necessary objects. This is time-consuming, especially for larger models. To use existing digital planning documents (*PlanPro*) or *ORM data*, we provide libraries extracting the data from these data sources. We also created a *Command Line Interface (CLI)*.

*Processors.* Having a yaramo instance, some common operations are usually necessary to enrich the model for further processing. Therefore, processors are taking the model as input and enrich it with their purpose. Currently, fully implemented is the *railway route generator*, which uses a depth-first search on the topology graph to find all possible routes in the topology.

*Exporters.* After enriching the instance, it can be converted to different output formats. The resulting files can be used for further processing by other tools. Currently, the export to *PlanPro* files and *SUMO simulation configurations* are possible. Besides this, a yaramo instance can also be used as input for other tools, such as an *generic interlocking logic*, by parametrizing them with the model.

## 4 Early-Stage Simulations of Digital Planning Documents

The introduction mentioned several applications of traffic simulations parameterized with digital railway planning documents. We are using Simulation of Urban Mobility (SUMO) as the traffic simulator, which is commonly used in the area of traffic simulation. SUMO contains several models for the movement of vehicles but needs a simulation model as input. This model mainly consists of a network and routes through this network.

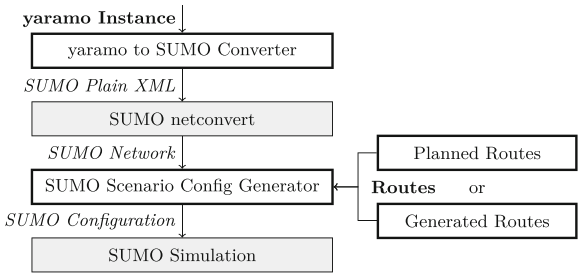



**Fig. 2.** The pipeline to convert yaramo instances to SUMO simulations. The grey boxes are provided by the SUMO tool chain, the bold boxes were developed as the exporter.

*Conversion to a SUMO Model.* The conversion of a yaramo instance to a SUMO simulation model follows a pipeline shown in Fig. 2 and is implemented in the SUMO exporter. First, files are created in the *SUMO-Plain-XML* format as the main conversion step. Hence, all points, track ends, as well as signals, must be converted to nodes via a graph transformation. Next, the SUMO tool *netconvert* transforms the plain-XML files to the SUMO network. The SUMO simulation configuration created afterward links the network file to a route file, containing the routes from the yaramo model. These routes were either planned in the PlanPro file or generated by the railway route generator. This completes the model for the simulation.

*Coupling the Simulation with a Generic Interlocking Logic.* To run the simulation, we developed a basic interlocking logic managing the railway network and its CCS architecture. This logic is parametrized with a yarmao instance. It offers an interface to set, free, and reset routes for trains. If a route for a train is set, the interlocking logic verifies that the required elements are not reserved by any other train and reserves them afterward. It also moves the points to the necessary position and sets signal aspects. Reserving overlaps, basic support for flank protection, and other operations are also supported.

Implemented as a library, the logic itself is not limited to SUMO. When instantiating the interlocking logic, it is necessary to pass *infrastructure providers (IPs)*, that couple the logic with any kind of infrastructure. The IPs get called by

the logic when moving a point or setting a signal. To couple the interlocking logic with SUMO, a SUMO IP is necessary. This passes the required states to TraCI (a SUMO interface) and affects the state of the simulation. We also developed an IP moving hardware points, proving the possibility of HiL simulations.

During the execution, the SUMO simulation determines the train positions and returns that position via the SUMO infrastructure provider to the interlocking logic. That mechanism is closely related to a train detection system realized by axle counters. To simulate train movements, a test driver needs to create trains in SUMO and set routes for these trains in the interlocking logic. This is the responsibility of the test developer, having the mentioned use cases in mind.

## 5 Conclusion

Digital planning documents of railway networks and their CCS infrastructure, such as documents in the PlanPro format, offer a variety of new applications for detailed data about the planned networks. The yaramo model and the related tool chain offer a lightweight framework to read and process PlanPro files and create SUMO simulation models based on the planning documents. These simulations can be used to experimentally evaluate the planned network in the early stages of development, e.g., regarding the performance. Other applications, like test automation of hardware prototypes, are possible as well since the simulation supports HiL experiments. Besides the simulation-based applications, also the transformation of publicly available data in ORM to digital planning documents or the lightweight creation of PlanPro files are further use cases of this model and tool chain. Both support the digitalization of existing railway networks.

In the near future, several more features will be added to the model and the tool chain. One major point of the ongoing development is the extension of the model while keeping it lightweight at the same time. We only add features, that are necessary for our use cases. Now, especially the support of level crossings and axle counters are in our focus. Another useful feature would be the functionality to merge multiple instances to combine largely available ORM data with a precise PlanPro model. Finally, the tool chain would benefit from a visualization of a model to make it easier to understand an instance.

In summary, the presented model and tool chain support the digitalization of the railway domain to increase the performance and reliability of the whole railway system.

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# Interactive Tool for Strategic Planning in a Railway Environment

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**Abstract.** An interactive tool for strategic planning is developed as part of the decision support and operational planning enhancements in the framework of the In2Smart2 project [1], working with Strukton Rail as the technology demonstrator.

The tool objective is to assist workers which form part of the decision process of strategic planning to visualize and analyze information, providing insights and useful conclusions in an interactive and straightforward way. The tool scope is the optimization of resources and company availability analysis to obtain forecasted workload optimization, the reduction of idle times and mobilization of adequate volumes of extra (external) capacity among others. It can be applied to a long-time horizon and to a short one.

The tool is implemented in Powe BI, elaborating methodologies and workflows for the implementation of the various interactive reports which support the decision-making and other managing and organizational tasks.

**Keywords:** Railway · Operational Planning · Decision Support · Business Intelligence · Data Mining

## 1 Introduction

In today's context, there exists a significant demand for a transformative shift in asset management, driven by innovative technologies, new economic possibilities, and enhanced legislative standards in the rail sector. This demand has propelled the In2Smart2 European project, aimed at intelligent asset management based on four key pillars: (1) Measuring and monitoring systems, (2) Data management, data mining and data analytics, (3) Decision support tools and systems and (4) Technology demonstration. These objectives led to the development of the interactive tool for strategic planning.

The outcomes pertaining to the creation of diverse methodologies, approaches, and conclusions analyzed and defined during the project are applicable to any other Use Case. However, the customized application resulting from the project is tailored to suit the needs of the company demonstrator, Strukton Rail, aligning with its organizational structure and databases.

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Strukton Rail operates across renewal projects and daily project management, each with distinct tasks and structures. There is a pressing need for optimizing resources and conducting an analysis of company availability to achieve tender offer optimization, reduce idle times, and secure adequate volumes of external workforce, among other goals. This tool can be applied to both a long-term horizon, involving the analysis of years of data, and a short-term horizon, enhancing daily maintenance activities by considering factors such as resources, costs, penalties, and work conditions.

## 2 Tool Implementation

In this section the different developments are detailed. During the project consecution two stages can be differentiated, a first stage which englobed the development of the main functionalities of the tool, and a second stage in which due to the accessibility to new resources new research lines are investigated to enrich the developments.

### 2.1 First Stage

The first step is the selection of the visualization tool. Different possibilities were analyzed (Shiny, Dash, Django and Flask among others). Finally, Power BI, an interactive data visualization software product developed by Microsoft with primary focus on business intelligence, is selected as the most adequate choice. This software provides cloud-base business intelligence services along with data warehouse capabilities such as data preparation, discovery and the creation of interactive dashboards. One of the great advantages of the software is its compatibility with other platforms, allowing data management using as data source platforms as Azure, or the use of visualizations based on other open-source and private software such as Python, RStudio or ArcGIS.

The next step on the developments was the data analysis. Since the different analysis and studies were performed on the provided data, the tool usefulness is highly dependent on the volume and quality of data provided. During the first stage of the project the datasets contain information about the client's track possessions, about Strukton Customer Relationship management offers and sales opportunities, the company available capacity per discipline and GIS information. To analyze the different information sources, they are loaded and filtered using Python in search of possible wrong data. The data is cleaned, calculations are made in reference to project duration, the information is categorized, and a daily capacity is calculated for the construction of capacity calendars.

The GIS information described in the previous section is provided as various file geodatabases. The open-source software QGIS is used to load the data, make selections of specific locations, perform intersections between map layers coming from different sources and exporting the data in the adequate format for its utilization in Python and Power BI.

For the GIS representation inside Power BI different possibilities are analyzed and due to the problems of ArcGIS Maps for Power BI to handle the high-volume target maps, Icon Map (from leaflet) is selected as the adequate visual object. The introduction of the GIS information into the Icon Map visual object has an intermediate step, in which the datasets are exported from the shape file as a.csv files using Well Known Text

format through QGIS software. This process allows the GIS information to be imported to Power BI as a data table, an afterwards introduced in the Icon Map visual object creating interactive maps.

Once all the data is pre-processed, removing missing and unimportant datasets, the information from the different datasets is connected by their Sales ID. The information from the projects is used to calculate the amount of work or Capacity measured in required shifts with respect to time for Strukton and its competitors. Since the fixed capacities per discipline is also provided, the available capacity with respect to time is also calculated. The different links between datasets and further capacity calculations are also performed using Python.

Power BI is used to analyze, transform and connect the data to generate the visuals. The data previously pre-processed using python and QGIS is introduced in the software.

Depending on the type of target visualization, it may be necessary to unpivot columns to generate visual objects filtered by attribute, for example, to filter per enterprise and discipline. When different tables are used in the same visual object, it may be necessary to generate new columns identifying to what type of data they belong to.

A date table is generated to be linked with all possible datasets to ease the process and further connection in the different visual objects. In a similar way, tables with columns listing the existing track possessions and project IDs are created with the same goal. Columns have been added with color codes to improve the visualization experience through format options.

For the visualizations to perform adequately the different columns from the datasets must be linked through model relationships to connect the information from the different datasets that are needed. The tables created to filter (date, enterprises and disciplines) connect the different datasets. For the elaboration of the connection models, the cardinality and cross filter direction of the active connections are carefully selected.

The adequate columns must be added to the visual object fields, depending on each visual object selected and the desired results, this data must be introduced selecting the adequate aggregation method (or none). Also, the different filters are defined and implemented.

The output for this part of the project is the interactive tool implemented in Power BI. Strukton Rail has access to the tool through a URL. The analysis is focused on capacity, maps, calendars, tables and other visual objects that will help on the decision-making process and any organizational and planning tasks and is organized in the following report pages:

- Sold capacity comparison: it provides at first glance an idea about the sold capacity of the company in different time periods in comparison with the volume sold by the competitors and the company resources, which aids the decision making relative to the acquisition of new projects and outsourcing.
- Capacity calendars: this page provides capacity information for the decision-making relative to the project acquisition and outsourcing, but also, since it is daily focused, it supports the decision making relative to daily planning and internal organization.
- Available capacity and absence: this approach helps to investigate the effect that the absence has on the available capacity, optimizing resources and improving the organization.

- Map with budget and capacity information: this report page helps in internal organizational tasks and management and optimization of resources
- Map with track possession information: this composition linked to the track possession information allow users to obtain useful information about capacity and localization that helps in internal organizational tasks and management and optimization of resources as well as to analyze the time dimension on the GIS study, providing position and capacity information with organizational purposes. Figure 1 shows this report page visualization.

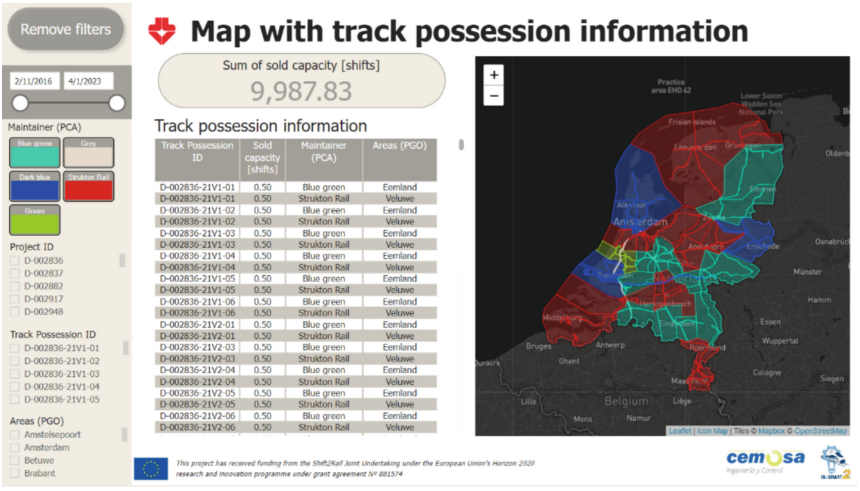



**Fig. 1.** Visualization of map with track possession information page. Generated with *Microsoft Corporation. Microsoft Power BI [Software]. Retrieved from* https://powerbi.microsoft.com.

## 2.2 Second Stage

On the second stage, after the development and deployment of the tool, new possibilities presented due to a time extension on the project and changes in the data provision allowed the research of complementary lines.

On the first stage, the tool was fully implemented based on the time and resources which limited the subtask, and after its finalization additional activities were strategically planned on the second stage to enhance the aforementioned tool in a series of research lines: (1) Dynamic data, (2) Machine learning, (3) GIS approach and (4) Fast access and key insights.

All previous developments (first stage) were made on a static database, meaning that all data provided was immutable throughout the Project. On the second stage, one of the objectives was the connection to the new **dynamic databases** provided by Strukton Rail, to generate visualizations which adapt to real-life scenarios. The first step for the dynamic connection was the generation of a dataflow. A dataflow is a collection of tables that are created and managed in workspaces in the Power BI service [2]. The dataflow connects with a series of static a dynamic data sources through a unique gateway, generating a

series of tables stores in the Power BI Service. This dataflow is used in Power BI desktop to load, transform, and model the data and generate the reports. The data is imported into Power BI desktop and a new model is generated with the dataflow information which is used to generate new report pages. The final.pbix file obtained can be used by any user to obtain up-to-date information visualized on the defined report pages. The possibility of uploading the report to a shared workspace was also analyzed, finding some limitation in terms of the Python and API connection functionalities.

On the **machine learning** research line, the possibilities of working with business intelligence and AI tools (Power BI and Python), not in a sequential but in an integrated way and what kind of developments would this connection allow in terms of machine learning analysis are studied. After the analysis Python is proved to be adequate for the generation of visual objects made from scratch using Python libraries instead of the built-in features from Power BI as well as for data transformation and advanced algorithms application.

Complex statistical models with supervised and unsupervised leaning methodologies are available within the available Python libraries within Power BI, as well as tools related to model selection, dimensionality reduction and time series analysis. Some of the algorithms that were highlighted during the study were the ones relative to learning methodologies: clustering methodologies, Discrimination analysis, Outlier detection, Decision Trees and Random Forest algorithms, Support Vector Machine and Neural Networks. As a prove of concept a Decision Tree is applied using sklearn library [3] to predict the state of a particular request (won or lost).

On the **GIS approach** research line, besides the creation of new report pages with maps displaying the information from the dataflow using leaflet, the ArcGIS for Power BI approach could be tested. The built-in visual object has the advantages of using ArcGIS elements, such as the use of basemaps, ArcGIS infographics, buffer/driver time, find similar tool, find places, selection tools and the addition of reference layers from ArcGIS. This last element is especially relevant since Strukton works with ArcGIS to manage their GIS information which means that introducing their ArcGIS account credentials they could include in Power BI any GIS information from their database.

Another key difference from the second stage is the access to a specific ArcGIS API tool which allows the download of the desired GIS information in different formats. A methodology to access the API is developed using parameters in Power BI database, to obtain the information from the API, interconnect it with the rest of the information and to allow its visualization in the report page. Since the credentials to ArcGIS API are restricted as an invited user, to access the information the URL has been used with an access token.

On the fast access and key insights side, the idea of the project is to generate tools that ease the access to information and their interpretation in a direct and user-friendly way on the day-to-day work. Two ways of improving this aspect have been defined: (1) Mobile phone layout for the original report which allow users to visualize all the previously defined report pages in a direct and comfortable way and (2) Generation of key insights specific reports, which only give key information oriented to a specific task or employee. As an example, one report is created using the same data model as the

global model, but this report is oriented only for the daily management of high and medium engineers.

## 3 Conclusions

In this project an interactive tool for strategic planning is created to support the decision-making and other managing and organizational tasks for Strukton Rail. On the first stage of the project, the static datasets provided were adequately pre-processed, processed and linked to obtain all possible useful information through Python and QGIS. The processed information is later used in Power BI software to generate the final data models to create the tool, which is distributed in different report pages where a series of visual objects, results and filters provide the desired information in an interactive way.

On the second stage of the project different research lines are analyzed to work with dynamic data and Python for the creation of the data model in an integrated way. The possibilities of applying machine learning technics are studied, new functionalities are analyzed for the GIS visualizations and improvements on the ease of the tool use are implemented including mobile phone layouts and specific report pages for key insights.

This project results can be analyzed from two different perspectives: on one hand the creation of the customized tool for the end-user in a shared environment with all previously defined enhancements, and on the other hand the creation of the different methodologies, connections, approaches and conclusions that can be applied to any other Use Case.

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# Artificial Intelligence (AI) System for Traffic Flows Monitoring. Evidences from the Interreg Mimosa Project

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**Abstract.** The traffic flows monitoring in a specific area is often an expansive and complicated activity for a public administration. Nevertheless, these data are fundamental for improving the urban and transport planning processes at local and regional levels. In the Italy-Croatia Interreg Mimosa project, an innovative open-source traffic flows monitoring system based on Artificial Intelligence (AI) was crated and tested. The collected results showed as the system is able to correctly recognize different typologies of vehicles (cars, bicycles, motorbikes, persons, light freight vehicles and heavy freights vehicles) using only open-source libraries. The aim is to provide to the decision makers new tools for the traffic monitoring and data-oriented decisions making on the topic of sustainable transport promotion. The Mimosa AI tool was published on GitHub and it is open access for all the interested public and private stakeholders. The paper presents the informatic architecture adopted, the key open-source AI tools used and it explores strengths and weaknesses related to the use of this AI tool.

**Keywords:** traffic flows monitoring · open-source AI system · Interreg Mimosa project · vehicle recognition · sustainable transportation · data collection automation

## 1 Introduction

Monitoring traffic flows in urban areas is often an expansive and complicated activity for a public administration. Nevertheless, these data are fundamental for improving the urban and transport planning processes at local and regional levels. In the Italy-Croatia Interreg Mimosa project, an innovative open-source traffic flows monitoring system based on Artificial Intelligence (AI) was created and tested. The collected results showed that the system is able to correctly recognize different typologies of vehicles (cars, bicycles, motorbikes, persons, light freight vehicles and heavy freight vehicles) using only open-source libraries.

The output of the project included the design of an AI tool based on computer vision and it was designed in order to be easily replicable in other contexts.

The pilot action has been designed to reply to the need to simplify and automize the traffic flows data collection for local administrations, that usually have limited budgets

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for traffic monitoring activities. Traffic flows data collection often requires relatively high-cost technologies (traffic radars, dedicated sensors, etc.) or a large staff involved in monitoring tasks spending time to collect the required data from the streets. Compared for example to the inductive loop detectors technology, the Mimosa AI solution has the advantage of not requiring infrastructure works on the roads. Moreover, AI allows the detection of bicycles and pedestrians more accurately compared to inductive loop detectors. Finally, thanks to AI it is possible to reduce the costs and the human resources needed to collect data on traffic flows.

The paper focuses on a new AI tool, that uses open-source algorithms and models to monitor vehicular flow. The pilot test conducted in Bologna (Italy) by the Institute for Transport and Logistics (ITL Foundation) in collaboration with "GoatAI SRL" and Bologna Airport, as part of the Interreg Italy-Croatia Mimosa project is documented.

A beta version of this AI tool for traffic monitoring is available on an online repository on GitHub.[1]

## 2 Artificial Intelligence Open-Source Approach

In recent years, AI has emerged as a powerful tool for analyzing vehicular flows, as it can process and analyze large amounts of data and images quickly and accurately [1]. The open-source tool developed in the Mimosa project uses AI system to analyze vehicular flows on a specific road. The key goals of the tool are:

1. Accurately count the number of vehicles in a flow.
2. Accurately classify the types of vehicles that go through an identified road.
3. Extract and analyze aggregate statistics related to vehicular flow.

Two key open-source AI key tools were adopted for the development of the AI tool for traffic monitoring:

- YOLOx for the Object Detection and Classification Models activities.
- Pascal VOC and COCO as datasets for training and testing object detection and classification models.

For the specific case of the Mimosa project, detection and classification were limited to a small subset of objects and sporadic errors do not significantly affect the final aggregate statistics derived from the analysis of several hours of footage. For these reasons, after careful consideration, we have determined that it would be more appropriate to adopt a one-stage detector as the first step for the vehicular flow analysis system. In particular, it is chosen to take advantage of one of the latest and best-performing variants of the famous open-source YOLO model, namely YOLOx [2]. YOLO (You Only Look Once) is one of the most famous open-source and real-time object detection and classification systems. Because of the state-of-the-art performance in terms of both accuracy and processing speed, YOLOx has been selected by the Mimosa team as most suitable option.

In relation to the training and testing object detection and classification models, two free datasets are used: Pascal VOC and COCO. Pascal VOC (Visual Object Classes)

[1] https://github.com/ITLBologna/Fluxus-AI.

is a benchmark on which several tools are tested [3]. Pascal VOC was surpassed by what now is probably the most important dataset when it comes to object detection and classification, i.e. Microsoft Common Objects in COntext (COCO). This dataset considers 80 different object categories, including animals, people and a variety of vehicle types. It has been used in many research papers and has inspired the development of various object detection algorithms. For these reasons, and because it contains almost all the classes of interest for the project, COCO dataset was selected for training the model used in the Mimosa project.

## 3 Mimosa AI Tool Architecture

This section provides the basis for understanding the artificial intelligence (AI) informatic architecture adopted for the implementation of the open-source Mimosa vehicular flows analysis system. The vehicular flows analysis system developed in the Mimosa project consists of three main modules:

- The video stream processing module.
- The short-term tracking module.
- The flow statistics generation module.

### 3.1 Video Stream Processing Module

The video processing module is a system designed to allow the offline analysis of one or more video streams. This analysis was conducted by utilizing YOLOx object detection model. To begin the process, each frame of the video stream is normalized and transferred to the graphics processing unit (GPU) for further processing. Once on the GPU, the frame is passed as input to the YOLOx model. The model analyzes the input image for all object categories covered by the COCO Dataset (on which the Mimosa model was trained). Note that the number of classes covered by the dataset (80 classes) is much larger than those of interest to the Mimosa project, which was limited to the following 7 classes: (I) light commercial vehicles, (II) heavy commercial vehicles, (III) passenger cars, (IV) motorcycles, (V) buses, (VI) bicycles, and (VII) pedestrians.

### 3.2 Short-Term Tracking Module

The short-term tracing module is a crucial component of the Mimosa AI system that enables us to analyze the movement and flow of vehicular traffic. It operates by taking the detection output from the video processing module, which independently analyzes each frame of the video stream, and linking them together over time to create time traces. This is necessary in order to extract meaningful statistics about vehicular flows and understand the patterns and trends of traffic within our system. The Mimosa project team decided to use the **SORT** [4] (Simple Online and Real-time Tracking) open-source tracking algorithm. It is designed to be used in scenarios where processing speed plays an important role and where accuracy in the short term is more important than overall consistency over the entire video.

### 3.3 Statistics Generation Module

Having processed the entire video through the two modules previously described, the Mimosa system will finally proceed to the analysis of vehicular and pedestrian flows taking into consideration the classification of the detected vehicles, as well as their coordinates and trajectories. In particular, the system has been created to detect:

- Count.
- Direction of travel.
- Classification of vehicular type.
- Frequency of passage.
- Average speed.

Using the statistical generation module, each of the above statistics can be aggregated by vehicle/pedestrian class, and/or motion direction, and/or road lane depending on the user's input query.

## 4 Testing Activities at the Bologna Airport and AI Tool Quality Check

The pilot test has been conducted within the premises of Bologna Airport. Bologna airport was selected as Mimosa testing area as it has an only access point for both freight and passengers' flows. This allows us to monitor all the traffic flows by using a limited number of cameras. The Mimosa project testing activities have been carried out using 3 GoPro Hero 10 cameras for video collection. Each recording session has been supervised by operators in order have a human check on the number and typologies of vehicles passing during the monitoring sessions. The position and inclination of the camera have been carefully made to maximize lane visibility. A vehicle traveling on the monitored lane should be visible at least 30 m from the camera location.

During the Mimosa pilot test, two data acquisition sessions were conducted in accordance with the Emilia-Romagna Region and the Bologna Airport key stakeholders. The first recording session took place on 03/08/2022. A total of 80 min of registration from two cams has been collected. A total of 1,557 vehicles and persons were monitored and classified. The second recording session took place on 01/11/2022. A total of 120 min of registration from three cams has been collected. A total of 2,581 vehicles and persons were monitored and classified.

The Mimosa AI solution reliability was tested empirically by selecting some frames of the registered video and checking if the number and typology of the detected vehicles correspond to the video frame and to the human counting activities conducted by ITL Foundation staff. This human check conducted by Mimosa project staff allowed to detect a complete correspondence among the vehicles detected by humans and by the developed AI solution.

## 5 Problems and Potential Solutions of the MIMOSA AI Tool

The main legal and organizational problems in the AI application on traffic flow analysis were related to:

- Recorded videos can be considered sensitive under the EU's data protection law.
- Short recording period due to action camera memory size and battery life.
- Bad camera positioning due to bureaucratic problems in installing the cameras in the right place.

The main technological problems in the utilization of an open-source AI technology for traffic analysis is:

- A limited number of vehicle categories available, in particular in relation to freight logistic flows;
- Requires dedicated and expensive hardware.

Potential technological and organizational solutions are:

- Privacy can be handled by displaying dedicated video surveillance warning signs that report GDPR General Data Protection Regulation. The warning signs must be positioned in a way as to be clearly visible before the interested party can enter the area.
- The short recording period could be solved using action cameras with increased battery life and by expanding the memory with SD cards.
- Limitations about the open-source nature of the tool can be solved by purchasing ad hoc software from a consultancy software house with AI and Computer Vision knowledge and/or by training the open-source tools in order to make the recognition of all the interested vehicular categories.

## 6 Conclusion and Recommendations

During this pilot action, Fondazione ITL in collaboration with the external technical experts GoatAI SRL, developed a tool for automatic traffic flow estimation based on Artificial Intelligence and Computer Vision able to (i) count the number of vehicles and people, (ii) classify the types of vehicles and (iii) extract aggregate statistics. This project aimed to provide decision-makers with a new tool for traffic monitoring and data-oriented decision-making on the topic of sustainable transport promotion. This information can be used, for instance, to optimize traffic signals, improve road design, and reduce congestion.

The proposed software has been tested at the Bologna Airport on two separate days. During the tests, a total of 02 h:10 m was recorded from three different cameras. The collected videos have been elaborated by the proposed tool. Videos have been promptly deleted after computation to be compliant with privacy regulations.

The data extracted during experimentation is intended to provide insights into urban mobility planning in a cost-efficient way. The solution has been designed to be replicable in multiple contexts where a camera can be easily placed in an elevated position above traffic flows. The software has been open sourced under MIT license and can be downloaded on GitHub.

In order to replicate the tests in other contexts, it is necessary to formulate a series of recommendations:

- Cameras should be positioned to face the incoming traffic (monitored vehicles should move towards the camera).

- A vehicle traveling on the monitored lane should be visible at least 30 m from the camera location.
- The camera should be placed at least 3 m above the ground. The defined position should not exceed 6 m in height.
- For long recordings that should last for more than 3 h, we advise employing preinstalled cameras, as the battery life of action cameras is usually in the range of 100–200 min.
- In the video collection activities, it is better to use filters allowing to cover vehicles license plates. This could be an important solution for reducing the needed legal checks.

The AI solution reliability has been measured on the most challenging reference benchmark namely COCO dataset. The good performance obtained by the AI solution shows good generalization capability and demonstrates that the system can be employed in different contexts.

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# Railway System Digital Twin: A Tool for Extended Enterprises to Perform Multimodal Transportation in a Decarbonization Context

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**Abstract.** To achieve our long-term goal of doubling the modal share of freight transport by rail and develop multi-modality in transports in France, a fine control over the railway network management is required to better synchronize rail transport with other modes of transport e.g., cars, trucks, trams. The Digital Twin (DT) of the railway system and the extended enterprise are central concepts in our approach to answer this problem. Our method aims at giving access to our railway system's Digital Twin through a Service Oriented Architecture (SOA). This architectural choice facilitates seamless communication and interaction with our partners, fostering a dynamic exchange of information critical for effective multimodal transportation planning. This article describes our approach with a successful implementation of an initial version of our infrastructure Digital Twin, complemented by services designed to meet the diverse expectations of users. This milestone underscores our commitment to leveraging cutting-edge technology and collaborative frameworks to enhance railway management, promote sustainable transportation practices, and contribute significantly to the reduction of GHG (Greenhouse Gas) emissions. As we continue to refine and expand our Digital Twin capabilities, we remain dedicated to advancing the future of intelligent and eco-friendly transportation systems.

**Keywords:** Digital twin · Decarbonization · Railway system · multi-modality of transport · Extended enterprise · Shared digital representation

## 1 Introduction

Transport accounted for 25% of EU greenhouse gas (GHG) emissions in 2018. The emissions of this sector come primarily from road transport (72%), while marine transport and aviation represent shares of 14% and 13% of emissions, respectively, and rail a share of 0.4% (emissions by diesel trains only) [13]. Apart from their direct contribution to global warming and air pollution, emissions that take place during the production, transmission

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and distribution of energy used by trains and aircraft are also considered. Transportation also leads to non-exhaust emissions of air pollutants, such as those generated by the wear and tear of brakes, wheels, tires, and railway tracks.

In the light of the above, it appears that rail transportation has less impact on the environment compared to other modes of transport in terms of GHG emissions (diesel locomotives represented only 0.4% of EU transportation GHG emissions in 2018). Unfortunately, the modal share of rail transport is yet currently the least important compared to all the other means of transport. This could be explained by the complexity of the railway network, which embraces current struggles to manage issues such as network aging, optimization in the use of assets.

The aim of the paper is to present a possible way of performing multimodal transportation in the framework of an extended enterprise using the concept of DT. This DT is a facilitator for managing and monitoring the railway system, which includes for instance: transportation plan, planned train scheduling and related real-time adjustments, network requirements, network physical assets, the supply chain and maintenance data. The DT also facilitates collaborations between partners, which is crucial in our context, since multimodality of transports entails a diversity of stakeholders working together e.g., Infrastructure Managers, Operating and Logistics companies. In this short paper, our objective is to describe the implementation of our DT, which natively supports an extended enterprise model required for data exchanges between all partners. In Sect. 2, we will start by giving an overview of transport multimodality. We will then explain in Sect. 3 our DT architecture in details. Finally, in Sect. 4, we will discuss the different kinds of services that the DT can deliver to stakeholders involved in multimodality of transports.

## 2 Multi-modality of Transport (Rail Transportation)

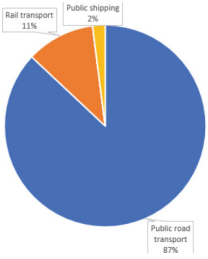



**Fig. 1.** Modal split of different modes of transport in France [10]

In France, the various modes of transport are responsible for 28.7% of national GHG emissions, equivalent to 113.6 million tons of CO2 [1]. Among the various modes of transport, rail transport has the lowest emissions (e.g., 0.4 Mt CO2 eq vs. 28.6 Mt CO2 eq for heavy goods vehicles).

To reduce these emissions, European authorities have already begun to work on decarbonization strategies and programs. For example, the French government has set up a national strategy for the development of rail freight. This strategy is a roadmap for rail transport but can also be applied to other modes of transport [12]. The expansion of the rail network in France must be carried out in close collaboration with managers of other modes of transport. Although road transport today emits an enormous quantity of greenhouse gases, it is still the most widely used mode of transport in France, because the distribution between the different modes of transport favors it and as it is accessible everywhere in the country (see Fig. 1 [5]). To promote decarbonization of the various modes of transport, it's clear that managers of the different modes of transport

at national, European, and even international level need to work together to put in place a global strategy to meet these environmental challenges. According to [12] and [5], the transport mode that emits the fewest greenhouse gases is rail transport, which is why it is so important to favor rail transport over other modes of transport, in the interests of decarbonization. For the industry, it is essential to be more efficient in terms of the services it delivers to its customers, whether passengers or freight. In the context of rail transport in France, we have set ourselves the goal of doubling the modal share of rail transport by 2030 [11]. The development of this mode of transport must be based on three essential pillars: (1) the optimization of the existing network, (2) the regeneration and modernization of the network, and (3) the provision of customer services tailored to their needs.

## 3 Description of the Railway System Digital Twin at SNCF Reseau

In this section, we first present the technical architecture we used at SNCF Reseau to implement our Digital Twin; we detail why the latter addresses questions of Data Governance and multi-stakeholder access. Secondly, we state the principles we selected to create a shared digital representation of the railway system, stored as data within the DT. Lastly, we mention how to create adapted services, also as part of the DT, to fulfil the expectations of each stakeholder in terms of information about the railway system.

### 3.1 Proposal of a Digital Twin Architecture in the Context of an Extended Enterprise

At SNCF Reseau, the Digital Twin is becoming the cornerstone of the Information System: the DT gathers, into a unique source of information, all company's data regarding the entire lifecycle of the railway system. The purpose of this unique source of information is to guarantee both the unicity and the accuracy of each datum, which are two quality characteristics essential related to data governance. Data Governance is however not part of the scope in this paper, it is still important to mention it since its principles led to the establishment of the DT as a unique source of information at SNCF Reseau. Furthermore, the latter is a prerequisite to implement a digital continuity as a founding principle for exchanges of data flows within the company (e.g. between several entities in the company, several digital tools), as well as exchanges between SNCF Reseau and other companies (e.g. partners, suppliers, operating and logistics companies). Therefore, the DT represents an asset for stakeholders ensuring activities at SNCF Reseau in relationship with our company. Multimodal transportation requires several companies exchanging data together, such as in an extended enterprise. In our case, stakeholders access the DT according to a Service-Oriented Architecture (SOA) and more specifically a Representational State Transfer (REST) Architecture [8, 14]. Clients request data stored in the repository of the DT through web-services, as shown in Fig. 2. Moreover, depending on the profile of the client, the data access could be restricted to a given scope or limited to reading only, if necessary.

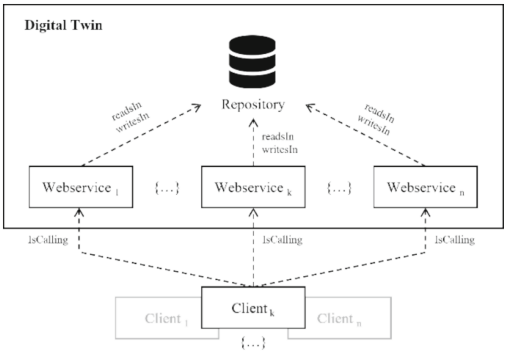



**Fig. 2.** Diagram of the technical architecture of the railway system DT at SNCF Reseau.

### 3.2 Production of a Shared Digital Representation of the Railway System

To produce this previously mentioned shared digital representation of the railway system, contained within our DT (i.e., precisely in the set of the DT repositories), we need a global model which describes all the concepts and relationships involved in this representation. At SNCF Reseau, this global model is named ARIANE [3]. It is made up of UML classes and is produced using the systemic and object-oriented approaches [7, 9]. Particularly, the shared digital representation is instantiated from ARIANE following the class – instance relationship in object-oriented programming [6] as shown in Fig. 3. In addition, the production of ARIANE lies in the application of the Object Management Group (OMG) modelling standard called Model-Driven Architecture (MDA).

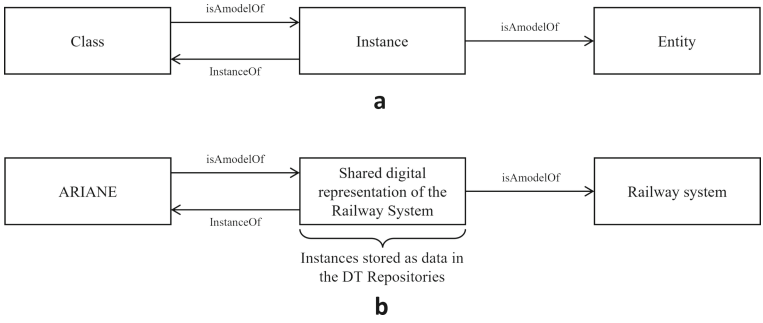



**Fig. 3.** a)Metamodel representing the instantiation/representation relationships between the different concepts that we use to handle the actual railway system along with related models. b) Shared digital representation of the railway system, produced with ARIANE, in conformity to the upper metamodel

### 3.3 Views upon the Shared Digital Representation of the Railway System

Web-services could process personalized, filtered and easily interpretable high-value information: based on data contained in the shared digital representation of the railway

system, services could offer to each stakeholder a dedicated 'view' on the railway system that fits its specific needs and use-cases, by containing all the necessary pieces of information in the required format. This is possible thanks to the Model View Controller pattern, described in [4]; several views can be constructed upon the same shared digital representation of the railway system.

## 4 Digital Twin for Supporting Multi-modality of Transport

In this section, we will be using digital twin technologies to meet the challenge of multimodal transport, known as combined transport. Combined transport involves using rail or ship to transport goods in containers, which are then transported by truck for the last few kilometers. Intermodal transport offers an energy-efficient logistical solution for modal shift. It is particularly relevant over long distances [5] (Fig. 4).

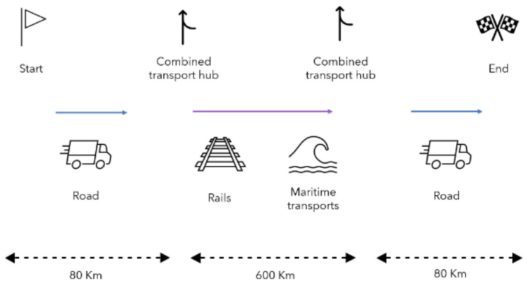



**Fig. 4.** Example of combined transport involving rail, maritime, road modes [13]

The digital twin provides a real-time representation of the state of the railway infrastructure [2]. From this representation, the railway infrastructure manager can know exactly how much capacity is available to run trains. This information is based on a combination of different sources of information, and therefore on the processing of heterogeneous data. Using diverse data sources, the Railway Infrastructure Manager can collaborate with managers of other transportation modes to extend coverage to areas not currently served by rail transport. To achieve this, we can share the necessary data with other transportation mode managers to facilitate coordination regarding the most suitable mode for passenger or freight transport, taking into consideration the previously mentioned criteria such as CO2 emissions e.g. a single train emits three tons of CO2, which is equivalent to the amount of emission generated by forty-five trucks [13].

## 5 Conclusion

In this paper, we highlight the pressing necessity to reduce greenhouse gas (GHG) emissions within the transportation sector, accounting for a quarter of the GHG emissions of the European Union in 2018. Rail transportation is a sustainable eco-friendly option for reducing GHGs in transportation, but it has not yet surpassed road transportation in terms

of its usage. Using a multimodal transportation approach, which combines long-distance rail with road transport for the final kilometers, seems to offer an efficient solution for environmentally friendly door-to-door transportation with reduced GHG emissions. Multimodal transportation entails multiple companies and stakeholders working together following an extended enterprise model. Therefore, these stakeholders must exchange accurate and up-to-date data about the railway system. To address this question, we introduced a Railway System Digital Twin solution to centralize all data related to the railway system at SNCF Réseau. The data of this Digital Twin will be accessed through services that can be utilized by stakeholders who contribute to multimodal transportation.

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# Sustainability and Circularity-Related Information Requirements for a Digital Product Passport for the Electric Vehicle Battery

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**Abstract.** Digital Product Passports (DPPs) have increasingly gained attention as enablers of more transparent and traceable electric vehicle battery (EVB) value chains. The new EU Battery Regulation requires all EVBs to have a digital record until 2026 and defines sustainability/ circularity-related requirements to be included in such a digital battery passport (DBP). This study goes beyond the legal requirements by systematically investigating which type of information a DBP would need to contain to comprehensively support sustainability/circularity-related decision-making of value chain actors. This is done by a mixed-methods approach divided into two phases: 1) a literature review, an industry actor survey and an EV user survey, and 2) two sets of interviews with experts from the battery's End-of-Life (EoL) and Battery Second Use (BoL) phases. The results consist of a refined and prioritized overview of information requirements that are of particular relevance for EVB value chain actors. They also allow for a differentiated insight into the requirements of specific use cases from the EoL and BoL stages. The paper thus serves as the foundation for developing a DPP prototype and for conducting sustainability assessments by providing a holistic perspective on EVB value chain actors' battery management and data requirements.

**Keywords:** Digital Product Passport · Electric Vehicle Battery · Circular Economy

## 1 Introduction and Theoretical Background

The present study aims to investigate which type of information a digital product passport (DPP) for electric vehicle batteries (EVBs) requires to contain to comprehensively support sustainability/circularity-related decision-making of value chain actors. This study

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is divided into two phases. Phase 1 is dedicated to identifying requirements of particular relevance for EVB value chain actors and thereby developing a validated and prioritized list of information requirements. Phase 2 aims at providing a more detailed insight into the specific requirements of use cases at the end of the battery's life. Both phases jointly contribute to a holistic and differentiated insight into the requirements for digital battery passports (DBPs).

The remainder of this paper starts with a theoretical background. Thereafter, the methods and the derived results are presented. Finally, the paper ends with the discussion and conclusion sections.

### 1.1 Digital Battery Passports for Enhancing Lifecycle Management

DBPs have increasingly gained the attention of policymakers [1], practitioners [2, 3] and researchers [4, 5] as enablers for transparent and traceable EVB value chains, thereby having the potential to enhance EVBs' sustainability and circularity information. The European Commission's Battery Regulation emphasized the relevance of DBPs for enhanced battery management and increasing a battery's durability and performance [1]. By 2026, all industrial batteries and EVBs are required to have a digital record containing accurate, reliable and up-to-date information on a battery and its components [1]. Accordingly, multiple initiatives emerged focusing on conceptualizing, a DBP such as the Global Battery Alliance [2] and Catena-X [3]. With respect to scientific research, one theoretical DPP concept [4] exists, whereas empirically founded DBP concepts focusing on sustainability/ circularity-related aspects and the systemic integration of EVB value chain actors' perspectives are scarce [5].

### 1.2 Information Requirements for a Digital Battery Passport

Besides establishing a framework for using a DBP for collecting, sharing and managing EVB product lifecycle data, the EU also defined certain information requirements to be included in the DBP [1]. These basic requirements are, e.g., information regarding the battery composition, dismantling instructions, safety measures and the State of Health (SoH) [1]. However, the current legal requirements only cover a few aspects of sustainability and circularity, keeping the wider potential such a DBP could offer for managing EVBs more sustainably untapped. From a research perspective, Berger et al. [4] have proposed the first (and as of now only) concept of a DBP for sustainable EVB management. This concept comprises 54 data points allocated to four main information categories. Thus, it provides the foundation for empirical investigations conducted in recently evolving research projects, such as CE-PASS [6] and Free4LIB [7]. The present study has evolved from the joint effort and close collaboration between these two research projects.

## 2 Methods

The study adopted a mixed-methods approach, divided into two phases, to validate and assess the EVB value chain stakeholders' information requirements. It further pursues a life cycle perspective, dividing the EVB value chain into four phases. The Beginning-of-Life (BoL) comprises all processes from the battery design and raw material extraction to

the finally produced battery pack. The Middle-of-Life (MoL) includes the distribution, use and maintenance of the battery, whereafter the Battery Second Use (B2U) describes the phase during which, if possible, the battery is refurbished and reused, e.g., as stationary energy storage system. The End-of-Life (EoL) phase contains all activities required when the battery cannot be adequately used anymore, such as recycling or other disposal.

### 2.1 Phase 1: Priorization of Information Requirements

In the first phase, a literature review was conducted to validate and refine the 54 data points identified in Berger et al. [4]. This served to condense the list to 40 information requirements. To quantitatively validate the refined information requirements, the respective list was an input for a survey (N = 26) sent to industry actors from the BoL, MoL, EoL and B2U stages. About half of the survey participants had at least four years of experience working with EVBs. In the survey, these practitioners were asked to rate the information attributes' importance on a six-point Likert scale. Further, the initial data point list was condensed and adapted to serve as input for a non-industry survey shown to electric vehicle users (N = 211). Here, the participants should rate their interest in 22 information attributes on a six-point Likert scale.

### 2.2 Phase 2: Assess Information Requirements for EoL and B2U Use Cases

Based on Berger et al. [4] and the preceding phase, the second phase was dedicated to exploring information requirements and DBP use cases in the context of EoL and B2U management of an EVB. Thus, two sets of interviews (total N = 20) with EoL and B2U-related experts were conducted. The derived qualitative material was then subjected to a qualitative content analysis and synthesized.

## 3 Results

Our results consist of a refined, prioritized overview of information requirements and allow for a more differentiated insight into the specific requirements of EoL and B2U actors. In line with the presented methods, they are divided into two phases.

### 3.1 Phase 1: Prioritized Information from Value Chain Actors' Perspectives

The refinement of the data point list from Phase 1 resulted in a list of 40 data points. Their importance was rated by industry experts on a scale from "1 = not important at all" to "6 = very important". Table 1 shows the ten data points which were, on average, ranked highest by the survey participants. It also provides an insight into how the information attributes were ranked by the actors from the different lifecycle stages BoL, MoL, EoL and B2U.

The results reveal, inter alia, that the SoH obtains the highest rank, being especially important for MoL and B2U actors. Overall, the attributes were rated highest by MoL actors while most attributes were considered comparably less important by BoL actors.

**Table 1.** Information attributes rated most important (scale 1–6) by value chain actors

| Information attribute | BoL | MoL | EoL | B2U | Total average |
|---|---|---|---|---|---|
| State of Health | 4.60 | 6.00 | 4.92 | 5.67 | 5.3 |
| Rated capacity [Ah] | 4.80 | 5.67 | 4.83 | 5.50 | 5.2 |
| Recycling information | 4.80 | 6.00 | 5.33 | 4.67 | 5.2 |
| Specification of electrodes | 5.00 | 5.67 | 5.58 | 4.33 | 5.15 |
| Critical Raw Materials | 4.80 | 5.67 | 5.08 | 5.00 | 5.14 |
| Long-term trend of the State of Health | 4.20 | 6.00 | 5.00 | 5.33 | 5.13 |
| Product-related energy [kWh] | 5.00 | 5.00 | 4.58 | 5.83 | 5.10 |
| Dismantling instructions | 4.60 | 5.55 | 5.25 | 4.83 | 5.00 |
| Voltage limits | 4.40 | 5.67 | 4.50 | 5.33 | 4.93 |
| Power capability [W] | 4.80 | 4.67 | 4.75 | 5.83 | 4.91 |

Since the second survey was presented to non-industry actors – EV users - the data point list was further adapted and compressed to 22 data points. These were rated on a scale ranging from "1 = not interested at all" to "6 = very interested". Table 2 presents the highest-rated data points, showing that two vehicle performance-based attributes were rated highest, expected lifetime and range. Similar to the industry experts, EV users considered SoH and the long-term trend of the SoH as very interesting.

**Table 2.** Information attributes rated most interesting (scale 1–6) by EV users

| Information attribute | Average |
|---|---|
| Expected lifetime | 5.72 |
| Expected range | 5.62 |
| Warranty on the project | 5.58 |
| Charging time | 5.41 |
| State of Health | 5.08 |
| Long-term trend of the State of Health | 4.99 |

### 3.2 Phase 2: Battery Passport Use Cases from an EoL and B2U Perspective

In general, two major DBP use cases were identified in the context of EoL and B2U. In an EoL context, a DBP was perceived to support efficient recycling processes. This comprises the choice of the recycling processes and more accurate estimation and handling of incoming waste streams. In this context, EoL experts emphasized the importance of battery chemistry and disassembly instructions. Regarding battery chemistry, they

expressed the need to know about the employed anode and cathode chemistry ratios (i.e., specification of electrodes). Control over disassembly instructions (incl. Type of employed screws, adhesives, wiring) was viewed as critical as this facilitates efficient disassembly steps and allows for planning and designing the disassembly process. Furthermore, the battery identification number, the number of total modules, the number of cells per module, and the number of total cells were classified as important for disassembly support. These listed information attributes were also viewed as important to support use cases related to disclosure and reporting requirements, or revenue estimations. In addition, to enable safe battery handling, interest in the SoH of an EVB (or respective modules) was expressed. Further mentioned EoL-related DBP use cases comprise reaction to customer requirements, logistical decisions, identification of critical raw materials and hazardous substances.

In a B2U context, a DBP was perceived to enable respective business models. Thus, a DBP needs to provide information about the SoH, as this is currently the most renowned indicator to decide whether an EVB qualifies for a B2U. Furthermore, control over in-use data, as well as maintenance history (incl. Maintenance triggers) was viewed important to identify suitable second life EVBs. The second most important data point identified was the one of disassembly instructions. The rationale provided was a rather economic one (e.g., time efficiency, personnel hours).

## 4 Discussion and Conclusion

This paper's results enable a more differentiated insight into the information requirements of EVB value chain actors. The information attributes that were ranked as most important by industry actors comprise both general performance-related information such as rated capacity and voltage limits, and sustainability/circularity-related information. The latter contains attributes like recycling-related information and dismantling instructions. The SoH and long-term trend of SoH, though, can be considered performance-related as well as circularity-related as it indicates the EVB's overall condition, which could also be beneficial for repair and maintenance activities and hence for prolonging the battery's lifecycle. The EV users also considered the SoH and its long-term trend as interesting. However, performance-related information was of higher interest to them. Overall, both industry and non-industry actors neglected social sustainability-related aspects.

Depending on the value chain actors' life cycle phases, they considered different information to be most relevant as they face diverging decision situations. The EoL use case revealed that the cell chemistry, dismantling instructions and SoH are very relevant to them which corresponds with EoL actors' survey results. However, while the SoH was emphasized within the B2U use cases, as well as these actors' survey results, dismantling information did not receive a considerably high survey rating while it was considered very crucial for the B2U use case. Overall, this study emphasizes the need to jointly consider both practitioners' perspectives, as well as sustainability/circularity-related research to include the actors' perceptions and sustainability / circularity information. However, this study bears some limitations. Firstly, the results show solely the "perceived" importance which is influenced by the subjective perception of respondents and secondly the number

of participants in the survey was rather small. Nevertheless, the results give important insights into the different information needs and can be a starting point for further research. Possible future research is already carried out in follow-up projects (i.e., CE-PASS [6] and FREE4LIB [7]), focusing on additional aspects of the development of DPPs, e.g., concerning on the design and the recycling phase's information requirements in high granularity. Other research approaches, e.g., from Tributech [8], cover the direct measurement of energy and emission parameters in the production phase, supporting carbon footprint calculation and the information exchange to and from EoL to BoL or B2U actors. They also aim for enhancing the integrity of all data collected, providing auditability and trust to external parties of the DBP ecosystem.

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# Recommendations and Roadmaps Towards Intelligent Railways

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**Abstract.** This paper provides an overview of the main results achieved within the Horizon 2020 Shift2Rail project named RAILS (Roadmaps for Artificial Intelligence Integration in the Rail Sector). The RAILS roadmapping process provided state-of-the-art, taxonomy, future research directions, and recommendations in three macro areas: Railway Safety and Automation, Predictive Maintenance and Defect Detection, and Traffic Planning and Management. RAILS findings shed light on the potential of intelligent technologies and provided essential guidelines for integrating machine learning into next-generation smart railways.

**Keywords:** Artificial Intelligence · Machine Learning · Autonomous Trains · Smart Maintenance · Train Delay Prediction

## 1 Introduction

To the best of our knowledge, RAILS has been the first international research project investigating the potential and limitations of Artificial Intelligence (AI) in railways, with the goal of *providing recommendations for next-generation railways and contributing to the definition of roadmaps for future research*. In

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RAILS, we addressed three main areas: Railway Safety and Automation (WP2), Predictive Maintenance and Defect Detection (WP3), and Traffic Planning and Management (WP4). Through relevant case studies, we have shown the practical usage of machine learning with appropriate datasets for AI training and testing.

In this work, we summarise the project's main findings and provide pointers to relevant deliverables and technical papers where the reader can find further details that could not fit into this paper due to page limitation.

## 2 The RAILS Roadmapping Process and Outcomes

In RAILS, we focused on developing roadmaps for strategic planning [1] for each of the technical work packages (i.e., WP2, WP3, and WP4). Table 1 provides a mapping between the roadmap steps, the project outcomes, and related publications (deliverables[1] and technical papers).

In the first phase of the roadmapping process (WP1), we defined a reference taxonomy for AI in railways and analyzed the State-of-the-Art of scientific literature and worldwide projects, and the State-of-Practice through a survey involving stakeholders (Steps 1 and 2 in Table 1).

Following the outcomes of the first phase, two pilot case studies were identified for each technical WP (Step 3 in Table 1):

- *WP2*: "Vision-based Obstacle Detection on Rail Tracks" and "Cooperative Driving for Virtual Coupling of Autonomous Trains";
- *WP3*: "Smart Maintenance at Level Crossings" and "AI-based Rolling Stock Rostering";
- *WP4*: "Primary Delay Prediction" and "Incident Attribution Analysis".

For each case study, an experimental Proof-of-Concept (PoC) has been provided to investigate AI applications (Steps 4, 5, and 6 in Table 1), including unsupervised Deep Learning (DL) for anomaly detection on rail tracks, Deep Reinforcement Learning for intelligent control in Virtual Coupling, and DL-based Graph Embedding techniques for train delay prediction.

In the following, research directions resulting from the RAILS roadmapping process are presented, namely: Fully Autonomous Trains in Open Environments (Sect. 3); Intelligent Infrastructure Inspection (Sect. 4); and Route-based Arrival Delay Prediction on Services Level (Sect. 5).

## 3 Fully Autonomous Trains in Open Environments

In RAILS, we investigated the use of AI in *open environments* compared to *segregated environments* (i.e., railway tracks protected through physical barriers) [2]. We addressed the threats affecting safety that can be mitigated using appropriate Safety Envelopes [3]. In this context, the RAILS project addressed the main challenges listed below.

[1] Deliverables are available at: https://rails-project.eu/downloads/deliverables.

**Table 1.** RAILS Roadmap Steps, Outcomes, and Publications

| Step | Outcomes | Publications |
|---|---|---|
| 1. Identify concrete railway problems | Taxonomy of AI for railways, Identification of Railway problems, Review of AI applications to Railway problems, Identification of research directions and uncharted areas emerged from the analysis of the state-of-the-art. | D1.1, D1.2, [8,9,11–13]. |
| 2. Identify constraints, applicability issues, and requirements. | Review of EU guidelines, Regulations, and directives on AI, Explainable AI, Criticalities and milestones, Ethical and Privacy aspects, Urgent issues, and Strategic application areas. | D1.1, D1.3, [8]. |
| 3. Specify technology areas, pilot case studies, and operational scenarios. | AI Emerging Technologies in sectors other than Railways, Transferability guidelines, Pilot Case studies identification, Scenarios definition. | D2.1, D2.2, D3.1, D3.2, D4.1, D4.2. |
| 4. Transform requirements into technology drivers. | Basic AI Usage Guidelines, Enabling Technologies, Reference datasets, and Machine Learning (ML) models. | D1.3, D2.1, D2.2, D3.1, D3.2, D4.1, D4.2, [4,6]. |
| 5. Develop AI-powered approaches, Identify alternatives, and their timelines. | PoCs for the selected scenarios: KPIs, ML models, Experiments, Results, and Possible alternatives. | D2.3, D3.3, D4.3, [5,10]. |
| 6. Identify innovation needs and recommended improvements. | Results of a SWOT* Analysis of the PoCs, Recommendations, and Innovation Needs. | D2.4, D3.4, D4.4 |
| 7. Create the Technology Roadmap Report | Timeline indications derived from i) previous steps, ii) relevant stakeholders' opinions, and iii) further available analysis results. Current criticalities and suggested research directions for innovation. | All the above, D5.3. |

DX.Y stands for work package X deliverable Y.
References refer to scientific works published under RAILS agreement.
* SWOT: Strengths, Weaknesses, Opportunities and Threats [7]

**Conceptual Shift.** We identified Grades of Intelligence (GoIs), which, building upon the Grades of Automation (GoA), define a gradual integration of AI in autonomous trains [4]: i) *limited or no autonomy (GoI1)*, where AI is not adopted in safety-critical functionalities but can be used to optimize the use of resources;

ii) *partial autonomy (GoI2)*, where AI is used to improve train operation or train protection; iii) *full autonomy (GoI3)*, where AI is adopted to optimize both operations and protection, e.g., in Virtual Coupling [5]; iv) and *full autonomy in fully connected environments (GoI4)*, where advanced AI functionalities are added to GoI3 through dynamic learning and adaptation.

**Structural Needs.** To move towards *GoI4*, we defined Levels of Intelligence (LoIs) based on edge, fog, and cloud computing to provide a reference architecture for the distribution of AI functionalities (see Fig. 1).

**Recommendations.** RAILS recommendations have been mainly oriented towards i) the identification of approaches to manage the complexity of AI systems (i.e., explainable AI); ii) the strategies for data generation (e.g., simulators and 3D editors), standardization, and sharing; iii) the definition of ad-hoc regulations for the certification of AI systems; iv) the investigation of approaches integrating Digital Twins (DTs) and Mixed Reality to test and validate AI-based safety-critical systems.

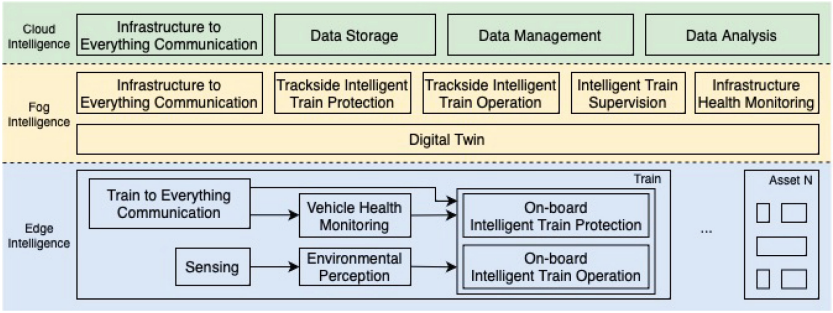



**Fig. 1.** Example Architecture for GoI4 Railway Lines.

## 4 Intelligent Infrastructure Inspection

AI is the main enabler for the paradigm shift from scheduled inspections to continuous monitoring and corrective to predictive maintenance. In RAILS, we identified the following main aspects supporting such a paradigm shift.

**Non-intrusiveness.** Railway components must comply with specific norms and regulations. In RAILS, we focused on the adoption of non-intrusive audio-video sensors, using artificial hearing and vision, to continuously monitor railway systems without interfering with train operations, and hence with no impact on compliance with reference standards.

**AI-aided DTs.** AI extends DTs allowing for the deployment of intelligent services such as predictive maintenance; also, it provides the capability of emulating the behavior of their physical counterpart. An example architecture for AI-aided

DT [6], including implementation guidelines. We showed that non-intrusive sensors combined with data processing based on AI can extract specific information that is crucial for the successful implementation of DTs.

**Recommendations.** Considering the aspects described above, the recommendations provided in RAILS mainly refer to the experimentation of non-intrusive monitoring, the investigation of possible solutions to integrate DTs, and the overcoming of some issues related to DT implementation (e.g., interoperability) and AI approaches (e.g., small-scale object detection and robustness to noise). In addition, data generation and collection to train and test AI models can also be critically sensitive; the same recommendations provided in Sect. 3 for data generation and collection also hold here, especially regarding deep transfer learning and domain adaptation.

## 5 Route Embedding for Arrival Delay Prediction on Service Basis

The Train Delay Prediction Problem has been investigated by a large number of studies. How to best represent certain features of a train is key to successful prediction. For instance, due to its complex topological nature, a train's route (i.e., origin, intermediate stations, and destination that a train service calls) is one of the most useful and essential features, but it is difficult to represent properly. Considering this, in RAILS we introduced graph embedding to identify the feasibility of its capability to understand and interpret the complex structure of a railway network including network topology, and train profile.

**Network Topology.** Incorporating both network spatial characteristics and historical delay information into a train delay prediction framework is a critical endeavor in enhancing the efficiency, reliability, and safety of modern railway systems. In addition to operational improvements, this integration also contributes to safety enhancements. By identifying and addressing vulnerable areas of the network, railway operators can proactively implement safety measures and reduce the risk of accidents occurrence.

**Deep Network Embedding.** A deep neural network-based graph embedding technique represents a cutting-edge approach for extracting rich and informative network features and enabling a wide array of applications across various domains by considering both the global and local aspects of networks. This methodology facilitates downstream machine learning tasks by providing a compact and expressive representation of nodes and edges within the network. As these techniques evolve, they are likely to play an increasingly crucial role in network analysis and data-driven decision-making.

**Recommendations.** Taking the aforementioned aspects into account, the recommendations identified in RAILS refer to the i) implementation of the Structural Deep Network Embedding approach, and then integrating it with dimension decomposition methods. To generate route embedding vectors as information entropy condensed features, contributing to the subsequent arrival delay

prediction. ii) Transfer learning in railway networks, i.e., applying knowledge from one network to another, which is valuable when data is scarce or for newly built networks. iii) Ensemble methods in machine learning, combining multiple models to enhance prediction accuracy and reliability. Different models have strengths and weaknesses, but ensembles leverage their collective wisdom, particularly when models are diverse.

## 6 Conclusion

We believe RAILS has provided a significant contribution to shaping the future of AI and machine learning technologies in railways due to the critical analysis of the state-of-the-art, specific taxonomy development, and case-study experimentation in selected areas. Furthermore, to better define the roadmaps towards effective AI adoption in railways, we also shared project results with worldwide railway experts from academy and industry. That allowed us to identify the current state of development of intelligent technologies in terms of their Technology Readiness Level (TRL). During project workshops, we collected experts' opinions on when specific AI technologies will achieve full maturity to be used in railway environments, and which will be the main criticalities to overcome.

Therefore, we expect that RAILS project results will have a significant impact due to the provision of essential guidelines and recommendations, as well as promising future directions for the successful adoption of AI and machine learning in next-generation smart railways.

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# The TANGENT Project Architecture: Towards New Traffic Management Approaches

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**Abstract.** The TANGENT project (www.tangent-h2020.eu/) aims to address the challenges of urban transportation, including traffic accidents, greenhouse gas emissions, and congestion. The project focuses on optimizing traffic management and enhancing mobility through a distributed, modular, and scalable architecture. TANGENT collects and harmonizes data from various sources, including sensors, users, vehicles, schedules, pricing, and traffic flows. It uses this data to create enriched information for different transport stakeholders. The project combines technologies such as data gathering, travel behavior modeling, traffic prediction and simulation, and transport network optimization to provide advanced transport management services. This paper is focused on presenting the project architecture developed to implement four services: data collection and harmonization, enhanced information service, real-time traffic management, and transport network optimization. The project involves a consortium of organizations from nine European countries and aims to pilot its integrated tool in multiple cities in 2024.

**Keyword:** Intelligent Transport Systems · Transport management · Multimodality · Data Harmonisation & Fusion

## 1 Introduction

With the growing number of vehicles and modes of transportation, and facing major challenges such as road traffic accidents, greenhouse gas emissions, and traffic congestion costs, it is essential to have efficient tools to optimize traffic management and enhance mobility in cities [1]. Transportation system managers are looking for new tools to address the integration of connected and automated vehicles, as well as innovative services to enhance traffic management operations. This requires collaboration between all private and public agents involved [2].

This paper presents the distributed, modular and scalable architecture designed for advanced transport network management, developed under the TANGENT project. The proposed architecture will contribute to support more efficiently traffic management in

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terms of congestion reduction, mitigation of environmental effects through the reduction of $CO_2$ emissions, and an increase in safety.

TANGENT deals with several heterogeneous data sources. This data is collected, harmonized, stored, processed and turned into enriched information to generate knowledge, inform the users and provide services to different transport stakeholders. In 2023, the project reached the milestone of validating its individual transport management technologies separately which, are being integrated into a single tool to provide the complete advanced transport management services. In 2024, the TANGENT integrated tool will be piloted in the cities of Lisbon, Rennes, Manchester and Athens.

TANGENT is being funded by the Horizon 2020 under the call 'Network and traffic management for future mobility'. This challenge aims to create and enhance smart systems and operational processes to monitor real-time traffic conditions and improve traffic flow performance. It also involves facilitating the real-time sharing of traffic information across networks and optimizing the entire system. TANGENT project counts with a consortium formed by 13 organizations (Universities, RTOs, SME and industry) from 9 different European countries (Spain, Italy, Belgium, the United Kingdom, Germany, France, the Netherlands, Portugal and Greece), and an external panel of experts, composed by vehicles manufacturers, road transport experts, City Councils, etc.

The paper is structured as follows. In Sect. 2 the main concept of TANGENT is introduced. In Sect. 3, the main services offered by TANGENT are presented and Sect. 4 gives an overview of the selected architecture. Finally, Sect. 5 summarizes the conclusions and next steps of this work.

## 2 The Concept of TANGENT Project

TANGENT provides a collection of tools to all traffic agents, managers and operators such as real time services, dashboards and simulation tools to orchestrate the different transport modes and systems to dynamically optimize traffic management operations in a multimodal transport network, considering also new modes of mobility. TANGENT combines several technologies to provide its services (see Fig. 1. TANGENT conceptual diagram.):

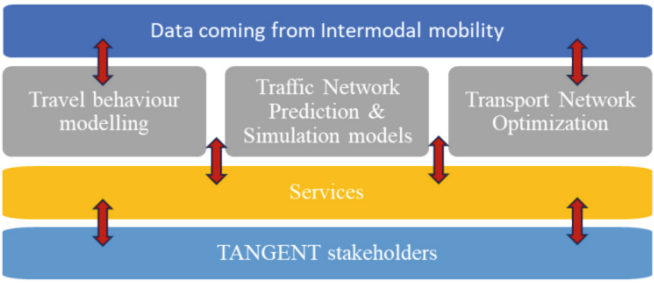



**Fig. 1.** TANGENT conceptual diagram.

- Data gathering of intermodal mobility, from sensors, users, vehicles, transport schedules, pricing, traffic flows, events, etc.
- Travel behaviour modelling, studying travel patterns of the individual transport users.
- Traffic Network prediction & simulation, creating models of demand and supply of transport, that enable to predict traffic congestion and potential bottlenecks.
- Transport network optimisation, to determine a set of actions for optimizing the traffic flows.

## 3 TANGENT Architecture

The TANGENT architecture is intended to define a distributed, modular and scalable system designed for advanced transport network management. The proposed architecture, shown in Fig. 2 is intended to define a structural framework to provide functionalities for current and novel modes of transport. These functionalities are classified into four services:

- Service 0 (S0). Data Collection and Harmonization Service.
- Service 1 (S1). Enhanced Information Service for Multimodal Transport Management Service.
- Service 2 (S2). Real-Time Traffic Management Service.
- Service 3 (S3). Transport Network Optimization for Transport Authorities.

TANGENT relies on data collected and harmonized by S0. S1 centralizes the data exchange between different system components and the Data API from S0. S1 delivers all project data centrally through the TANGENT API. S2 supports two subservices to handle the management of traffic whenever expected or unexpected events occur and depending on the level of severity of those incidents. And finally, S3 offers Network Optimization features, to assist S2 on the decisions to be taken upon those incidents. Further details about the services and their architectural implementation are given below.

– S0 - Data Collection and Harmonization

Data is the key element in TANGENT. How it's collected, transformed, processed, visualized and interacted with defines the scalability of the project. S0 will be responsible for providing access to the different data sources, external to the project, for each TANGENT case study, considering the requirements of both static and dynamic data.

S0 utilizes RDF standards for metadata and data source harmonization. Two types of interactions are expected: access to data sources in the native format through the Raw Data API, and access to harmonised data sources through the TANGENT API, as depicted in Fig. 3. Data sources are accessed by S0 to be collected or the sources access S0 to deliver the data. S0 then harmonizes it and delivers it to S1 through an API.

– S1 - Enhanced Information Service for Multimodal Transport Management

S1 plays a crucial role in data management and data delivery, being composed by the TANGENT API, the Dashboard and a Calculated Data module.

The TANGENT API serves as the central hub for exchanging data between various project components. This API implements a REST-based architecture alongside a message-oriented middleware (MOM) architecture. In both it uses JSON data encoding

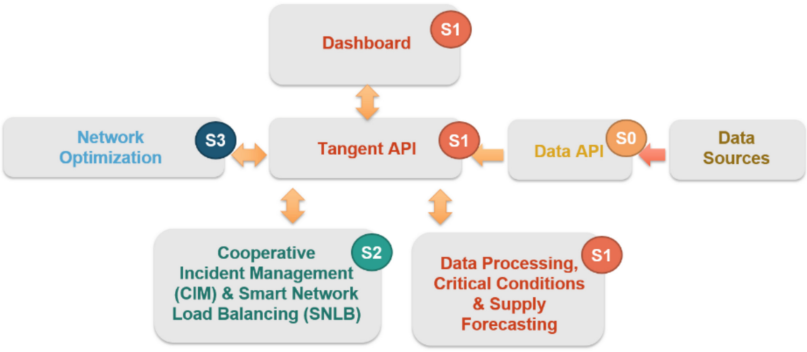



**Fig. 2.** Top-level technical architecture

for compatibility with modern API standards and OpenAPI specifications. It stores data in a Document Database, ensuring flexibility in handling structured and non-structured JSON data without the need for complex database mapping. Data from S0 is transferred to S1 through three channels: AMQP for real-time data, HTTPS fetching for larger data, and raw data proxying for specific data streams.

The Dashboard serves as the user interface for project stakeholders. It comprises modules for dashboard customization, data visualization, and integration with the TANGENT API and supports various UI modules. This service allows users to access live and future information about the roads and transport network.

The third module is the Calculated Data which consumes static and dynamic data from the TANGENT API and generates new data that is then fed to the TANGENT API using the AMQP Service when new data is ready. This data is composed of the Supply Forecasting module, responsible for forecasting traffic; the Data Processing module, responsible for extending dynamic traffic and forecast data with new calculated metrics more intuitive for visualisation in the Dashboard; and the Critical Conditions module, responsible for detecting anomalous events and modelling the duration of existing and detected events. This is shown in Fig. 3.

– S2 - Real-Time Traffic Management Services

S2 is composed of two subservices: Smart Network Load Balance (SNLB) and Cooperative Incident Management (CIM). SNLB and CIM are very similar processes that are used to handle network issues and incidents, tactically and strategically. Their purpose is to address and solve the event causing abnormal situations and resume normal operations. Both subservices are based on templates provided by S3. They start by notifying about specific degrading conditions of the transport network and suggesting a response plan for those situations. The difference between CIM and SNLB is that CIM involves several stakeholders at once, requiring their coordination by the system, whereas SNLB only involves a single actor from a single entity.

The transport network balancing provided by SNLB involves pre-defined triggers/conditions and rules for actions to be taken. These actions will suggest, for instance, new traffic lights timings changes to public transport (PT) scheduling, instructions for

Connected and Automated Vehicles (CAVs), dynamic toll pricings according to congestion levels and, also, information for passengers about specific traffic and transport conditions (e.g., inform about a closed metro line, protests blocking a bus route, usually providing alternatives). This balancing approach can cope with pre-defined scenarios where decision making is simple and does not involve more than one specific stakeholder. For more complex cases, human cooperation is necessary. This is where CIM comes in. Also based on triggers/conditions to be launched, CIM is configured and managed from the TANGENT Dashboard by the involved stakeholders in the existence of an event or incident in the transport network. CIM usually combines more than one action groups. Three CIM functionalities are being implemented: the synchronization of traffic control and public transport (PT), the synchronization of Demand-Responsive Transit (DRT) with PT and the synchronization of PT and the connected autonomous vehicles (CAV).

S2 is supported by three distinct modules: the Dashboard (S1), the Monitoring Module (S2), and the Response Module (S2), all interconnected through the TANGENT API. The Monitoring Module receives commands from the TANGENT Dashboard to monitor or stop monitoring Triggering Conditions. It then notifies the API about Triggering Conditions that fail or stop failing, which is subsequently consumed by the Dashboard in order to provide user alerts for the triggering conditions. These alerts allow the users to address the incident at hand using specific templates from S3 that relate the current abnormal transport network states with a response plan. The Response Module handles Response Plan Implementation, receiving requests to apply specific Response Plans and making relevant information available through the TANGENT API for involved parties. Additionally, it ensures the resumption of normal operational conditions by sending action information to the API for compliance by the operational systems of stakeholders. The Dashboard manages the state management and persistence of CIM, and SNLB entities and handles UI interactions for these entities and the interactions S3 - Transport Network Optimisation for Transport Authorities.

S3 is responsible for the creation of the Common Operational Picture (COP) used in CIM, the creation of the Response Plan Package (RPP) used in SNLB, and the simulation of 'What-if' Scenarios for urban mobility planning. Both the COP and RPP act as templates for response to pre-defined scenarios like a flood in a specific city or an overload in the metro network. Both contain the relevant information to suggest a response plan depending on the level of coordination mechanisms required. In addition, S3 also offers internal TANGENT stakeholders the possibility to execute the simulation of hypothetical transport network scenarios directly, where the only difference to the COP and RPP functionalities is that these scenarios are only simulated, not being subjected to any optimization process. S3 needs three modules to provide these functionalities together with the Dashboard from S1: The Optimisation Module, the Consensus Module and the Simulation Module. The Optimisation Module has an engine which oversees the control of a transport simulator and interacts with the TANGENT API. The Consensus Mechanism supports the Collaborative COP Preference and Consensus definition by weighting the Response Plans & KPIs preferences from each actor and producing a consensual view which is delivered to the Dashboard. The Simulation Module uses Aimsun Next traffic simulator to find the optimal response plan for each scenario.

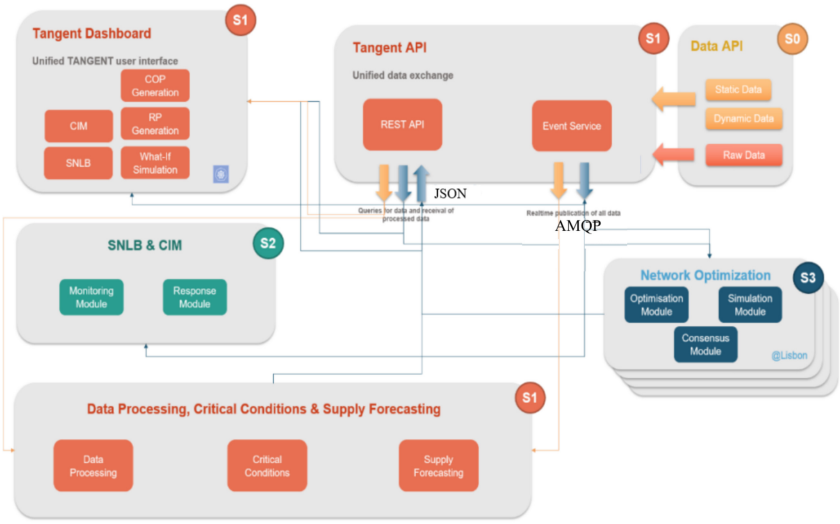



**Fig. 3.** TANGENT Detailed Technical architecture.

## 4 Conclusions and Next Steps

The TANGENT project is delivering a scalable modular platform for advanced transport network management. This paper presents an overview of TANGENT's underlying architecture, designed to manage urban transport networks after expected or unexpected incidents, providing a tool to allow coordination among transport stakeholders, thus reducing congestion, mitigating environmental effects through the reduction of CO2 emissions, and increasing road safety.

The TANGENT project is currently testing its core technologies separately, followed by integrating them into a comprehensive tool and later be piloted in several European cities in 2024.

## 5 Disclaimer

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# Rail Defect Detection Using Distributed Acoustic Sensing Technology

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**Abstract.** In recent years, advances in Distributed Acoustic Sensing (DAS) technology have resulted in significant progress in the detection of vibration sources. However, its use in railway monitoring is still relatively new, even though thousands of kilometers of optical fiber cables are already set up for telecommunication purposes, thus potentially exploitable.

In this paper, we explore the possibility of using a DAS system and machine learning tools to detect rail defects along the track. Rail defects are defined as anything other than a smooth rail, and we focus on the detection of rail joints, which are common elements along the track. In this study, measurements were carried out on a short railway section of a few kilometers between two train stations in Paris. The results show that nearly all rail joints along the track are correctly detected, demonstrating the ability of the system to detect these elements with a spatial accuracy of a few meters. Lastly, some future perspectives for the study are proposed, such as a more in-depth analysis of the detected locations or the integration of field information to enhance the reliability of detections.

**Keywords:** Distributed Acoustic Sensing · Optical Fiber Sensors · Rail defects · Rail joints · Machine Learning · Track monitoring

## 1 Introduction

Using optical fibers for data transmission has transformed the way we communicate, enabling instant transfer of information over long distances. Yet, despite its potential, little work has been done in the railway industry. Recent works have shown that DAS technology can detect a wide range of vibration events in the railway environment, such as a moving train, or rock falls. Specifically, when a train passes over a rail, it produces an acoustic vibration that could contain valuable information about the track condition.

For example, apart from a broken rail, if rail defects are not quickly identified and repaired, they can ultimately cause a train to derail. As such, they represent an important issue for rail safety. Currently, most defects are detected either by inspection vehicles, visual inspection, signaling systems or derailment [1].

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Unlike these methods, DAS technology does not require an expensive deployment on the tracks. All that is required is a connection to an optical fiber and a single device can monitor a line up to 193 km [2]. This method can therefore be used for continuous track monitoring to detect defects before they become safety problems. Several studies have already analyzed the ability of DAS to monitor the track [3] and detect broken rails [4]. An in-house study has also been carried out demonstrating the feasibility of broken rail detection using DAS and signal processing techniques [5].

This paper proposes to automate the detection process using machine learning techniques, which has the advantage of being less dependent on parameters. We focus on the detection of rail joints as they are common elements along the track and exhibit behavior similar to rail cuts [5]. This article is the result of a collaboration with Société du Grand Paris (SGP) in charge of the Grand Paris Express program. Covering nearly 200 km, this major urban program seeks to connect suburban areas without passing through Paris, by developing new metro lines and extending existing ones.

## 2 Distributed Acoustic Sensing

Distributed Acoustic Sensing (DAS) relies on Rayleigh backscattering. When light travels through the core of an optical fiber, some of it is scattered due to interactions with the fiber material imperfections. A portion of this scattered light is reflected to the source. Any vibration source near the optical fiber will affect both the amplitude and phase of this signal. These vibrations can hence be detected and monitored by recording and analyzing the backscattered light.

In this study, the DAS system uses coherent heterodyne detection [5], with an optical frequency shift of 18 MHz. The acquisition is performed at a sampling rate of 125 MHz. The pulse rate is 4 kHz with a spatial resolution of 10 m.

## 3 Proposed Approach

The study was carried out in an environment similar to the new metro lines under construction by SGP, i.e. a few kilometer railway section between two stations in Paris connected by an underground tunnel. The study section is equipped with numerous fibers with different layouts resulting in an optical fiber length of approximately 20 km.

Two types of fibers run along the tracks: one is placed under the concrete beneath the tracks (type 1), and the other is laid in the cable trays attached to the tunnel structure (type 2).

The study section has been configured to ensure coverage of both tracks in the test site and to alternate between the use of the two types of fibers.

### 3.1 DAS Data

For our purposes, we use the differential phase computed from the DAS phase data. It is then pre-processed by applying a high-pass filter, followed by a normalization step based on the estimated noise standard deviation. The result is a two-dimensional waterfall of the vibration activity over time along the track. Figure 1 shows an example of a waterfall.

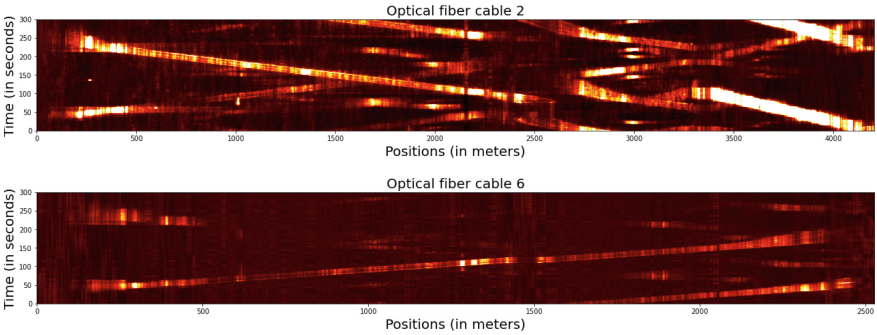



**Fig. 1.** A 5-min waterfall for two optical fiber cables in the study site showing vibrations induced by moving trains. Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

Given the large number of optical fiber cables available, the study will focus on only two cables, one of each type: cable 2 (type 2) and cable 6 (type 1).

Figure 1 shows the vibrations activity when train wheels pass over the tracks. When they encounter a rail joint, a specific pattern can be observed. Figure 2 shows several examples of rail joint vibrations on different rail joints along the tracks.

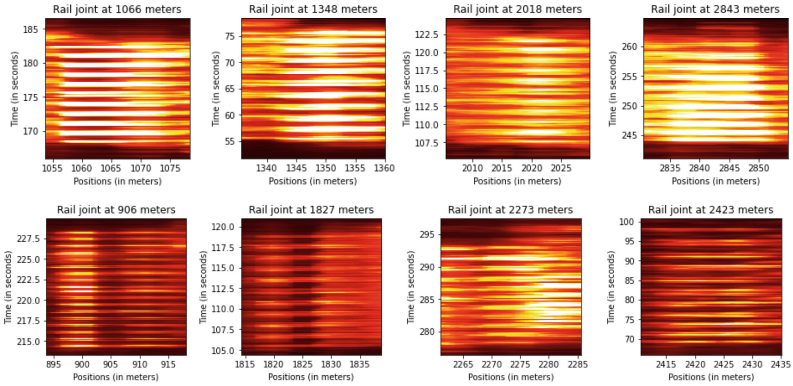



**Fig. 2.** Rail joint vibrations on different rail joints along the tracks. Data from the first row comes from cable 2, while the second row comes from cable 6. Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

Rail joint vibrations are more intense and regular over time. These high vibration intensities correspond to the impact of all the train's wheels on the rail joint.

In Fig. 3, vibrations measured from optical fiber cable 2 show a track section of approximately 500 m containing two rail joints. The distinction between the vibrations generated by a track in good condition and a joint is clearly observable. Similar observations can be made when examining data from cable 6.

We can notice that vibrations between the two fiber cables are quite different. These differences can be explained by the way the cables are installed. Data from cable 2

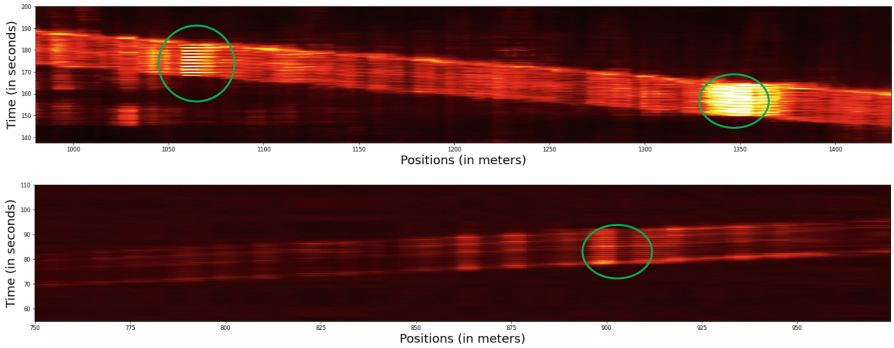



**Fig. 3.** Zoom on rail joint vibrations observed as a train travels along a track section (first row: data from cable 2, second row: data from cable 6). Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

shows more intense vibrations and more noise caused by interferences with surrounding vibrations, as this cable is not buried and therefore more sensitive. In contrast, vibrations from cable 6 are less intense (buried cable), less noisy, but sharper and clearer.

By considering the features mentioned above, a rail joint detection algorithm can be proposed.

### 3.2 Detection Algorithm

The proposed detection method consists of two steps. First, the signal of interest, i.e. the one associated with the moving train, is detected. Next, the rail joint positions are identified using a classification model trained to classify the signals into two classes (Track in good condition / Rail joint). To ensure an accurate classification, a set of distinctive features related to joints must be extracted and used.

Several studies have been conducted and the most relevant features found include energy, autocorrelation and a frequency analysis of the frequencies excited by the joints.

The importance of the energy feature is quite apparent based on the vibrations observed in Figs. 2 and 3.

The periodic aspect of these vibrations was highlighted through an analysis of the autocorrelation signal. Autocorrelation consists in quantifying the similarity between a signal and a time-shifted version of itself. It is therefore well-suited for discerning patterns in a signal.

Additionally, a frequency analysis showed that the rail joint information fell within a particular frequency range. Figure 4 shows the distribution of frequency peaks in the frequency signal from cable 2. Green vertical lines correspond to identified rail joints positions in the field. We can notice that most peaks are located at rail joint positions. However, other locations also show a strong frequency content. As the selected features are weakly correlated between each other, these positions will be later excluded through the combined use of features by the classifier.

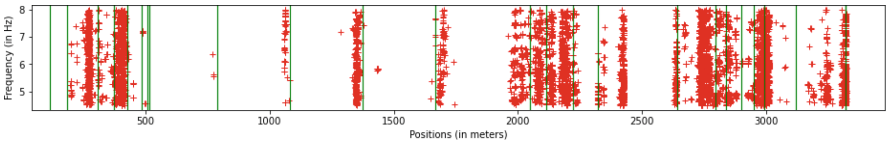



**Fig. 4.** Distribution of frequency peaks in the signal from cable 2 (range [4.5 Hz – 8.0 Hz]).

# 4 Results

## 4.1 Performances

After features were extracted, a classification model was trained using Grid Search with k-fold cross validation to find the best parameters. Several classifiers were studied including Support Vector Machine (SVM) and XGBoost.

Table 1 shows the performance of our algorithm, obtained on a dataset of approximately 15,000 samples. For the calculation of the evaluation metrics presented below, around 4000 samples were used.

**Table 1.** Performance of the proposed rail joint detection algorithm

| | Accuracy | Precision | Recall | F1-score |
|---|---|---|---|---|
| SVM | 0.906 | 0.91 | 0.90 | 0.91 |
| XGBoost | 0.927 | 0.93 | 0.93 | 0.93 |

It should also be noted that the ground truth is reliable within a 5-m margin which has an impact on the performance of the algorithm. It only considers positions of $\pm$ 5 m around the ground truth as joints. Therefore, slightly off-center joints outside of this scope are considered as false positives, thus lowering the algorithm accuracy.

## 4.2 Results Visualization

Figures 5 and 6 show results obtained on optic fiber cable 2 respectively on a 5 min and 25 min of peak hour traffic between 6PM and 7PM. We can see that nearly all rail joints have been detected several times (except for example at ~ 700 m and ~ 3200 m). This shows that the algorithm is consistent and repeatable. The solution can detect the same joint on multiple occasions. And when it does not detect a joint (positions listed above), these positions never seem to be detected later.

In addition, many railway equipment is located at the entrance and exit of train stations, which explains the high number of false detections at these locations.

Similar results have been obtained from cable 6 data, using the same approach. Thus, the proposed method is effective on both types of optical fibers. However, only features extracted from the direct measured vibrations have been exploited. Further research will involve adding field information about the track section (its geometry, axle loads or rolling stock types) that can strengthen the reliability of detections.

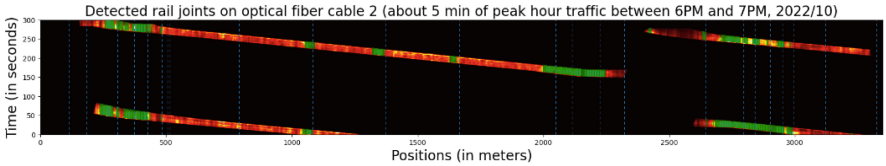



**Fig. 5.** Detected rail joints on 5 min of peak hour traffic (XGBoost, cable 2). Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

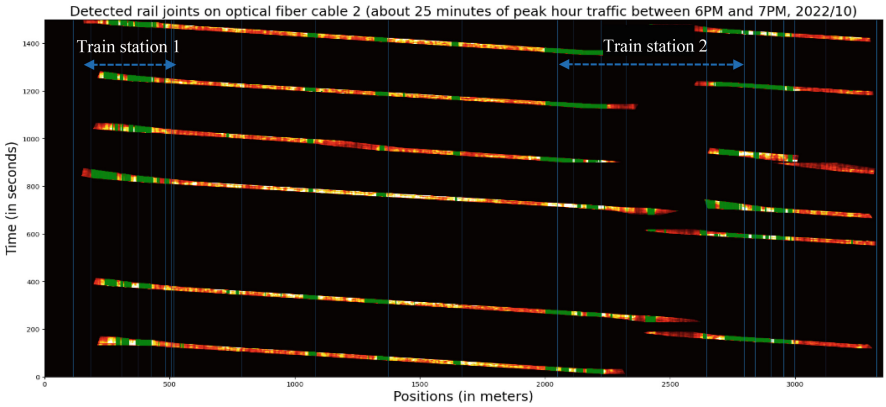



**Fig. 6.** Detected rail joints on 25 min of peak hour traffic (XGBoost, cable 2). Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

## 5 Conclusion

This study shows the effectiveness of using Distributed Acoustic Sensing technology to detect rail joints. These elements leave a discontinuity between two rail segments in a railway track which generate an acoustic vibration that is different from normal train vibrations. We can assume that other rail defects can be similarly detected, as they also have an impact on the track by breaking its smooth surface. The challenge is then to be able to separate and identify these defects from each other.

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# Railway Ground Truth and Digital Map Based on GNSS and Multi-sensor Big-Data Acquisition

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**Abstract.** Satellite-based localization solutions are expected to boost railway digitalization and in particular, they will enhance evolution and efficiency of railway signaling systems. The development of multi-sensor solutions is ongoing, but some gaps remain. This paper addresses two of them: the need for innovative high accuracy and precision Ground Truth and Digital Maps, essential elements of a EGNSS train positioning system and a V&V environment. These two objectives are focused in the RAILGAP EU project. For each of these tools, this paper presents the main high-level requirements and the selected architectural design exploiting specific data fusion algorithms. The novelty of the EGNSS multi-sensor solution proposed is that it does not require to install or modify any equipment on the track. It is based on datasets acquired through commercial runs in Italy and Spain, leveraging on regular train trips in different operational scenarios and time.

**Keywords:** EGNSS · train localization · sensor fusion · digital map · ATO · Fail-Safe Train Positioning · ERTMS · signaling

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## 1 Introduction

The increasing demand for rail transportation is accelerating the adoption of digitalization technologies with the advantage of new products being developed for automated driving in the automotive sector. Some of these technologies are also foreseen for train control and monitoring systems and for improving the economic sustainability of the ERTMS signaling system, particularly for ETCS level 2, paving the way for the hybrid level 3 up to the full level 3 moving block for which the satellite train positioning is recognized as a game-changing technology. The use of Global Navigation Satellite Systems (GNSS) for train localization added a new tool providing high accuracy, confidence and integrity level, not affected neither by the train speed nor the rail-wheel adhesion. However, the railway environment presents its own challenges and opportunities when it comes to infrastructure and its fundamental elements. Railway tracks are often installed along challenging and harsh environments for the use of satellite signals like urban canyons, tunnels, or forested areas. On the other hand, the tracks constrain the vehicle dynamics to two dimensions. The combination of European GNSS (EGNSS) with other sensors like inertial sensors, cameras and LIDAR allows to compensate some of the sensor drawbacks and can guarantee continuous train localization in any operational scenario together with the availability of digital railway maps. RAILGAP project has been awarded by EUSPA within the H2020 program in order to contribute to the roadmap for their introduction in the railway sector. Two gaps are targeted here: first, the availability of Digital Maps (DM); second, the need for a reliable Ground Truth (GT) that will allow the quantitative evaluation of the new developed solutions and for the validation of Control-Command and Signaling (CCS) systems i.e., ATO, Fail-Safe Train Positioning, Hybrid or full Level 3. Conventional survey techniques are not as efficient as desirable for rail applications in terms of time and cost. Therefore, we propose a novel EGNSS multi-sensor solution and to develop these two tools (DM and GT) without any dependence or modification of trackside equipment. In this project, a "big dataset" collected with different sensors through several runs in Italy and Spain is analyzed and processed to yield the mapping information as well as ground truth data, leveraging on regular train trips in different operational scenarios and time.

This paper presents the main requirements and the selected architectural design to build a reliable, robust and accurate GT and a DM toolset exploiting specific data fusion algorithms. The paper also discusses the methodology, integration of processes, sensors and systems to ensure the validity, scalability of the GT and DM toolsets to contribute to the standardization process for the adoption of GNSS positioning in the ERTMS standard.

## 2 Ground Truth

The concept of "Ground Truth" is a well-established principle in cartography, where remotely collected data is validated by in-situ measurements. These measurements can be used, for instance, to calibrate remote sensing devices (e.g., satellite sensors), verify or correct experimental inferences, and update geographic databases. Cartographic methods have significantly improved thanks to GNSS-based positioning methods, interoperable

data standards for the rapid exchange of highly interrelated and accurate information and devices and interfaces that visually deliver information on demand for different user needs.

### 2.1 Ground Truth Definition

In RAILGAP, the Ground Truth is defined as a set of georeferenced data with known accuracy, availability and reliability, built by means of a well-described process, to be considered (a) a stable and true reference, suitable for the purpose of comparison and validation of other data sources in the railway domain according to established requirements and (b) the basis for developing other railway components such a high accurate Digital Map [1]. In practice, this concept translates into a set of variables that, for each epoch, determines the position and dynamics of the train, like:

- Timestamp (UTC): Instant of time (k epoch) in the time scale to which all other GT variables are referred – usually provided by the GNSS receiver
- Absolute position (WGS84): Location of the vehicle, with respect to the Earth, at the time specified by Timestamp – determined by GNSS/INS measurements
- Speed: derived from the GNSS/INS measurements
- 3D Acceleration (with respect to the Body-frame): instantaneous 3D acceleration – derived from GNSS/INS measurements
- Attitude (with respect to the Body-frame) – derived from GNSS/INS measurements

### 2.2 High Level Requirements

In RAILGAP project, a specific attention has been devoted to the analysis and definition of the user requirements for the "Ground Truth as a "product" concept, at functional and non-functional levels. They are aligned to the following issues:

- Handling and pre-processing of data from different sources (37% of the requirements)
- Computational aspects related to the derivation of the Ground Truth (47% of the requirements)
- Output data management and outcomes visualization (8% of the requirements)
- User interfaces (8% of the requirements).

These requirements have been then further detailed up to a lower level corresponding to the toolset development, considering also the algorithmic recommendations and the outcomes from the experimentation performed within the project.

### 2.3 Functional Architecture

The functional architecture of the Ground Truth is presented in Fig. 1. Particularly, this diagram provides the relation between the GT logical architecture and the GT toolset.

**Input data**. A set of sensor devices is integrated into an On-board Unit (OBU), deployed on board of each train and properly configured as per the analysis performed during the project. This OBU will record all the observables (input data) required for the Ground Truth Computation.

**Data Fusion and FDE (Faut Detection & Exclusion) Algorithm**. The input data are then validated and processed in order to detect the presence of outliers and faulty data and eventually exclude them from further processing. To obtain a combined full solution of a potential Ground Truth, a data fusion is then performed.

**Ground Truth Construction**. The fused data set is then processed by the Ground Truth Computation Module. The GT computation may be supported by additional sensors or technologies such as cameras, or LIDAR for certain functionalities, such as track discrimination. After this computation, a set of checks are performed to validate the results.

**Output management and Database construction**. After this computation, a set of checks are performed on the obtained values for their validation and computed data are stored in a dedicated database, which will be accessible to the user by means of the corresponding interface.

**User interface**. The User Interface is in charge of handling input data and configuration settings defined by the user according to the different use cases, and presenting the output data in a kindly and understandable manner.

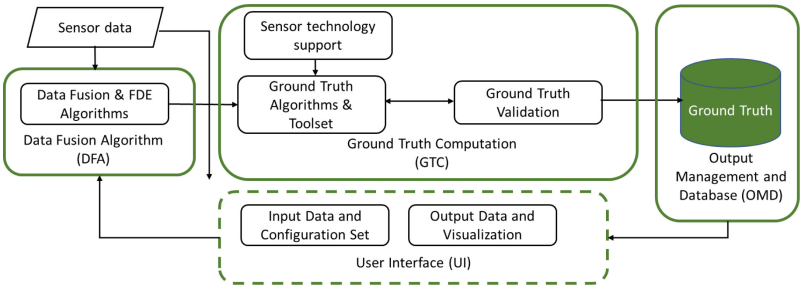



**Fig. 1.** Functional architecture of the Ground Truth

## 3 Digital Map

The "Digital Map" as a concept is related to the description of the railway network infrastructure in terms of the following information [2]:

- Topology: the track network as described as a topological node edge model, graph based [3].
- Geometry: it connects the objects of the topology to the physical word.
- Railway infrastructure elements: a variety of railway signaling relevant assets that can be found on, under, over or next to the railway track, e.g., balises, platform edges.
- Immaterial objects: encompass features that are closely linked with the railway infrastructure (e.g. speed limits, gradient, radio coverage area…).

### 3.1 Trackside Digital Map

In RAILGAP project, the Trackside Digital Map (TDM) tool is a comprehensive digital mapping tool designed for the needs of railway companies, operators and maintenance personnel. It provides an up-to-date and detailed representation of the entire railway network, including track layouts, infrastructure, and signaling systems. The map displays information such as track configurations, railway signals, switch points, and grade crossings, making it easy to understand the location and status of various components of the railway system. In addition, the TDM could provide information on rail yards, maintenance facilities, and other critical infrastructure components, helping to improve overall operational efficiency and reduce downtime and also supporting maintenance activities such as inspecting tracks, identifying potential problems, and planning track upgrades. Overall, the TDM provides a powerful and intuitive tool for optimizing railway operations and maintenance ensuring the efficient and reliable operation of the rail network.

### 3.2 High Level Requirements

User requirements for the TDM have been set in the RAILGAP project, at functional and non-functional levels. Particularly, TDM shall be able to:

- Process time-synchronized data coming from different sensors based on GT, imaging and ranging sensors (i.e., cameras and LIDAR) acquired through commercial trains equipped with the RAILGAP measurement subsystem.
- Detect, classify and georeference typical signaling object components of the TDM.
- Build the TDM in standardized format and semiautomatic way.
- Perform continuous monitoring, control and automatic update of the TDM when significant changes occur.
- Scale the TDM structure allowing aggregation of additional information layers and the connection of different sections of the railways network (national or European).

### 3.3 Functional Architecture

The TDM functional architecture is presented in Fig. 2. *Sensors* block provides raw measurements from IMU, GNSS, stereo camera and LIDAR sensors, acquired by the On-Board Measurement block and made available to the TDM by the Trackside Data Collector block for off-line processing. *Fault Detection and Exclusion* block is responsible for detecting faults in the sensors data, and if necessary, correcting or excluding them by appropriately configuring the processing chain.

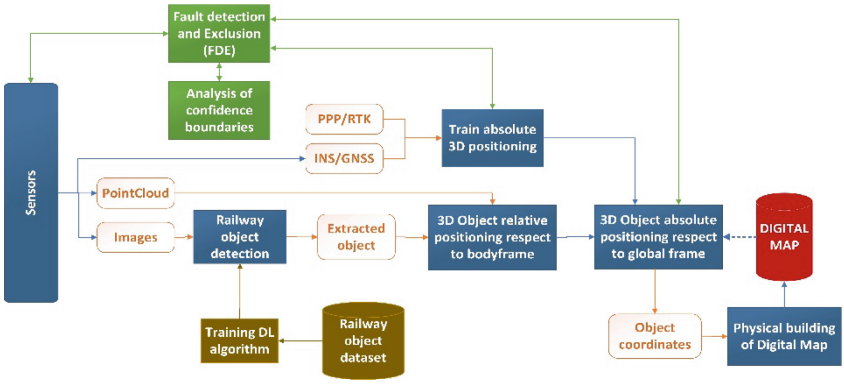



**Fig. 2.** TDM Functional Block Operational Workflow

*Analysis of confidence boundaries* block provides the computed confidence boundaries associated with the Train absolute 3D positioning and Object absolute 3D positioning blocks. *Train absolute 3D positioning* block processes IMU and GNSS raw data to provide accurate 3D position of the train [4]. *Railway object detection and classification* block consists of a set of techniques for object detection and classification based on AI techniques for image, video, and point cloud analysis [5]. *3D Object relative positioning respect to body frame* block computes the position of the detected objects with respect to the train itself as both resulting bounding boxes from camera and LIDAR are expressed in the local sensor coordinates. *3D Object absolute positioning respect to global frame* block takes as inputs the detections provided by the Object relative 3D positioning block and the output of the Train absolute 3D positioning block to compute the 3D position of the detected objects in the global reference frame. *Digital Map* block is the database containing the DM, the toolsets and algorithms responsible for building it based on the coordinates (and any other data) provided by the Object absolute 3D positioning block. Topology and geometry information of the track network and relevant railway infrastructure elements data, are stored in the DM. The DM is also used by the Object absolute 3D positioning block to retrieve and update objects coordinates and associated information in a certain area.

## 4 Conclusion

The paper provided an overview of the main goals of the EU project RAILGAP addressing two gaps still hindering the adoption of satellite-based systems in railway applications: the lack of high-quality Ground Truth data and the need for a modernized process for mapping existing train tracks cost-effectively, by deriving mapping information directly from trains in commercial operation. GT and TDM toolsets were described in terms of architectural design, methodology and integration of processes, sensors and systems. The outcomes will enable obtaining high accuracy and reliable reference data and characterizing even the most challenging railway environments by exploiting the huge amount of data collected from GNSS receivers and other sensors such as IMU, LIDAR and camera, without operational overheads, at minimal cost in hardware while

removing any need for trackside infrastructure. Digital Map should be part of the characteristics of any line. At near future, after having properly defined a procedure, the Infrastructure Managers (as RFI and Adif) should provide such information (and such a service) to any operator that will run on a line equipped with HL3 or moving block.

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# Fiber Optic Sensors in Asphalt Pavements: Investigation of the Sensor and the Asphalt Pavement

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**Abstract.** Implementing fiber optic sensors (FOS) in asphalt pavements provides a wealth of data with multiple applications. Successful integration of FOS into asphalt pavements depends on two key requirements. First, the sensor embedded in the asphalt must withstand the paving process without damage. Second, the cable must neither compromise the performance nor the durability of the asphalt.

These requirements were rigorously evaluated in a joint effort between the Technical University of Darmstadt and RINA Consulting S.p.A. Using realistic forces and material temperatures, asphalt samples were compacted and cable functionality and integrity were non-destructively evaluated. Standardized mechanical tests were used to conduct asphalt performance under dynamic loading. Void distribution within the asphalt specimens were evaluated using asphalt petrology techniques.

Results confirmed the integrity of nearly all cables tested, with minimal impact on asphalt void content and structure. Mechanical tests provided insight into the durability and performance of FOS-containing specimens.

**Keywords:** Fiber Optic Sensor · Asphalt Performance · Asphalt Petrology · Void Content · Monitoring

## 1 Introduction

Asphalt pavements are a critical component of modern transportation networks and are subjected to severe and varied stresses from vehicular traffic, climatic variations, and environmental factors. As a result, continuous monitoring and evaluation of the structural health and performance of these pavements is essential to ensure road safety, optimize maintenance strategies, and extend pavement life. Traditional pavement monitoring methods often fall short in providing real-time and comprehensive data, requiring innovative approaches that overcome traditional limitations.

FOS (Fiber Optic Sensors) are a relatively new approach to pavement condition monitoring. Embedded in the asphalt structure, they allow accurate assessment of strain

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and stress distribution across the pavement structure, which, when combined with temperature data, is of great importance in understanding pavement performance and failure mechanisms [1]. During the installation of the FOS in an asphalt pavement, they are usually exposed to difficult conditions such as high temperatures, humidity, strong compaction forces, frequent heavy loads and other similar factors. However, it must be checked to what extent the cables can withstand these conditions and whether this measure actually results in the asphalt's performance properties not deteriorating.

## 2 Literature Review

### 2.1 FOS in the Field of Transportation Infrastructure

FOS have been used in numerous applications in transportation infrastructure. Various methods have been used to protect the cables.

One implementation is in the realm of smart cities, where FOS cables have been embedded within asphalt layers to continuously monitor traffic loads, temperature fluctuations, and strain distribution. This approach serves for the optimization of maintenance schedules and the enhancement of inner-city road durability [2]. The cables were laid in the ground next to the road to protect it. The quality of the road surface does obviously not suffer, but the measurement process is not as direct.

At an airport pavement test facility in the USA a study was conducted involving the installation of an inventive polymeric plate technology on four distinct pavement test sections to assess the strain response under traffic-induced loads [3]. However, the production of the plates is very complex and it is uncertain to what extent the measurements are still accurate.

A high viscosity asphalt mortar was used in Japan on a slope of an under-construction asphalt-faced dam to protect the installed cables. The FOS were fixed to the asphalt base with a primer and finally built over. Preliminary assessments demonstrated FOS survival during hot mix asphalt fabrication, involving compaction at temperatures exceeding 170 °C [4].

### 2.2 Feasibility of FOS for Planned Application

Fiber optic (FO) are essentially a core normally made of glass surrounded by a transparent cladding of glass with a lower index of refraction. The difference in the index of refraction of the two layers of glass causes the total reflection phenomena, which permits the light to travel in the core. FOS are based on waveguides where deviations in the physical characteristics of light waves that propagate from external stimuli/signals through the optical fibers are sensitive to numerous external signals. Being by their nature very fragile, FO are normally coated with further materials to achieve higher resistance. Introducing such coating materials, it is necessary to ensure a proper transmission of external signals (i.e., strains and temperature changes) to the FOS through the coating's materials. For this reason, a study on commercially available FOS was performed to identify the best solution in terms of coatings materials able to transmit properly external signals and to protect the FO during the asphalt construction process. Among the different

possibilities, SOLIFOS FO were selected. Such cables are armoured with central metal tube and structured polyamide (PA) outer sheath. They can resist up to 30 MPa of hydrostatic pressure and for short periods (about 15 min) can operate at very high temperature (180 °C). In particular, being necessary to monitor both strain and temperature changes three different solutions were identified: BRUsens DSS 3.2 mm V9 grip: 1 strain sensing cable with strain range up to 1% ∅–3.2 mm, [ID: DSS V9]; BRUsens DTS STL PA: 2 temperature sensing cables with operating temperatures between −30 °C and +70 °C ∅–3.8 mm, [ID: DTS PA]; BRUsens DSTAS V13: 2 strain sensing cables with strain range up to 1% and 4 temperature sensing cables with operating temperatures between −30 °C and +70 °C, ∅–6.5 mm [ID: DSTAS V13].

## 3 Laboratory Program

### 3.1 Preparation of Specimens

To simulate the paving process with FOS placed directly on wearing course, a special preparation method had to be developed. After several tests, a variation of the compaction process using the Marshall Impact Tester was used. At first, base specimens with a thickness of minimum 3.5 cm were produced. The Marshall compaction mould has a height of 9.7 cm. Hence, 6 cm thickness to pave over the base with the binder layer were left. Both, the base and the binder specimens were built out of asphalt concrete AC 22.

Before the paving process, the base was applied with a suitable amount of bitumen emulsion to ensure a sufficient layer bonding. After the breaking process of the emulsion was finished, a cable part with the length of roughly 50 cm is placed inside the compaction mould. The mould was prepared in such a way that the integrity measurements could be conducted afterwards. After the cable positioning, hot mix asphalt is put into the compaction mould. The asphalt is then compacted using the Marshall impact tester. After cooling, the produced Marshall-cable-specimen is pressed out of the mould. In total, six specimens were produced.

### 3.2 Integrity Measurement

Once embedded in the asphalt the integrity of the FOS was checked by injecting a laser light into the fibre cable and verifying the light passing through in the FOS. In particular, a beam of laser light with a wavelength around 650 nm, which is visible to the human eye, was used. Being FOS waveguides, they can transmit light inside only if intact, without excessive bending or compressive zones, otherwise the light would come out from the waveguide. Therefore, seeing the light exiting from the opposite extremity of the FO cable means that the waveguide is properly working (Fig. 1).

Six samples for each typology of FOS cable were manufactured and tested. All the tested FOS resulted to have been correctly embedded in the asphalt (cf. Table 1).

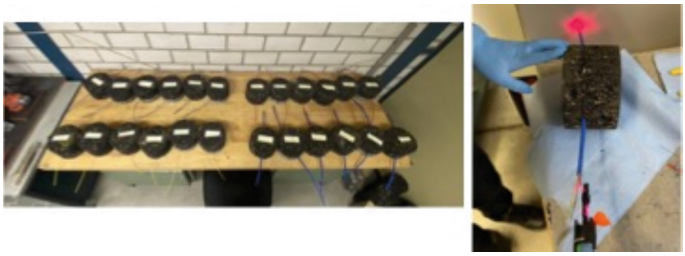


**Fig. 1.** On the left - samples realized for the experimental campaign; on the right - one of the performed tests.

**Table 1.** Summary of tested cables and rate of survival of tested cables.

| Sample | | Number of available cables | Number of tested cables | Tested cables (%) | Number of survived cables | Survived cable (%) |
|---|---|---|---|---|---|---|
| ID: DSS V9 | Strain FO | 6 | 6 | 100 | 6 | 100 |
| ID: DTS PA | Temperature FO | 12 | 9 | 75 | 9 | 100 |
| ID: DSTAS V13 | Strain FO | 12 | 10 | 83 | 10 | 100 |
| | Temperature FO | 24 | 11 | 46 | 11 | 100 |

### 3.3 Impact on Pavement Quality

**Asphalt Petrology**

Asphalt petrology is a geology science-based method for analysing the internal structure of asphalt samples. The sample to be examined is first cut to the desired dimension. The prepared specimen is placed in a vacuum chamber with pigmented epoxy resin that can penetrate the smallest cavities under negative pressure. Finally, the samples are scanned with a UV-scanner for image-analytical evaluation (Fig. 2).

Figure shows examples of the asphalt petrological sections for each FOS sample and a reference sample without cable. A total of three sections were produced and examined for each cable, each showing an equivalent pattern. The sensors can be seen in the green boxes with the voids in yellow. It can be noted that the cable with the smallest diameter (ID: DTS PA) has the fewest cavities, which also correlates with the results of the uniaxial cyclic compression test. Overall, however, it can be assumed that the bond between asphalt and FOS is very good, as no significant accumulations of voids around the cable can be detected.

**Uniaxial Cyclic Compression Test**

The uniaxial cyclic compression test describes the behaviour of asphalt under continuous load cycles and a temperature of 50 °C. Specimens are prepared according to [5]. During

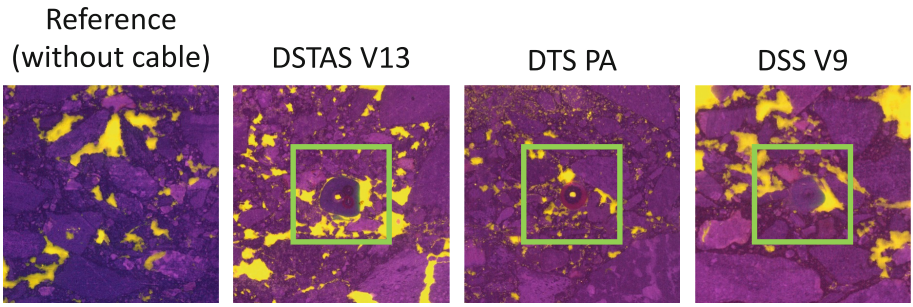



**Fig. 2.** Asphalt petrological sections of the three FOS samples (DSTAS V13, DTS PA, DSS V9)

testing the samples are loaded with 0.35 MPa lasting a loading time of 0.2s and relaxed with a load of 0.025 MPa lasting 1.5 s. This cycle is repeated until the stop criteria of a strain of 80‰ is reached or 10,000 cycles have passed. The influence of the cable on the asphalt quality can be determined by comparing the samples with each other (cf. Table 2). Three tests were carried out in each case and the outliers were neglected.

**Table 2.** Results of the cyclic compression test

| Sample ID | Sample | Impulses [n] | End strain [‰] | Strain Rate [‰$10^{-4}$/n] | Mean Strain Rate [‰$10^{-4}$/n] |
|---|---|---|---|---|---|
| DSTAS V13 | A | 4250 | 80 | 72.7 | 75.0 |
| | B | 5450 | 80 | 77.2 | |
| DTS PA | A | 10000 | 14.4 | 3.6 | 2.5 |
| | B | 10000 | 9.3 | 1.3 | |
| DSS V9 | A | 10000 | 34.6 | 33.4 | 34.0 |
| | B | 8600 | 80 | 34.7 | |

The strain rate at the inflection point is suitable as a decisive factor for describing the resistance to permanent deformation. This is given as the mean value from two individual measurements for the tested samples in Table 2. The smaller the strain rate, the more resistant the specimen. A decrease in deformation resistance can be seen from sample DTS PA to sample DSTAS V13. Sample DSS V9 is in the middle range. The test results thus indicate that the deformation resistance decreases with the increase of the cable diameter.

## 4 Conclusion

As part of this research, a laboratory program was developed to investigate the effect of compaction on the integrity of FOS specimens, as well as to determine the effect of different FOS specimens embedded in asphalt on the quality of an asphalt pavement. The

integrity tests showed that the compaction process replicated in the laboratory did not result in any damage to the cables. The subsequent analysis by asphalt petrology revealed that the cable with the largest diameter has a slightly void-richer microstructure. Since no significant void accumulation around the cables is visible, a good adhesion between cable and asphalt pavement is assumed. Finally, the uniaxial cyclic compression test showed that the cable thickness affects the deformation resistance. The specimens with the thinner cables led to a better deformation resistance. However, since the cores used for testing represent only a small area in relation to the total area of a road pavement, it is necessary to validate to what extent this applies on a full-sized paved road construction. Nevertheless, the presented research is a first step towards the usage of FOS inside the asphalt pavement without protective measures.

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# Unlocking Digital Collaboration: The MINERVE Project as Catalyst for the Railway Infrastructure

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**Abstract.** The railway sector brings together heterogeneous industry bodies and actors to design, build, and operate railway systems. The digitalization of the rail sector is supported by numerous technologies and the abundant developments go beyond the organization level and require coordination at the sectorial level. As French railway infrastructure manager, SNCF Réseau has launched the innovative research and development project MINERVE. This project brings together the main players in the French rail sector to build a collaborative ecosystem around railway infrastructures challenges and to develop a shared vision of digital continuity. The challenges addressed in MINERVE are related to the transition towards a more efficient, reliable, and environment-friendly railway operation by designing and building with collaborative digital methods and tools. The main objective is to reduce the overall cost and impact of the railway system while increasing collaboration between stakeholders.

MINERVE outcomes are related to specific, standardized, and interoperable methods and tools, for all technical fields, and that can be implemented and adopted by all stakeholders. The MINERVE project is a one-of-a-kind project to unlock digital collaboration at the sectorial French industry level to improve the life span of the infrastructure as well as the environmental performance of railway projects including biodiversity and resilience to climate change.

**Keywords:** Digital continuity · BIM · Digital Twin

## 1 Introduction

Railway companies have launched digitalization programs integrating BIM and the digital twin (DT) to improve their performance and internal production processes. Rail services are produced based on technical and organizational resources involving most of the time many supplier companies, service providers, manufacturers, etc. Infrastructure managers, for example, rely on the construction industry, but also on companies

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specialized in electronic and computer systems, engineering systems, and consultancy companies to manage the handling of trains and traffic management. As a result, significant changes in the production methods of an infrastructure manager have a heavy impact on the entire railway sector. At the same time, to improve their performance, contributing companies are also led to carry out transformations to better respond to their customers. In this context, the individual transformation programs of each company will not be enough to address sectoral issues that require coordination not only at the level of each company but at the scale of the whole industry.

Sectoral collaborations are limited to the creation of standards for the exchange of data and best practices on digital tools. For example, the railway industry has collaborated at a global level for the integration of railway concepts in the ISO 16739 standard (IFC) to facilitate the interoperability of modeling tools. The players in the railways sector also collaborate within various digital projects for new products and components. The question that then arises is the following: is this collaboration enough to allow the sector to address challenges such as global performance, or environmental issues (decarbonization, climate change…) ? In the literature, digital collaboration is most often approached from the angle of a collaboration platform or even collaborative design or co-engineering processes (Felson (2013) Karrasch (2017), Danfulani and Anwar (2018)). Within these approaches, actors attempt to integrate sectoral concerns such as the integration of the environment into disciplines by finding innovative methods. Questions about the method of sectoral collaboration to facilitate integrated solutions are rarely addressed.

The production of railway infrastructure is carried out with strong coordination between stakeholders to ensure the safety of train movements. The decisions of some stakeholders during the design phases may have an impact on other actors in the railway system. In this context, process improvements and more particularly digital transformation approaches internal to stakeholders can have a global impact downstream of productions carried out with new methods. Furthermore, the challenges on environment require collective coordination of stakeholders to adapt each production to these issues and find optimal solutions that meet these challenges. Accordingly, the railway infrastructure manager launched an original project to facilitate stronger sectoral coordination for coherence of digital transformations at the industry level. The MINERVE project was launched by the main players in the rail sector in France to address the issues of the rail sector from both a scientific and process point of view in a context of strong pressure from public authorities on increasing performance for transporting large numbers of people without increasing carbon emissions.

This paper will first discuss the collaborative approach underlaying the whole project, then expose an overview of its first results and finally will discuss those results and give a glance at the upcoming developments of the MINERVE projects.

## 2 MINERVE, A Collaborative Research Initiative with All the Sector Stakeholders for Tackling Railway Challenges

The railway infrastructure sector brings together many heterogeneous industry bodies and actors to design, build, and operate railway systems. In the context of accelerating digitalization, it is essential to coordinate heterogeneous approaches to build and implement the digital continuity as an enabler for the railway infrastructure performance over

the entire design - operation - maintenance cycle. Indeed, the digitalization of the rail sector is supported by technologies such as BIM, DT, AI, and IOT, as well as by the adoption of systems engineering, and the development of traffic simulation tools. These ongoing developments go beyond the organization level and require coordination at the sectorial level. That is why the MINERVE project has been designed as a collaborative innovation project at the industry level, bringing together the two main French infrastructure managers (SNCF Réseau and RATP Infrastructures), engineering companies, public work companies, research institute and academics.

The MINERVE project outputs will contribute to accelerate the transition towards a more efficient, more reliable, more environmentally friendly railway construction and operation, by designing and developing efficient digital methods and tools for infrastructure modeling to reduce its overall impact on climate change while increasing its competitiveness. More specifically, the MINERVE project aims to:

- *Anticipate and optimize the construction phase*, based on sustainable BIM methods and tools, taking into account each civil work domain characteristics.
- *Develop the DT,* explore the potential of AI as a decision support tool for exploitation and maintenance of the railway infrastructure, capitalizing on the BIM models.
- *Develop an industrializable*, standardized, and shared vision of the interfaces, by building a collaborative ecosystem around the modeling of linear infrastructures.

Capitalizing on the wide experience of its members, the MINERVE project is built as action research since it pursues action (or in the current situation experimentation) and research (or understanding) at the same time to identify and experiment value-added actions to coordinate all organizations towards reaching common goals at the sectoral level. Therefore, the project methodology relies on:

- *Semi directive interviews* to identify needs of the railway industry actors and formalize them in operational requirements to identify convergence points and required alignments of tools and methods to increase their industrial performance.
- *Recent research results on railway reference architecture building* (Sango et alii, 2022), conceptual data models, ontologies, and multidisciplinary and multimodal optimizations. This reference architecture is a shared foundation of the MINERVE project. It aims to handle system requirements and components performance, and to facilitate the use of heterogeneous data structures to address different system capabilities. Moreover, such an architecture is a prerequisite to build a multi-domain and multi-phase collaborative platform that could be ultimately used on all phases of the design - operation - maintenance cycle.
- *Experimentation of solutions on real railway infrastructure construction sites*, when partners have identified that a digital solution brings added value on one or several phase of the design - operation - maintenance cycle.

# 3 First Results of the MINERVE Collaborative Project

## 3.1 Common Understanding of the Impact of Introducing Digital Technologies on the Railways Sector Production

In the field of railway design, an important area of work was to share a common understanding of the production tools of the different actors, their functional areas (electric traction, tracks, telecom, signaling) and what BIM methods change in current production. Feedback took place in all domains and allowed railways sector stakeholders to share best practices allowing real performance gains. These exchanges also make it possible to progress on common sectoral specifications for the entire sector (Fig. 1).

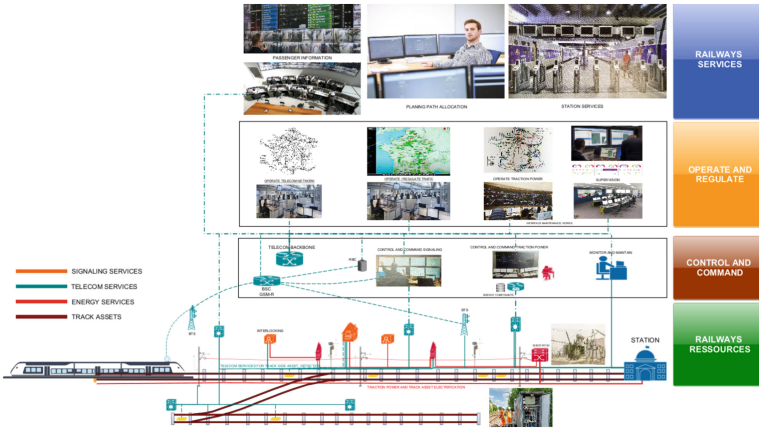



**Fig. 1.** Illustration overall railways architecture, designed within the framework of Horizon 2020 – Shift2Rail projet Linx4Rail, Grant agreement ID: 881826

## 3.2 A Digital Twin Concept for the Design of Performant Railways

Monitoring the global performance of a railway system is becoming increasingly important as new constraints are imposed on the system: increased number of travelers, multiplication of environmental constraints linked to climate change, reduction of the environmental impact of rail transportation. Besides, designing and building railway assets are complex tasks, which calls for better collaboration between the various stakeholders and for digital services that enhance it. Complexity arises for several reasons. First, the subsystems are numerous and heterogeneous including tracks, civil engineering structures (bridges, tunnels, earthworks), equipment (mechanical, electrical, electronic), the fauna and flora surrounding the tracks. Second, various human organizational structures are established at the subsystem and system levels for carrying out the design and building tasks. Third, the global performance of the railway system strongly depends on its subsystems. For instance, a retaining wall damaged by a flood, an organization that struggles to respect a work schedule are local issues that can result in a series of disruptions and impact the global performance of the railway system.

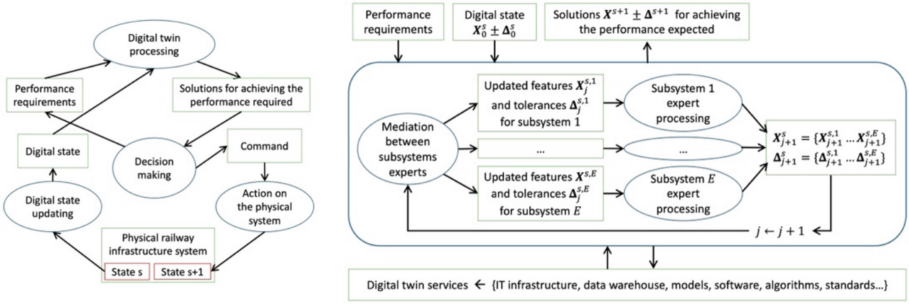



**Fig. 2.** DT concept for designing and building railway systems at the organizational level. [Left] Railway manager perspective where the outputs of the DT processing are used for aiding decision. [Right] The proposed DT concept integrates the engineering practice with an iterative process organized by subsystems experts.

DTs in the design phase of engineering projects has been recently investigated as for instance in the work of Thelen *et al*. (2022) and van Beek *et al*. (2023). In the framework of the MINERVE project (railway engineering), a DT concept for designing infrastructure systems that reach global performance requirements has been proposed by Jehel and Vialle (2023). At the organizational level, the DT processing enhances collaboration between stakeholders providing them with digital services during the process (see Fig. 2). At the functional level, families of services that the DT should provide have been identified during a series of 21 interviews with subsystems experts. From these interviews, the following 5 functions are expected:

- *Retrieving the current state of the railway infrastructure.* Whether in brownfield or greenfield projects, the already existing railway assets as well as the environment and context should be retrievable at the beginning of the project and then maintained in the DT.
- *Executing repetitive tasks.* Tasks are repeated either by the same people or by different people. Such tasks should be automated and shared as much as possible.
- *Checking essential specifications.* If such a specification is not satisfied, the whole project is at risk. They should be checked automatically as often as possible.
- *Managing uncertainties and tolerances.* Each subsystem should be able to develop between margins that are admissible by the other subsystems.
- *Fostering mediations between subsystems experts.* Digital services should be developed to assist them in this process for communicating their results and understanding the results of the others.

Ongoing work in the development of this DT for designing and building is at the operational level where case studies such as clearance checking along the tracks are being investigated in a multi-disciplinary group where all the interdependent subsystems are represented. The objective is to identify what needs to be digitally instantiated in the DT to support the tasks and processes involved in for instance clearance checking, and then to effectively instantiate it for testing the DT.

### 3.3 Algorithm and Method for Massive Detection of Railways Asset on Large Lengths of Track

The production of BIM models of existing infrastructure is essential but costly in terms of time and investment, particularly in a context of very extensive linear networks. In MINERVE project, the objective is to produce methods and algorithms for detecting railway objects in points clouds to massively produce BIM models of legacy infrastructure to better anticipate the planning of operations. The results will allow software publishers to improve the functioning of their tools in context railway.

Object detection in images or point clouds is already addressed in several initiatives. In our project, we are particularly interested in the components of the railway system both to identify objects, to extract information or even to extract geometric elements used in business production. In many situations, the challenge remains to feed the knowledge we have of legacy components or to produce models with a view to creating a new design. This has been particularly experienced in the engineering works professions and in the field of tunnels, electric traction professions and telecommunications. The detection of rail wires is also tested (Fig. 3).

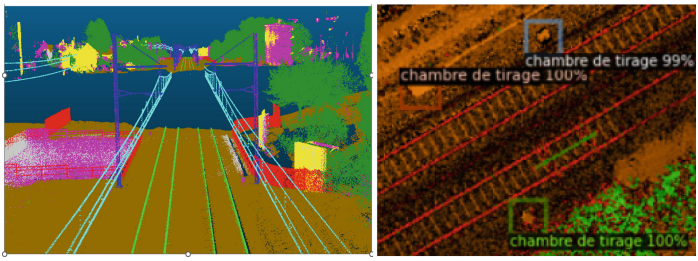



**Fig. 3.** Illustration of track (a) and telecom equipment (b) detection in a point cloud data, 3D point clouds of the French railway network processed with SNCF Reseau proprietary softwares.

### 3.4 Results of the First Set of Experimentations on BIM to Field

As described above, lot has been done with BIM in the design phase of a rail infrastructure. Today, there is a discontinuity between the design and construction phases of a railway infrastructure project. Construction operatives have different work patterns than design operatives. That's why mixed or augmented reality (AR) can address their needs. For instance, using 3D helps the construction staff to put things into context very quickly, to locate themselves in the worksite and, by simulating the movements of road-rail shovels or work trains, become aware of potential dangers. Other use cases of AR on site is the ability for the construction workers to locate themselves very precisely thanks to a tablet or a smartphone ou to check the conformity of the ongoing construction with of the 3D model and compare both, check the recolement to ensure/verify the coherence between the actual realization and the model as built…

In early 2023, SNCF Réseau tested its first site briefing using BIM models. Safety is one of the company's top priorities, and even more so when carrying out rail works. One of the objectives of this first experimentation of BIM to field was to provide a

better contextualization of the work situation and its environment, using kinematics representing the first 8 h of work. One of the first feedback from the organizer of the site briefing is that this kinematics helped during his speech to remind visually the safety elements for each situation (not only but pointing out on the construction plan).

SNCF Reseau is now intending to go further in the development of BIM to field, together with the MINERVE project partners. We are currently working to improve and make more reliable 3D simulations using 4D planning. One of the key results targeted in the MINERVE project is to specify and experiment different methods for developing BIM in the field.

For BIM to be useful and fully integrated in the construction phase, we need to go beyond technical experimentation and support those involved on the site to work differently, in a more collaborative way, by demonstrating them the added value of such technologies, improving the reliability of the work carried out in terms of time.

## 4 Discussion and Conclusions

At the end of the work phases, the civil work companies deliver an executed work file in PDF (non-digital) which constitutes the main information source for the asset manager. With BIM productions, new data schemas have appeared with the IFC format allowing management of data from the design construction phase. Infrastructure managers databases for asset management are quite far from this format. The objective of the project is to propose methods, architecture, and prototype tools to test how BIM can feed asset managers databases without manual re-entry.

Furthermore, the concepts of system integration and system architecture in railways and concurrent engineering appear and allow process optimizations and work reliability thanks to digital data. This project involves exploring the opportunities offered by these methods with the aim of improving existing processes.

Finally, the production of BIM models opens the way to the more extensive exploitation of data from the design and construction phases to the downstream phases, in particular operation and maintenance within the framework of DT concepts of assets. This project will be about progressing on these concepts and proposing uses of the DT in connection with the laws of aging of structures for maintenance planning, but also avenues for managing subjects such as adaptation to climate change.

This paper presents some of the efforts deployed in the MINERVE project for unlocking digital collaboration in railway infrastructure projects among all the stakeholders. The MINERVE project is planned to run until 2026. Hence, it will further strive to improve its technological developments and go a step further on experimentations to become a major provider of methods and tools specifications towards sustainable railway infrastructures.

The research and developments carried out in the MINERVE project should be accompanied by changes in the architecture, engineering, and construction industry to achieve operational progresses. Indeed, practitioners are facing increasingly difficult decisions regarding what capabilities to select when deploying a DT. Agrawa et al. (2022) state that a DT nowadays offer many capabilities and sophistication levels and that there is a risk of a DT being rejected by practitioners in case of an inappropriate selection among these capabilities. Therefore, they proposed a digitalization framework

to help practitioners select an appropriate level of sophistication in a DT by weighing the pros and cons for each level. Besides, compared to the traditional design – bid – build approach, more global methods like Integrated Project Delivery where major stakeholders in the project become signatory to a single contract agreement have been successfully implemented to encourage collaboration.

**Acknowledgements.** The MINERVE project has received funding from the French Government under the France 2030 – CORIFER research and innovation programme.

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# A Schematic Plan for Train Position Identification Using Digital Twin and Positioning Sensors

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**Abstract.** This paper presents a schematic plan outlining a methodology for determining train positions using digital twin technology and commercially available positioning sensors. The plan involves an offline step and an online step. The task in the offline step includes: building a library of 3D models for objects on railway tracks, and constructing a real digital twin environment. Then in the online step, train positions can be accurately determined by automatically generating real-time semantic point clouds from images and matching them with the 3D objects in the digital twin. Along with these tasks, a City Geography Markup Language (CityGML) Application Domain Extension (ADE) for modeling railway tracks in 3D will be developed and suggested as Open Geospatial Consortium (OGC) standard for similar applications. All these procedures will be conducted in a controlled environment using remote-controlled cars before being applied to an actual railway track. It is hoped that this localization methodology can enhance traditional positioning methods, ultimately leading to improved network operation and maintenance.

**Keywords:** railway Operations · trains · train positioning · digital twin · railway maintenance

## 1 Introduction

Train positioning, while crucial, was not a primary focus in the earlier days of railway operations. The static traffic block system was sufficient to ensure the safety of trains, with margins typically being adequate. However, with the introduction of the European Rail Traffic Management System (ERTMS), the emphasis on train positioning has grown [1, 2]. ERTMS has been instrumental in modernizing railway operations, emphasizing interoperability, and enhancing safety across European rail networks. Additionally, there's a shifting focus towards railway track and infrastructure condition monitoring using in-service vehicles. This shift underscores the importance of accurate train positioning, especially in a regional context, as efforts to revitalize regional rail intensify and the need to monitor track conditions using onboard sensing devices becomes paramount [3].

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Despite the emphasis on accurate train positioning, numerous challenges persist. Trains often operate in harsh railway environments, where they encounter interference, insufficient satellite availability, and signal blockages. These blockages are especially prevalent in specific areas like tunnels, valleys, or due to meteorological conditions. Such challenges have been identified and discussed by several researchers [4, 5]. The quest for precise train positioning often presents a trade-off: opting for high accuracy necessitates expensive equipment and infrastructure, such as advanced communication systems. Conversely, a moderate infrastructure and equipment setup might result in less accurate positioning.

However, technological advancements, particularly in the realms of digital twins and digital mapping, combined with the emergence of cost-effective and efficient positioning sensors, are paving the way for more affordable and efficient train positioning solutions. Vision-based methods, for instance, are being developed for line-side switch rail condition monitoring and inspection, ensuring safer railway operations [6]. Building on this foundation, this paper presents a schematic plan that leverages digital twin technology and onboard train positioning sensors to accurately determine train positions, offering a comprehensive solution to the challenges faced in the realm of train positioning.

## 2 Methodology

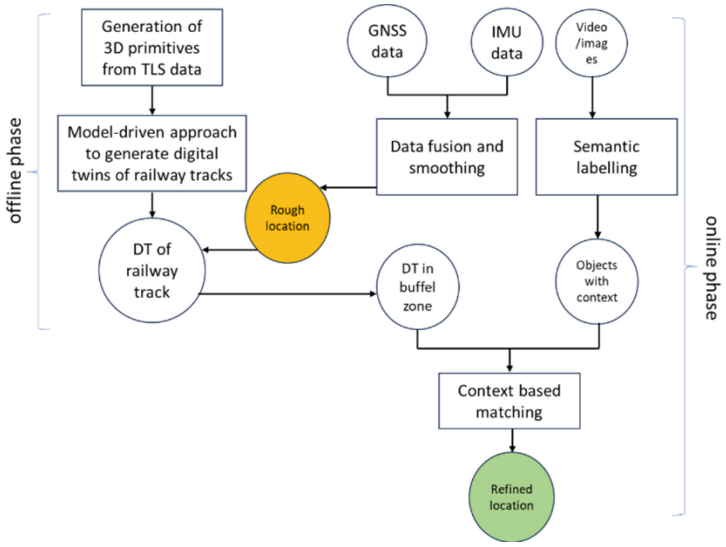



**Fig. 1.** The framework of the proposed approach for fine positioning of trains

As depicted in Fig. 1., the proposed method consists of two phases: an offline phase, which involves generating a digital twin of the railway track environment using a model driven approach with Terrestrial Laser Scanning (TLS); an online phase, for which data captured from on-board sensors such as GNSS sensors, an IMU (Inertial Measurement

Unit), and cameras, will be combined and matched with the offline digital twin model to obtain the train's real-time highly accurate locations.

### 2.1 Offline Step

There are two tasks in the offline phase: defining CityGML schema for railway track and generating digital twins with semantic information for railway tracks in the test area. So far, there exists research work about integrating railway infrastructure into CityGML [7]. However, in their concept, railway is modelled as Level of Detail 1 (LoD1) -like object without further decomposition in semantical and geometric domains. In this work, we will conduct a comprehensive inventory of objects that could appear on railway tracks to collect information about their geometrical, semantic, and attributive characteristics. Then knowledge graphs will be used to describe the semantic and topological relations of objects on railway tracks. On this base, code lists will be defined for all possible objects on railway tracks but following the sequence of from leaves to roots on the knowledge graphs. Finally, UML diagrams will be generated to describe feature classes and their hierarchical relations of objects on railway tracks.

For each object on the leaf node of the knowledge graph, a 3D digital model will be created to build up a library of 3D models for railway track modeling. In our project, TLS will be used to acquire 3D point clouds with high density, full coverage and high accuracy in positioning and geometries. In the next step, semi-automated method will be used to extract objects from 3D point clouds. At the same time. Line segments, circle-formed objects and planes will be detected from point clouds of the objects. Then outlines of the components of an object can be extracted, and further regularized in terms of shapes and topology. Finally, these primitives of objects can be modelled in CityGML. It should be noted that we will follow the mechanisms similar to city furniture modelling in CityGML. In other words, they will be modelled in a local coordinate system with the centroid of the objects as the original of local coordinate system.

After the library of the primitives of 3D models are made available, a digital twin for railway track in the test area could be generated by using model-driven approach from TLS point clouds [8]. The reconstructed 3D models of railway tracks will be stored in CityGML format in the online phase.

### 2.2 Online Step

In the online step, the train will be equipped with GNSS sensors, an IMU, and at least four cameras at the front, back, and two sides of the train. Data captured from all the on-board sensors will be combined and matched with the offline digital twin model to obtain the train's real-time highly accurate locations.

Typically, standard GPS systems offer an accuracy of about 5 to 10 m under open skies. However, this accuracy is often not sufficient for most railway operations. To improve accuracy, many railway systems employ Differential GPS (DGPS) or other augmentation systems like RTK (Real-Time Kinematic) GPS. DGPS can improve accuracy to less than a meter, and RTK GPS can provide centimeter-level accuracy. Nevertheless, the adoption of these technologies is associated with significant financial implications.

The proposed method avoids the adoption of such expensive sensors while maintaining high positioning accuracy.

First, the GNSS signal will be employed to determine an approximate position of the train. In addition, the train's IMU data will also be utilized, which provides the train's orientation and velocity. This IMU data, based on the train's latest known position, can further refine the current estimated location of the train. Such refinement is crucial for enhancing the accuracy of GNSS data, particularly in scenarios where GNSS signals are compromised, such as in tunnels or valleys, or when signals are completely obstructed due to extreme weather conditions. Utilizing the approximate position derived from both GNSS and IMU inputs, a buffer zone is then created around this position within the offline 3D digital twin.

Next, four cameras, ideally positioned at the train's front, rear, will capture images of the surrounding environment. Railway track and trackside objects will be extracted from the multi-view images using image detection and segmentation neural networks, and their neighborhood contexts will be established. These objects will be matched with the objects in the buffer zone of the digital twin. The buffer zone can largely reduce the searching area and increase the positioning efficiency.

### 2.3 Control Environment Testing

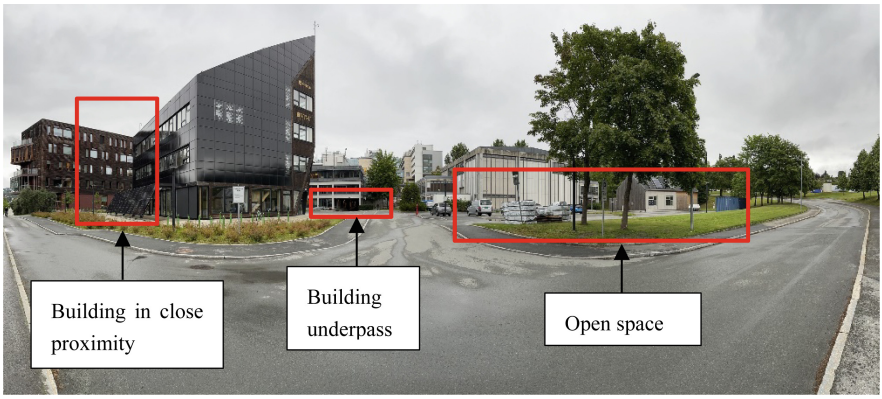



**Fig. 2.** Test Environment at NTNU

Before implementing this methodology on an actual train, it's prudent to test it in a controlled environment, primarily due to safety and security concerns. From a safety perspective, the installation of equipment, especially cameras, necessitates strict regulations and approvals from train operators and owners. On the security front, the train's position, especially if derived from on-board data, may not be readily accessible to external or unauthorized individuals. Thus, it's advisable to initially test the methodology in a broader setting and subsequently adapt it to the railway domain.

Given the generic nature of the approach, the strategy is to conduct tests in an open environment without compromising safety. A suitable location for this would be the

campus of the Norwegian University of Science and Technology (NTNU), as depicted in Fig. 2.

The campus environment offers a variety of features that can simulate railway conditions. Buildings in close proximity can mimic valleys, building underpass can represent tunnels or enclosed areas, and open spaces can serve as typical open terrains. Specific landmarks and objects within this environment will be positioned in the digital twin for accuracy.

To simulate the train, a remote-controlled car will be employed. This car will be equipped with the same sensors as those on the train (i.e., GNSS sensors, cameras, and an IMU). First, an offline 3D digital twin of the test site will be generated using the methods described in Sect. 2.1. Next, the car will traverse the campus, while the data captured by all its sensors will be combined and matched with the digital twin to obtain the car's real-time locations. The algorithm will be continuously tested and revised until the positional accuracies achieve satisfactory.

## 3 Potential Challenges

Several challenges can be anticipated at this stage:

**Monotonous Objects:** While railway tracks are lined with numerous objects, many of these are repetitive in nature. For instance, the shapes of rails and sleepers remain consistent over long stretches. Relying solely on images for object identification can be problematic when environmental differences are minimal. Hence, it's crucial to incorporate other data sources, such as velocity, train position, and high-frequency trackside objects.

**Weather Conditions:** Conditions like heavy rain, snowfall, fog, or a snow-covered environment can obstruct or degrade camera visibility, compromising image quality for identification. In such scenarios, alternative data sources or methods should be considered to address these challenges.

**Difficult Locations:** Locations like tunnels and valleys are notorious for obstructing GPS signals. Additionally, these areas are often dimly lit, further complicating positioning efforts.

**Lighting:** Proper lighting is essential for accurate camera image identification. In low-light conditions, the accuracy of train location identification may be compromised. Potential solutions could include using cameras capable of functioning in low light or installing additional lighting on the vehicle.

**Odometer Data:** The resolution of odometer data logging can vary, presenting challenges if there's significant deviation. Different odometers have varying logging frequencies, which can affect the accuracy of positioning.

**Communication System:** Transmitting real-time position data to a central system can be challenging, especially when commercial communication infrastructures are unavailable, particularly in regional contexts. It's essential to process and compress position data to ensure it's transferable, even though systems like GSM-R.

**System Integration:** Once developed, system compatibility might pose challenges. The on-board system could differ from the testing version. If the system is to be implemented on-board, seamless integration with existing systems is vital to avoid substantial investments. Ideally, a plug-and-play solution would be most beneficial in this context.

## 4 Expected Outcomes

Through this methodology, the ambition is to pinpoint train positions with a precision of $\pm 25$ cm. This level of accuracy is a marked improvement over certain maintenance vehicles, which currently have positioning accuracies more than $\pm 15$ m. Another anticipated outcome is the potential for this methodology to be seamlessly implemented across all trains in Europe. The ideal scenario would be a plug-and-play solution, subject, of course, to rigorous security checks and full compliance with established standards.

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# Designing the Procurement Logistics Processes of a Smart Factory Based on Virtual Building Models

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**Abstract.** Smart factory research has primarily concentrated on the manufacturing sector, without taking the building sector into closer consideration. Combining these two ventures can lead to a variety of synergies to minimize the $CO_2$ emissions of existing buildings. By producing facade and roof panels on an industrial scale for energetic refurbishments, Construction 4.0 and prefabrication can make a significant contribution to achieving climate targets. In this context, the purpose of this paper is to identify, how data of a virtual building can be used in procurement logistics of a smart factory. To achieve this, this paper follows a case study analysis. At the beginning, the procedure of developing a virtual building model is described. This is followed by the design of the inbound workflows of a smart factory in the construction industry. The findings demonstrate how the information from virtual building models can be leveraged to control procurement processes of a smart factory.

**Keywords:** Virtual Building Models · Smart Factory · Procurement Logistics

## 1 Introduction

The expected effects of Industry 4.0 on the economy are remarkable. The Organization for Economic Cooperation and Development predicts that the global gross domestic product will almost triple by 2060 [1]. The implementation of smart factories alone could add at least €1.35 trillion in value to the global economy. Currently, most studies focus on the six main industries – machinery and equipment, electrical and electronic equipment, automotive, chemicals, agriculture, and information technology – which are expected to have a value creation potential of €78 billion by 2025 [2].

In comparison, the potential of Industry 4.0 for the construction industry has received relatively little attention. The existing building stock contributes to 40% of the total energy use and 36% of the $CO_2$ emissions. The majority of European residential buildings, of which approx. 51% have been built before 1969, are in high need of renovation. The North Sea region (NSR) alone contains 22 million dwellings which cause 79 Mton $CO_2$ emissions annually. To deal with the climate crisis, climate and energy objectives were defined. By 2050, $CO_2$ emissions should be cut to at least 80% compared to 1990

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and buildings should be energy-neutral [3]. However, the building renovation industry applies mainly manual on-site techniques, resulting in a low renovation pace (ca. 2% p.a.), high labor costs and a long duration [4]. Thus, the ambition to achieve the climate targets is challenging for the sector.

The integration of smart factories could enable growth in the construction industry, as the manufacturing of housing units could take place on an industrial scale. Automated processes create efficient manufacturing approaches in residential renovation to reduce $CO_2$ emissions to a necessary limit [5]. In this context, this paper aims to identify how data generated by 3D models of residential buildings can be used for managing the procurement processes of a smart factory in the construction industry.

## 2 Related Work

### 2.1 Impacts of Digitalization on the Construction Industry

In recent years, efforts have been intensified to invest in the digital transformation of the construction industry. Initiatives are being subsumed under the term "Construction 4.0". However, similar to Industry 4.0, there is no consensus on what Construction 4.0 means. Some authors describe it as a manifestation of Industry 4.0 in the construction industry and the use of modern technologies such as the IoT, Big Data, AI or advanced manufacturing, as this could enable a decentralized, cost-effective production in smart factories [6]. A second group considers Construction 4.0 as an opportunity to find complementarities between technological approaches to address the current challenges facing the construction industry [7].

This paper follows the view of the first group of authors that industrialization in construction can lead to the implementation of smart factories. Accordingly, this requires a redesign of supply chains, as building material is now processed in factories before being delivered to the construction site, instead of being delivered directly.

### 2.2 Smart Factories in the Construction Industry

A smart factory is defined as the integration of artificial intelligence (AI), mechanical engineering, and information technologies. It can be understood as a flexible production facility of Industry 4.0, based on intelligent units, where machines coordinate production processes independently and autonomous transport vehicles carry out logistical tasks. The involved objects, such as machines, products and/or vehicles, exchange information autonomously in real-time via the internet [8]. The Internet of Things (IoT) is used to integrate resources, allowing the manufacturing system to have sensing, connecting and data integration capabilities. In this context, data is the most important basis for a smart factory. It is used in all areas, from the initial design of the products, through procurement to manufacturing [**Error! Reference source not found.**]. This enables a dynamic production structure where processes are no longer statically predetermined, but adjusted based on the individual customer order. A flexible manufacturing system is created, which utilizes a continuous stream of data from connected systems to learn and adapt to new requirements [9].

In regard to the future of the construction industry, entire house units can also be autonomously prefabricated in factories. These Smart Construction Factories aim for more standardized, cost-effective, and faster production compared to on-site construction processes. The labor costs of the construction sites are consequently converted into capital costs. In addition to new buildings, the market for refurbishment can also be addressed, as these factories can produce serial renovation packages. They consist of facade and roof panels, solar collectors and heating, ventilation, air conditioning (HVAC) systems.

### 2.3 Virtual Building Models

The building sector adopted in the past innovations for design such as 3D drawing and Building Information Models (BIM), which allow to seamlessly integrate different engineering disciplines, to have a closer look on construction details and material use as well as to realize a higher construction quality. To further automate the procurement and production processes, more information is needed and thus more detailed models of the products are required. Therefore, high-resolution models can be used. The data level of detail of these models extends BIM. High-resolution models and BIM both contain the same data such as 3D geometrics, material or components use and installations. However, high-resolution models also contain additional data of (hygro-)thermal bridges, air flow paths, air leakage and operational schedules for e.g. lighting and occupancy, HVAC and domestic hot water systems as well as embedded renewable energy systems [10]. Using this data, a comprehensive virtual model of the building and its performance is generated, paving the way for subsequent mass production.

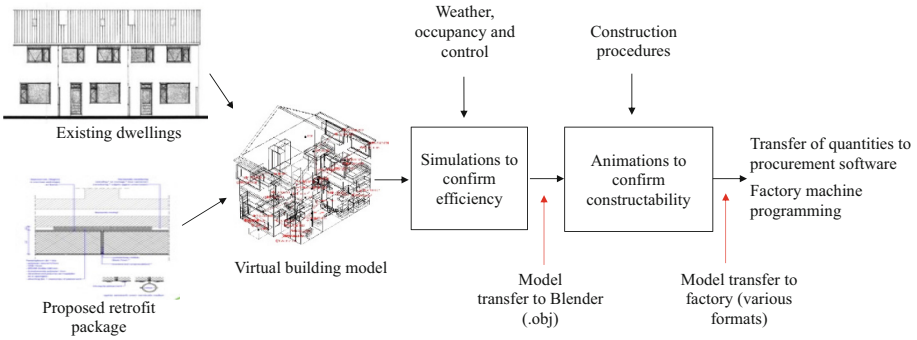



**Fig. 1.** Construction processes based on high-resolution building models.

High-resolution models can help to simulate all properties of the building, such as the condition following an energic refurbishment in which the building is renovated with panels from the Smart Construction Factory. The virtual model consists of the data of the existing building and the new facade and roof panels. Within the model, energy calculations and assembly simulations can be performed (in Blender) to verify the retrofit achieves the desired standard. If it passes, the.obj-file formats can be forwarded

to the smart factory and be transformed to other machine language protocols to initiate production and logistics processes, such as procurement logistics (see Fig. 1) [11].

## 3 Methodology

This contribution focuses on describing and analyzing a case-study. Case study-based research distinguishes between a descriptive analysis, in which correlations are described, and an explicative analysis, in which correlations are additionally examined with respect to their variability [12].

As this contribution emphases on the identification of the influence of virtual building models on procurement processes of a smart construction factory, a descriptive case study methodology according to [13] is applied. Here, five components of a research design are important:

1. The research question,
2. Its propositions,
3. The unit of analysis,
4. The logic linking of the data to the propositions,
5. The criteria for interpreting the finding.

Following the five components, this study focuses on the research question, how building data can be used to control procurement processes of a smart factory (1). The assumption is, that the use of virtual building models can increase the efficiency of the procurement processes (2). The case study of this paper is the scientific project INDU-ZERO (3). A virtual building model can increase the costs and the effort involved in the design stage (4). At last, the study needs to verify that the new automated processes can cover the additional effort of creating a high-resolution model (5).

## 4 Application of Virtual Building Models in Procurement Logistics

To tackle the need for energetic renovations, six countries of the NSR collaborate in the Interreg project INDU-ZERO "Industrialization of house renovations toward energy-neutral" with the ambition to upscale the current renovation process and to create the necessary facilities. INDU-ZERO aims to design a smart factory blueprint to produce 15,000 fully integrated prefabricated renovation packages per year per factory suitable for all NSR countries at a reduced cost of 50% [4, 14].

In the INDU-ZERO project, a high-resolution model was generated as a 3D representation of one building to be refurbished after it was scanned. Based on the measurement points and using specifications, it was developed into a digital design that includes a structured hierarchy of product information and associated naming criteria, tabular metadata and a common organization via databases.

Procurement logistics comprises the connection between the supplier's distribution and the manufacturer's production. Its objects are raw materials, supplies and merchandises that have to be made available to the manufacturer. Correspondingly, it is the function of procurement to provide, maintain and develop delivery capacities.

To provide coherent instructions for the procurement processes of the Smart Construction Factory, the manufacturing data describing the product parameters had to be converted into readable data sets for the product lifecycle management (PLM) system. Material requirements such as material quantities, design and insulation specification were generated in the PLM system. For each construction order, the combined design and PLM data was in turn queried by the Enterprise Resource Planning (ERP) system and ordered from suppliers according to the pull principle (see Fig. 2).

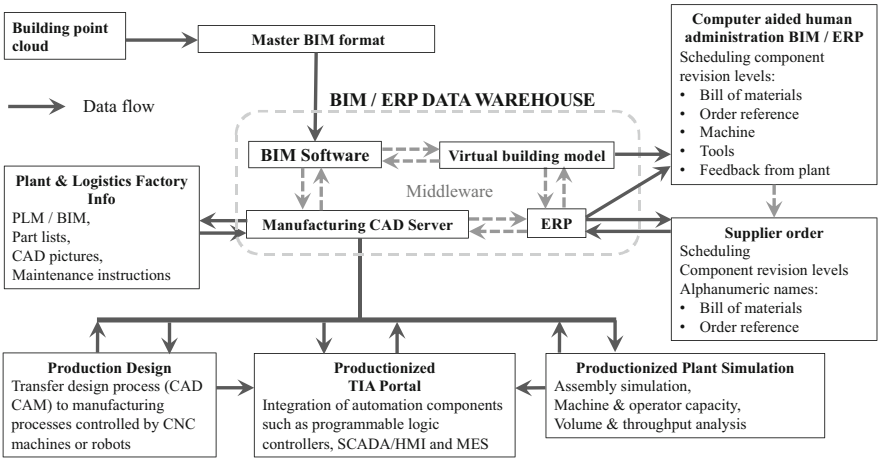



**Fig. 2.** Design of the information flows in a Smart Construction Factory.

In the implementation phase of the case study, an enterprise service bus (ESB) was used as a middleware for the data transfer between the systems. It was able to forward the data from the high-resolution model to the PLM and ERP system. After receiving the data of the materials, the suppliers prepared the transportation. Regarding the purchase, suppliers referred to predefined agreements so that individual orders do not have to be renegotiated. With this scenario, analogue administrative processes between the procurement, production and sales departments were avoided.

Furthermore, it was not only possible to benefit the procurement logistics processes from the virtual building model, but also to use its data to design the product and simulate the production processes of the smart factory and thus test their success.

## 5 Discussion and Results

The case study shows how high-resolution building models can be used for the procurement logistics of a smart factory in the construction industry. This applies in particular to the supplier ordering process of materials by transferring the BIM data to the PLM system and then to the ERP system with the help of an ESB middleware.

From a logistical point of view, the process changes that resulted in the case study have the most impact on the accuracy of purchase orders, the rate of emergency purchases

and purchasing time. Automated purchase orders and predefined master agreements not only shorten order times, but also allow the immediate release of order quantities from actual materials used. Supplier availability, fulfillment rates, and invoice accuracy from contracted details are also met, ensuring that there should be no bottlenecks as suppliers commit to fixed quantities at specific prices and times.

From a manufacturing point of view, the most valuable components of the new information flows between the systems are algorithmic and parametric product designs. They describe the geometry of all individual parts that compose the bill of materials for the facade and roof panels, which can then be used by the PLM and ERP system to comprehend the design context and automate production and logistics processes.

Thus, the assumption made in the methodology that efficiency gains are possible is confirmed. By creating uniform interfaces in the software system landscape in advance, procurement and production processes can be automatically adapted to the building structures in the future without increasing the workload during operation.

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# A Framework for Compliance Verification Based on Trusted Data and Blockchain Identity

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**Abstract.** Ships generate huge amounts of sensor data, which is largely underutilized due to lack of standardization. The ad-hoc data collection and transmission procedures and proprietary nature of sensor naming conventions make it challenging to implement and scale digital solutions based on this data. Ensuring data integrity can present an additional challenge as data is generated by multiple sensors onboard a ship with constrained connectivity to shore. Sensor as well as stakeholder identities are significant here, in order to reflect ownership structures, maintain access control and link actions with the entity that performed it. In this paper we present Vidameco, an integrated hardware and software framework for standardized data collection and tamperproofing. Dockerized microservices are developed for data collection, hashing, publication of hashes on the blockchain and verification by data consumers. Further, we present an architecture to integrate this tamperproofed data with sensor and stakeholder identity in order to create an underpinning for a digitalized value chain. Sensors are named in a hierarchical structure using the ISO19848 standard and this structure is interfaced with digital identities of stakeholders on the blockchain such as from the European Blockchain Services Infrastructure (EBSI). Finally, taking EU's Monitoring Recording and Verification (MRV) regulations as a case study we conceptually demonstrate this framework. MRV reporting is a complex value chain involving multiple stakeholders and extensive documentation and forms the basis for EU's Emissions Trading System (ETS), which is set to include shipping from 2024. This case study presents and evaluates an end-to-end digitalized ETS ecosystem based on tamperproofed data using MRV as the Oracle in smart contracts for ETS trading.

**Keywords:** Blockchain · tamperproofing · MRV · ETS · identity · standardization

## 1 Introduction

Maritime transport is the backbone of the global supply chain, carrying over 90% of the world's merchandise trade, an estimated 11 billion tons of cargo each

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year [1]. The importance of maritime transport came into sharp focus during COVID-19 crisis as shipping dependent supply chains were key not only for business continuity and keeping the economies functioning, but also to critical supply lines, delivering essentials and keeping food on the table. The pandemic has also shown the vulnerabilities of the sector and the need to increase resilience in the face of challenges. A recent World Bank-IAPH report [1] advocates for a broader and better coordinated integration of digitalization into the supply chains, particularly creation of a digital ecosystem which can unlock significant efficiency gains with lower emissions and more resilient supply chains.

However, today, data streams generated on board vessels are transmitted to data consumers on shore by ad-hoc and disparate means and thus requires keeping track of several different and non integrated data pipelines. Such a complex system is not easily scalable as adding a new data resource or supporting multiple services using several separately collected data points becomes challenging. Also challenging, is ensuring data integrity between processes in resource constrained environments where data transfers are not immediate. The integrity of the data is vital, as possible undetected tampering can severely undermine trust in the data and services relying on it. Further, investing into these improvements can translate into the bottom line. A study by BCG [2], estimated that digitalization can reduce OPEX in shipping by 15%, significant in such a price sensitive sector. Regulatory actors such as IMO have also pushed for digitalization through their Facilitation Convention, making electronic data exchange mandatory since 2019 with guidelines for integrity, authentication and confidentiality of information exchanges in the maritime sector.

EU's MRV and IMO's DCS regulations as well as the inclusion of shipping in the ETS program show the growing importance of traceability of emissions in shipping. ETS has a market value of €751 billion in 2023 [3] and the projections for ETS costs for shipping alone are €3.1 billion (2024), €5.7 billion (2025) and €8.4 billion (2026) [4], factoring in the 3 year phase in. With the introduction of market based measures comes the incentive to adjust emissions reported in order to reduce costs. For instance, some years ago, Europol found that carbon credit fraud in the ETS system cost a loss of tax revenues of €5 Billion [5]. More recently, in 2023, an instance of a multi-million euro ETS fraud was found in Bulgaria [6]. With the current granularity and accuracy of emissions as well as verification procedures, this may not be easy to discover. The estimated daily ETS cost of €10k for a container ship would translate to north of a million per annum per vessel [7] assuming more than 100 sailing days. With the current acceptable margin for error in MRV (5%) this would mean a difference of €50k per vessel per year. As such, the proposed approach if implemented can improve granularity and accuracy and reduce attempts at cheating so that the EU and IMO regulations will have greater effect and contribute to a fair distribution of costs.

## 2 Architecture and Conceptual Implementation

### 2.1 Standardization and Tamperproofing

Our solution addresses standardization and edge data integrity using two salient building blocks- Dockerized microservices and Blockchain respectively. Docker is a platform that simplifies the delivery of application code by bundling it with operating system (OS) libraries and dependencies creating containers—self-contained and standardized execution units that can run in any environment. Docker containers can be run in a Swarm mode to ensure high availability and scalability. Further, Docker containers can be used to deploy microservices. Microservice architecture granularizes and modularizes functionality into separate standalone components that can collaborate. This architecture creates interchangeable, scalable components, plug and play by design.

Blockchain, also known as a Distributed Ledger Technology (DLT) is the technology that underpins Bitcoin, and other cryptocurrencies but the applications of this technology have now expanded to enterprise use cases such as supply chain management, personal identity, IoT asset administration and trading renewable energy. Blockchain is so named as it consists of blocks of transactions chained together though cryptographic hashes. It is a shared ledger of immutable records, maintained by peers in a network using consensus algorithms such as Proof-of-work, Proof-of-stake or Proof-of-Authority to determine the transactions and the correct order of transactions in a block. This immutability makes it possible to use it for tamperproofing of data.

Figure 1 shows the architecture of the Vidameco solution. Microservices are developed to collect edge data batches. These batches are hashed, and the hash is published to the blockchain. Later the data consumer can use our DApp to access a microservice for verification of data integrity based on the published hash. These microservices are deployed as Docker containers making a modular solution with plug and play components. MQTT broker is used for inter-process communication. Vidameco can be used to enable standardization and data integrity for a variety of use cases. In more traditional sectors such as shipping this can drive digitalization. Focusing on EU's MRV regulations, implementing the Vidameco approach, can reduce redundancy in data collection and quick verification of both, the data used as input to the value chain and the certification produced at the end, ensuring traceability from the former to the latter. Tying the stakeholder activities and data to their identity will reduce complexity and avenues for mistakes and fraud.

### 2.2 Oracles and Federated Identity

Blockchain based solutions often need to take in data from the outside world. Oracles enable a blockchain ecosystem to access data as well as advanced computations. For instance if a smart contract encodes a bet between two individuals based on the outcome of a race, this information must be delivered into the smart contract. However, blockchain oracle mechanisms using a centralized

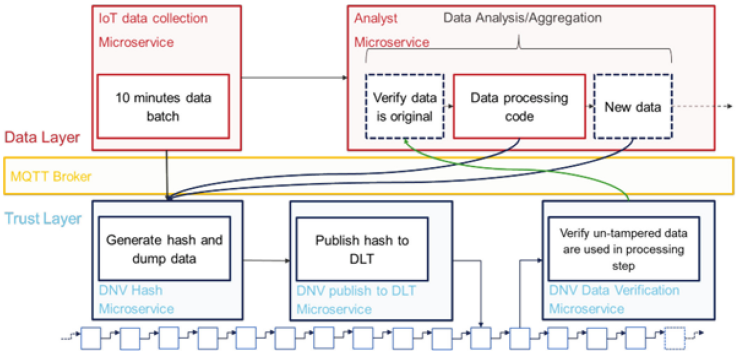



**Fig. 1.** Vidameco architecture

entity to inject data to a smart contract create a single point of failure, defeating the entire purpose of a decentralized blockchain application. Further, identity on the blockchain is important as it is in the real world. The EU has created EBSI with the ambition to provide a digital identity to every person and legal entity in the EU. However, identity can be used not only to authenticate parties, but also as an intuitive way to structure data by identifying components. The DNV sensor naming rule Vessel Information Structure (VIS) [8] based on the ISO 19848 standard provides a hierarchical naming scheme for sensors and components based on function. As seen in Fig. 2, we propose an hierarchical and integrated identity to ensure traceability of data at the granularity level of sensors and linking this with the EBSI identity of stakeholders. Further, such an identity created by interoperability of VIS and EBSI can be issued by a trusted issuer and be used to tamperproof the data streams. The identity, certificates and tokenized carbon assets as well as coins can be stored in a blockchain wallet. The source data can be stored in an offchain storage solution. This enables the creation of hybrid smart contracts combining on-chain and off-chain code, data and infrastructure. Further, as the oracle inputs are based on tamperproofed data, this creates an evidence based system where proof can be produced on demand. Thus, an Oracle for trusted data, middleware for blockchain interoperability between VIS and EBSI, interface between on and offchain storage, access control as well as a wallet will be needed. To provide all these capabilities, a Decentralized App will be developed for end to end traceability covering this entire value chain and providing a user friendly experience for all stakeholders.

## 3 MRV

MRV will be used for ETS reporting when maritime transport is included in the ETS system in 2024. The MRV reporting value chain is complex, with many stakeholders, each with their own systems of record and data. Currently, annual emissions calculations are not based on sensor measurements on board a ship.

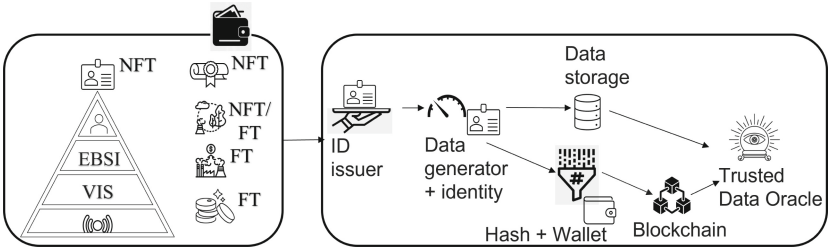



**Fig. 2.** Identity and trusted data

These are estimated based on the fuel consumption data and operational data reported by the ship in daily reports called the noon reports. The fuel consumption reported in the noon reports is substantiated by invoices on fuel sale and by sample studies done in laboratories on samples of fuel from a batch. In order to comply with reporting requirements, all this data must be submitted to an accredited verifier like DNV, for consistency check and verification before being submitted to the EU Commission. The documents are delivered to the verifier by email from each stakeholder in an unstructured fashion, as seen on the left hand side of Fig. 3. Sorting and structuring these documents, requesting missing documents, as well as checking for class certifications and validations is an extensively paper based and document heavy process. Additionally, as regulation is now moving towards demanding more granularity and transparency in emissions reporting, such aggregated annualized reporting may not be sufficient in the near future. Finally, as regulation continues to evolve, this unstructured data makes it more challenging to keep up. Data that is granular, tamperproofed and structured by identity will ease combining data sets in different ways, reducing rework and producing evidence based reports.

The right hand side of Fig. 3 shows our proposed solution. Here, a fuel supplier issues a bunkering invoice and tamperproofs it using our solution so that the hash of the bunkering invoice is published on the blockchain against the identity of the fuel supplier. This hash is meaningless without the source data and cannot be used to get any information about the source data including size of data. Similarly, the laboratory produces and tamperproofs their reports. The ship starts the voyage and collects and hashes data in 10 min batches using the hierarchical identity and publishes the hashes to blockchain. The source data for all three stakeholders is stored in an offchain repository. Later, when the MRV verifier is given access to this off chain database, they are able to retrieve the data stored, structured by stakeholder as well as sensor identity and verify its integrity against the hash stored on the blockchain.

## 4 Discussion and Conclusions

We now compare and contrast our approach with the current document heavy approach. **Robustness** and resilience to failure is an important characteristic for

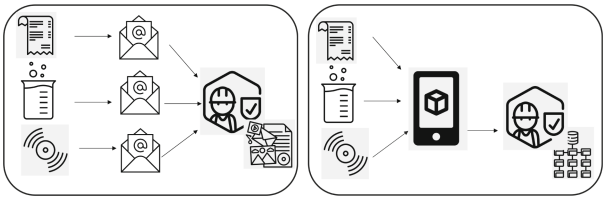


**Fig. 3.** MRV data pipeline current(left) and proposed(right)

such a system. Here, the Docker based data collection infrastructure in Swarm mode ensures availability so that when one Docker container fails, another one is automatically spun up to take its place. Further, the tamperproofing as well as the identity infrastructure uses blockchain which is maintained by a peer network meaning that each peer maintains a copy of the network, ensuring availability. In the current approach, there are many single points of failure that can be as simple as missing an email. **Scalability** is one of the main benefits of such a solution as it is scalable by design. The Dockerized microservices can be replicated as needed, and the standardized and structured fused data and identity eases adding in a new data source or combining multiple data sources, making it much more scalable than the current approach. **Verifiability** of presented reports will be essential as the regulations evolve, enforcing more traceability. Currently, the values presented in the reports are checked for consistency based on a model but integrating granular sensor data as proposed will improve Verifiability at each step of this value chain. Further, compared to a centralized Oracle, that defeats the purpose of blockchain, evidence is essential to ensure accountability.

The proposed approach will digitize the maritime value chain, beyond compliance reporting like MRV, improving robustness and ensuring end to end traceability.

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# MOTIONAL: Advancing the Future of European Railway Systems Through Digitalization and Integration

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**Abstract.** The Flagship Project "MOTIONAL", supported by Europe's Rail initiative, paves the way for implementation of the future European Capacity Planning and Traffic Management System, built on digitalisation, automation, connectivity and multimodal integration.

Lead jointly by Hacon and Trafikverket "MOTIONAL" with its 89 partners aim to achieve a significant advancement in the state-of-the-art railway systems by pursuing the way to digitalization and interoperability across Europe. To achieve the expected results activities are carried out in two different working domains. The first domain covers three focus areas; planning, operational activities - which includes managing future interactively coupled timetable planning; and finally operational traffic management systems - which also includes integration activities for door-to-door mobility. The second domain refers to the delivery of a set of digital enablers for all European rail destinations, i.e., crosscutting, to support the development of destination-specific digitalisation solutions. The main outputs of the project will be significant improvements to the railway systems in Europe through the development and implementation of a range of technical enablers. The results of FP1 MOTIONAL will enhance the strategic and tactical capacity planning of the network by enabling a seamless cross border planning and integrated yard and station capacity planning and using modern optimisation and simulation technologies.

**Keywords:** Mobility · Interoperability · Rail Traffic Management Systems · Simulation · Rail Operations · Cross border

## 1 EU-Rail Flagship Project 1: MOTIONAL

The EU-Rail Flagship Project "MOTIONAL" aims to improve the planning and operational management of rail services through digitalization, automation, connectivity, and multimodal integration. This project, supported by Europe's Rail initiative, will enable the future European railway system to be interoperable, resilient, and integrated efficiently with different services, including last-mile operations. The project methodology is based on use cases, functional requirements and associated specifications coordinated

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with involved stakeholder groups and close dialogue with the EU-Rail System Pillar. Key advancements include the improvement of planning and operational management of rail services, the development of digital enablers like digital twin technology, and the integration of rail with other transport modes. The goal is to make rail the backbone of a multimodal transport system for passengers and freight, with the perspective of achieving a Single European Rail Area. The "MOTIONAL" research project aim to achieve a significant advancement in the state-of-the-art railway systems by pursuing the way to digitalization and interoperability across Europe.

## 2 Planning

The main objective for Planning is to improve the strategic and tactical planning of the network with optimization and simulation functionality short term (adjustments) and long-term planning (longer than one year). This is done by specification, development and demonstrations.

Today new processes are under development to enable European wide capacity allocation and to connect planning and operational traffic. There is an ongoing technical and digitalization development in CMS (Capacity Management Systems)/TMS (Traffic Management Systems). Planning activities are focused in three areas:

- In cross border planning we improve planning between borders nodes/network areas within nation and between nations.
- In Advanced algorithms we develop and demonstrate decision support for timetable planners/Capacity management system operators.
- In Simulation and operational feedback, we develop simulation methods for improved capacity planning and simulating capacity effects for new DATO technologies (Digital automated train operations) and European Train Control System (ETCS).

**Cross Border Planning and Integrated Capacity Planning**
One of the objectives is to deliver future railway processes and solutions with seamless cross border planning and integrated yard and station capacity planning. Seven demonstrations are planned to achieve expected results in three technical enablers. These are: European cross-border scheduling with international train path planning; Improved capacity allocation using rolling planning and TTR; Integration of planning systems and TMS with yard capacity planning and station capacity planning.

**Advanced Algorithms and Decision Support Tools**
Another objective is to deliver optimized timetables by enhancing the processes, as well as by using knowledge from actual operations and simulations. Development of advanced algorithms for the generation and adjustment of timetables and rolling stock planning. The algorithms are demonstrated in decision support tools based on defined use cases and problems/solutions/effects. Four demonstrations are planned to achieve expected results in three technical enablers. These are: Decision support for short term planning; Train path and schedule optimization methods and strategies for capacity efficiency, punctuality and energy saving for different parts of the network and different

traffic situations (level of punctuality); Integration of planning systems and TMS with yard capacity planning and station capacity planning.

**Simulation and Operational Feedback**
To simulate operational processes and to develop feedback loops between operations and planning as well as to develop simulation methods for TMS – C-DAS/ATO and simulate/study effects. Development of simulation methods for evaluating C-DAS/ATO. Development of simulation methods for evaluating European Train Control System (ETCS), such as optimal braking behavior (new generation braking coming from Destination 2) and ETCS Hybrid level 3. Two demonstrations are planned: Improved simulation models; Simulation of new technologies which includes ETCS HL3 and ATO to estimate capacity effects.

## 3 Operations

Today, rail traffic is managed by IMs (Infrastructure Managers) on national or regional level, usually supported by legacy systems with a poor level of digitalisation and weak integration with systems of other domains or actors participating in the overall traffic planning and management process.

Taking advantage of the potential of digitalisation, operational and technological solutions are developed for different business areas, paving the way towards the implementation of the future European Rail Traffic Management System to make rail the backbone of a multimodal transport system for passengers and freight.

**Integration of TMSs and Processes**
Within use-cases, processes and interfaces are developed for achieving a much higher integration level of functions and decision processes including the increase of the precision of the traffic prediction as part of TMSs. In focus are also the alignment between different TMS areas including cross-border and the integration of TMS with yard or station functions, Electric Traction Systems as well as RU (Railway undertakings) related data sources for consideration of e.g., actual rolling stock constraints. The availability of appropriate interfaces between the different clients and stakeholders and applications will help to support an aligned re-planning and management of capacity on railway lines and station or yard tracks including graphical visualisation, conflict detection and resolution. The new possibilities will increase the interests and the level of engagement of RUs in traffic operation.

**Improved Resilience and Efficiency of Disruption Management**
We develop modules for a cooperative multi-actor optimisation and decision support supporting the management of incidents and disruption. Through an advanced HMI the system resilience and efficiency of disruption management using future TMSs will be increased. TMS operators' workload will be reduced by task automation where possible to enable human focussing on critical situations.

More efficient traffic management is also achieved by better consideration of human factors being enabled by new HMI design and technology as well as extended decision

support featuring "what-if?" scenario evaluation with a specific focus on disruption and incident management. Automated feedback operational observations to planning allow for improved robustness of future plans.

**Linking TMS to ATO/C-DAS for Optimized Operations**
Aims on testing integration between TMSs and ATO/C-DAS systems or components providing significant added value by increasing network capacity, timetable robustness, energy efficiency and punctuality. A seamless integration of TMS and ATO will be demonstrated by testing both together in an emulated "real-world" environment by human-in-the-loop demonstration and test bench. The testing environment will cover interaction of train-drivers, TMS operators and signallers, each using their own (emulated) workplace working and communicating together in simulated traffic states. The activities include human-factors research to achieve optimum and realistic results considering behaviour of loco drivers, signallers and TMS operators.

**Automated Decisions and Decision Support for Traffic Management Optimization**
Focuses on development of algorithms and modules including verification of their suitability for future TMSs providing decision support and whenever possible automatic decisions for traffic management based on optimisation and real-time conflict detection & resolution. Automation is demonstrated e.g., for requesting real-time Movement Authorities in ETCS L3 hybrid and L3 full moving block-based operation.

Different algorithmic or technology approaches including AI are used to demonstrate their application railway networks, lines and local environments such as yards, terminals, depots or stations. Different solution options are evaluated in accordance with "What-If?" and impact analysis paradigms prior to triggering the implementation of the final decision in the operational plan. Thus, disruption and operational imbalances can be dealt with providing a higher level of confidence.

## 4 Multimodal Integration

In terms of operational outcomes, the integration with other transport modes to deliver door-to-door mobility is a major driver for the development of rail attractiveness. The very objective of MOTIONAL in this area is to make Rail the backbone of Multimodality. This is supported by three technical and business pillars described in the text below.

**Inclusive Mobility**
Commuting between transport modes, especially for travelers with disabilities has always been complex and time consuming leading to a reluctance to use rail transport. MOTIONAL answer to that consists in a set of services focusing on the environment In railway hubs in order to ease customer journeys, we foresee: Cutting hedge technologies delivering Hands-Free User Experience; In Door Navigation with UWB (Ultra-Wide Band), BLE (Blue Tooth Low Energy) and Biometrics; Platform based guidance, as well as Interactive digital travel assistance, and finally In station PRM services including dedicated kiosks and communication with staff and escort, and/or Interactive assistance during transfer.

**B2B Integration**
Multimodal integration is not achievable without the cooperation between Mobility Providers. In order to favor this cooperation, MOTIONAL proposes the improvement and development of B2B platforms and services in the areas of Sales, Distribution, Financial services and Traffic information. Key technical features associated with these business objectives includes Cross-operator and cross-mobility support and the Compatibility with SaaS deployment, as well as the usage and enhancement (when applicable) of standards including: OJP, OSDM, SIRI, NETEX.

**Anticipate Demand**
Anticipating passenger demand and adjusting the service accordingly is key to rise travelers' satisfaction and to optimize mobility providers' operation. MOTIONAL ambition in this area is to design solutions and services integrating multiple transport modes, allowing hence a thigh and dynamic cooperation between rail and other transport modes. Features in scope includes Long-term demand forecast calculation, and short-term demand forecast calculation in real-time. It also includes simulation of demand and associated reaction of mobility networks by using Digital Twins, as well as Disruption management, and finally processing demand data across mobility modes.

## 5 Digital Enablers for the European Rail System

Digitalization is a major and fundamental transformational process of the European Rail System that pervades all domains: from delivering passenger services to maintenance, from engineering, construction and building to energy management, from traffic management and train operations to financials and accounting, and others. While the range of specialized advanced digital applications needed to cover such a large scope is very large and diversified, a set of underlying common enablers has been identified by the EU-Rail partnership to provide fundamental capabilities that can be leveraged by each specialized field of application.

**Rail Federated Dataspace**
A cybersecure, reliable, scalable, distributed, data sovereignty-preserving and interoperable mechanism for data sharing and communication across and open ecosystem of autonomous business entities and heterogeneous systems is a recurring problem in the Rail System, particularly as the progress of digitalization extends the requirement across multiple domains. The MOTIONAL project is developing the "Rail Dataspace", a natively distributed system for content-independent, cybersecure, reliable, scalable, interoperable, data sovereignty-preserving data exchange across a federation of participants providing by design of digitalized trust, and governance policy enforcement and digitalized data provision contract negotiation. The Rail dataspace will be designed as the underlying technological infrastructure of the European Data Strategy and supported by actual available open-source software.

**Conceptual Data Model**
While the Rail Dataspace must provide an essential mechanism for data sharing a communication that is independent of the data contents, it must be complemented with a set

of machine-readable and processable description of this data contents likewise independent of how it is shared. Conceptualization of the digital representation of Rail concepts, objects and phenomena will allow for heterogeneous and autonomous entities participating in the exchange supported by the Rail dataspace to communicate not just the data, but the meaning and intent of the exchange. Only the combination of common conceptual data models and common data sharing and communication mechanisms independent of each other can provide full interoperability of heterogeneous systems and autonomous organizations.

**Digital Twins Development and Execution**
Finally, while the adoption of digital twin technology able to model structure and dynamic behavior of cyber-physical systems accelerates in the Rail System, the need is recognized to provide developers with a common set of architectural guidelines, modeling languages and tooling to enable the composition of complex simulation applications involving interactions between multiple cyber-physical systems. Specialized digital twins developed independently by multiple organizations must therefore also be able to interoperate. To this end, the MOTIONAL project will deliver a common digital twin development and runtime environment for the Rail System as an enabler of the development of natively interoperable digital twins.

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# Intelligent Access, e-waybills and eFTI Developments in Estonia

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**Abstract.** The research objective is to contribute to more effective and greener road freight transport with HV's, without damaging aging road infra below. One of the best solutions in 21st century is to use all kinds of digital data (temperature; GNSS; OBW etc.) and road maps to control the logistics in the most optimum way, depending on the used vehicle's load type (Intelligent Access IA). It's a very cost-effective system. Since the HVTT15 & HVTT16 conferences, much work has been done in Estonia in the logistics digitalization area. In Transport Administration the e-waybill has been piloted to become in 2024 as a compulsory measure in building contracts for the greener infra buildings. Estonian Ministry of Climate has developed the architecture and started to pilot eCMR and eFTI in wider scale and also more widely all over Europe.

**Keywords:** Intelligent Access (IA) · Estonian VELUB System · OBW Automated Mass Control Integration · CEDR Road Freight Transport (RFT) workgroup · Estonian eCMR and e-waybill development · EU electronic freight transport (eFTI) regulation

## 1 Introduction

Since 2010 Estonian Transport Agency (ETA) has been developing Intelligent Access (IA). In the beginning, it was meant only for the wintertime 52t timber transport, if the pavements were frozen at the min 0,5m depth. For that reason, the digital vertical temperature sensors (max 2,5m deep) were installed over Estonia [1]. At the same time, the strong infra corridors were analyzed and mapped [2] (in the SmartRoad – the green color digital road corridors with daily update time at 4 pm). In the VELUB system, it is possible to apply for the special vehicles permit for up to 1 year [3].

As the climate change proceeded, the wintertime allowed corridor window decreased quickly, we started in ETA to develop the year around 52t (the violet corridors) IA system [4] with the legislation [5]. IA has been used since 2015 by ca350 truck/y, mostly by timber trucks so far, but also increasing others.

ETA signed on 9th April 2020 the memorandum to develop with 9 other stakeholders the e-waybill for the bulk material transport in road maintenance sector. After that we

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have had many pilot contracts and are going to use it as mandatory since year 2024 in our road building.

To be ready for the application of the provisions of the Regulation of the electronic freight transport information (eFTI), Estonian Ministry of Economic Affairs and Communications has developed and tested during the years 2020–2023 a cross-border eCMR indexing prototype together with the partners from the Nordic Baltic region.

Also, Estonia as a lead partner, together with other EU Member States have just recently in spring 2023 started a new, 3-year long project eFTI4EU co-funded by Connecting Europe Facility (CEF) with a big part of it being piloting the eFTI Gate solution.

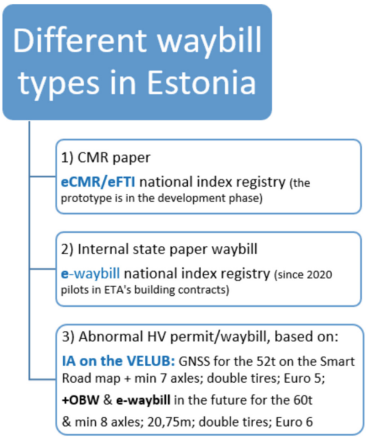



**Fig. 1.** – Different paper & e-waybill types in Estonia

In the following paragraphs, a very short overview will be given about Estonian's different e-waybills developments and research (see Fig. 1).

## 2 VELUB Intelligent Access

Since the HVTT15 paper [6], much work has been done in Estonia in the logistics digitalization area which has been also described shortly below to understand in the better way, the different cloud-based logistic systems, and their common ground (see also the HVTT16 paper [7] and the EU Aeroflex project workshop [8]).

For example, if the (i.e. abnormal) HV is in the wrong road corridor or has a total OBW [9] mass over the limited value etc., the cloud-based eCMR can change the cell red and send the notice to controlling organizations (and also on the Smart Road map can blink as the red dot, etc.). It's possible in the longer future to make automated direct enforcements as well – kind of like the speed cameras does now.

In CEDR report Intelligent Access (IA): current NRA practices [10], there has given good overview about IA ongoing developments. Also, in the Revision of the Weights and Dimensions Directive 96/53/EC [11] there is already mentioned eFTI and IAP using

possibilities. The proposal is also establishment of **technical and operational standards for information exchange on the transport of indivisible loads** and the development of Intelligent Access Policies (**IAP**).

## 3 eCMR Pilots and Ongoing Process

EU Regulation 2020/1056 Electronic Freight Transport Information (eFTI) demands EU member states to accept the digital transport documents at the level of competent authorities starting from the first half of 2026. In order to be ready for eFTI Estonian Ministry of Economic Affairs and Communications (as of July 2023 Ministry of Climate) has developed and tested during the years 2020–2023 a cross-border eCMR indexing prototype between Estonia, Latvia, Lithuania, and Poland during the DIGINNO-Proto, DINNOCAP and The NDPTL Goes Real-Time economy: eCMR projects. During the pilot projects the technical development took place, and the concept followed a logic of not uploading any eCMR documents to the central database but linking them via national indexing scheme. Central point or connecting layer for secure data exchange between economic operators and competent authorities such as Police or Customs was created and called as index registry (see Fig. 2) [12].

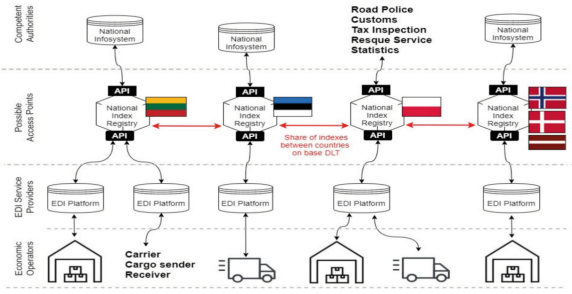



**Fig. 2.** Cross-Border eCMR indexing ecosystem

The process of establishing implementing acts for eFTI is ongoing at European Commission and it is an honour to note that the architecture that was tested during these above-mentioned pilot projects proved to be also the preferred option for eFTI technical architecture (chosen from the 8 different options).

The findings from the pilot projects confirmed the understanding that a successful distributed eCMR and eFTI architecture needs a middle layer - a National Access Point at every member state (see Fig. 3) in order the cross-border data exchange to function.

In 2022 Estonia conducted an analysis on Estonian National Access Point [13] which provided a comprehensive and exhaustive mapping of the different options, solutions, risks, and threats for the development, ownership and location of eFTI NAP (now called eFTI Gate), taking into account the legal and economic specificities of the different economic sectors.

During the same years, and intensively starting from 2019, Estonian experts from the abovementioned projects have provided support to European Commission and its

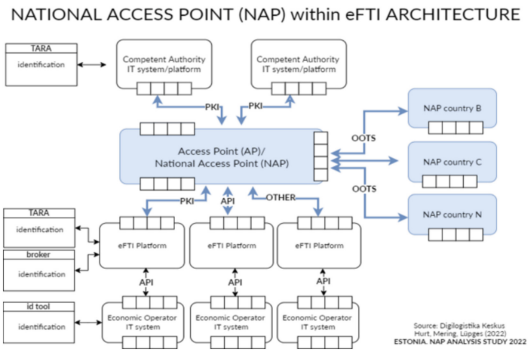



**Fig. 3.** Estonian NAP Analysis Study 2022 [13]

expert group Digital Transport and Logistics Forum, gathering feedback and reflecting the architecture principles for eFTI and the structure of indexing and identifiers.

In 2023, Estonia as a lead partner together with project partners from Finland, Lithuania, Germany, France, Italy, Portugal, Austria and Belgium and observers from Spain, Ireland and the Netherlands got funding from CEF for project called eFTI4EU. The goal of the eFTI4EU Project envisages to develop the eFTI Gate technical requirements to the fullest and establish harmonised rules for trusted networks of eFTI Gate platforms and its components. Project involves in total 22 different partners (public and private) from the abovementioned countries. The total budget is 28.3 million euros from which 50% is funded by CEF, and the project will last three years – from 2023 to 2026.The work is carried out in parallel with the setting up of the requirements of the eFTI Platforms and Service Providers – the ones responsible for managing and maintaining the transport data for economic operators.

## 4 Internal State e-waybill Using Experience

In 2020, ETA carried out three procurements, where it was mandatory to use an e-waybill of lading for the transport of the bulk materials for the road building. The special requirements for documenting, the works applied to both: the contractor and the owner's supervision. All consignment notes for the bulk materials and the summary tables, compiled based on them, had to be prepared in an electronic data exchange platform [14].

The pilot projects assumed the use of either the Waybiller (a service provider) environment developed in Estonia or an analogous electronic data exchange platform (at the moment 3 different service providers). The procurement required that the digital platform allow the creation of separate objects and GNSS location-based tracking of each load. The vehicle and/or trailer number information had to be generated automatically from the traffic register database and had to reach the electronic environment on the e-waybill. If the truck had a special cargo permit of 48 or 52 tons, its data, permit number, and the validity period had to be included. Supervisors and subscribers needed to have access to the environment so that they could control the information through the cloud.

The e-waybill had to contain at least the number of the truck and/or trailer, the number of axles, the permissible weight/load capacity of the truck; the mass and name of the material, the name of the driver, the hauler, the owner of the load and the quarry. If the transport was on public roads, an e-waybill had to be created for the transport from the intermediate warehouses to the site (except for the intermediate warehouses immediately adjacent to the site). An indication had to be made on the e-waybill, whether the material came from a quarry or an intermediate warehouse. Building contract annex (2 pages) has been prepared for contractors, which contains detailed minimum technical requirements for the e-waybill. This will make it easier for the new service providers to bring data exchange platforms to market and will be better traceable to all parties [15].

As mentioned, the owners' supervision was also obliged to use the electronic environment of the e-waybill. For example, he had to check the e-waybills for bulk materials provided by the contractor and confirm receipt of the load in the digital environment. Also, during the asphalting works, the engineer used a data exchange platform to validate the e-waybill of asphalt loads arriving at the site. In total, more than 5000 paper waybills were avoided by using e-waybills in the 3 smaller pilot building contracts.

In 2022–2023 over 30 pilots were made to prepare for the full transition to e-waybills in 2024, for the transport of the bulk materials.

## 5 Conclusions

E-waybill development in Estonian state road building, abnormal transport IA, and other areas have given us already a lot of savings in $CO_2$ emissions, making transport more efficient at the same time - with the single data entry to the cloud, etc. Defiantly there is still a lot to do and develop in coming years, to achieve EU's climate targets in the transport sector, using digitalization as a tool for helping it.

Estonia together with neighbouring countries, and other EU states, are working together to achieve the EU digitalisation goals and to make the freight transport between the states, and inside the state, more efficient.

ETA's bulk material e-waybill piloting and usage is just a small part of internal transport (ca 5%), but it is a huge step to digitize all internal waybills (over 2 mln/y) together with Climate Ministry, and together with international eCMR, based on the eFTI regulation.

In 2024 ETA is planning to demand e-waybills in all building contracts. There are already now many interested IT companies with big interest to develop e-waybills in Estonia, as it's not so complicated in 21 century anymore.

Digitized cloud-based transport and road information systems are allowing much further IA development - to protect road constructions and increase traffic safety. At the same time, transport transparency increases. Hopefully standardized IA data fields (vehicle data, see p.2) will be compatible with the eFTI data fields (freight data, see p.3), so the EU road owners can have good tool in the future to protect the aging infra and at the same time to allow more efficient and greener transport. Standardized fields allow the service provider to offer the standardized service all over EU and compete each other on the free EU market with the increasingly better service – it opens the doors to the better and greener HV transport system in EU.

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# Hybrid Approach for Estimation of Traffic Hazards: Fusion of ML and Pure Statistical Model

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**Abstract.** Precise travel and traffic information are becoming increasingly important to road users. This is backed up by a growing number of users who are planning their trips before they start their journey. People primarily aim to avoid or minimize the travel delays by knowing alternative routes or changing the departure time beforehand. Furthermore, they are increasingly customizing their travels to maximize efficiency and convenience. From years of experience, and considering the Traffic telematics report [1], ASFINAG, as the national operator of Austrian motorways and highways, has recognized this need and has focused on bringing the accuracy of our traffic information to real traffic conditions. In this paper we present our hybrid approach that combines two methodologies to provide traffic information that is closer to the real traffic conditions, with a special focus on the traffic jams and delays. Our main goal is to improve the accuracy of the travel delays and traffic jams both in terms of time and location. The first methodology, which is a fusion of data from various data sources, is based on pure statistical model, whereas the second methodology is a machine learning (ML) model. This hybrid approach is not a comprehensive one but rather restricted to selected road sections.

**Keywords:** Traffic state · Traffic jams · Machine Learning · Data Science · Data Fusion · C-ITS

## 1 Overview

ASFINAG plans, funds, builds, maintains, operates, and collects toll along almost 2,249 km of Austrian motorways and expressways. In the last years, we have been extending our sensor infrastructure where most of the sensors support current wireless technologies such as the CEN Dedicated Short-Range Communication (Toll stations) [2], Bluetooth (BT), WLAN, ITS-G5 (C-ITS) [3], and TLS (Technische Lieferbedingungen für Streckenstationen) also called as speed detectors in this paper.

Based on our analysis of the traffic data, it's clear that relying on a single statistical model to estimate traffic jam and travel delays across the entire road network is not the

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most effective approach. Apart from the traffic volume in urban and rural areas, traffic jams and travel delays are impacted by traffic events, and road and weather conditions. Keeping these additional parameters in mind, we came up with idea of developing a hybrid approach for traffic jam and travel time delay estimation. Here we combine the statistical model with the ML model to make our estimation more context aware. We primarily focus on the cases or regions where the pure statistical methods are not giving us satisfactory results. In this paper, we present this approach as well as the comparison and the evaluation results of non-ML (pure statistical model) model and the ML model. We accomplish this as a part of project and system "ASFINAG Traveltimes & Trafficstate Management System" (ARMS) [4].

## 2 Non-ML Approach

In the non-ML (pure statistical) model, we employ fuzzy logic to determine weights for individual data sources: Bluetooth and WLAN detectors, Toll transactions from the trucks, and speed detectors. The raw data from these data sources is post processed to calculate the single vehicle travel times for predefined section. The only exception is the data from the speed detectors. The data from the speed detectors are resampled in one minute intervals. The result is an average speed of the vehicles in a 60 s time window. To harmonize the traffic data from different sensor types, we have divided our road network into 200-m segments, which are referred to cells. The measurements obtained for a particular cell are interpolated to the nearest cell. Each nearest cell is assigned a weight, which is determined by factors such as measurement age, variance, and the proximity to the measurement location. Linear interpolation is the method we utilize for this purpose.

$$c_k = \beta_k \cdot d(mcell, icell) + \beta_{max} \tag{1}$$

$$\beta_k = (\beta_{max} - \beta_{min}) \cdot |\alpha|_T + \beta_{min} \tag{2}$$

$$|\alpha|_T = \frac{var_T}{var_{max}} \tag{3}$$

$$var_{max} = \sum\nolimits_{t=0}^{N} \lambda(t) \tag{4}$$

$$var_T = \sum_{t=0}^{N} \lambda(t) \cdot |v_t - v_{T-t}| \tag{5}$$

Equation 1 calculates the confidence level ($c_k$) of the received measurement based on the distance between the measured cell (*mcell*) and the interpolated cell (*icell* – cell to which we interpolate the measurement) and slope coefficient $\beta_k$. Equation 2 calculates the slope coefficient based on the standardized slope (weighted variance / max weighted variance). Weights are calculated by using a time function $\lambda(t)$ (the older the measurement lesser the weight). Equations 4 and 5 calculate the weighted and maximal variance values.

Once the data from each data source is assigned and interpolated to every cell in the network, our ARMS system performs a weighted mean calculation to determine a traffic state for each individual cell. The traffic state is quantified on a numeric scale ranging from 0 to 100. We refer this value as "availability". A value of 100 signifies that the current traffic state is indicative of free-flow conditions, whereas a value 0 indicates stationary traffic. Furthermore, we have employed an aggregation technique to assess the extent of a traffic jam. In this approach, we spatially and temporally aggregate the neighboring cells based on the similarity of the calculated traffic conditions.

## 3 ML Approach

In this section we explain our ML model, which is implemented to predict future travel times. Like the non-ML, the ML-model also uses the single vehicle travel times from the Bluetooth, WLAN, and Toll detectors, and the average speeds sampled over one minute from the speed sensors. Likewise, the data is harmonized to bring to a homogeneous data structure. In addition to these data, the model incorporates contextual information such as weather data, planned and unplanned events, and calendar data. To train our model, we have considered the last 6 months of data from above mentioned data sources. Although the 6 months of data appears to be relatively small, it has proven to be sufficient for our needs. It is detailed and consistent, which enabled the model to reach our expected accuracy in travel time prediction.

The data from Bluetooth, WLAN, and Toll detectors are preprocessed with Hampel outlier detection method [5]. The Hampel's approach is designed to be robust when dealing with extreme values in the data set. This is especially relevant in the travel times data set as some vehicles could stop in a parking area for a significant amount of time, resulting in extreme travel times. Concerning to the data from the speed detectors, it is important to note that the data used for our model has already resampled at 1-min intervals. This ensures the data is free from outliers. After the outlier removal, the travel times data are resampled at N-minutes time window (where $N = 15, 20, 30$), followed by feature engineering. In our model this involves assigning time features, holidays, unusual travel time patterns, etc. A detail explanation of feature engineering is skipped, as the focus is on the hybrid model.

The modeling is done using XGBoost [6] regression model, which is further finetuned by hyperparameter random grid search and 5-fold split cross-validation. XGBoost is an advanced machine learning technique, which operates by constructing an ensemble of decision trees to predict continuous numeric values. Each decision tree learns from the errors of its predecessors iteratively, allowing XGBoost to progressively refine its predictions. During training, the algorithm assigns initial predictions and calculates the associated residuals. Subsequent trees are then built to minimize these residuals. To prevent overfitting, regularization terms are introduced, and trees are pruned based on their depth and leaf weight. The trees predictions are combined, with each tree contributing to the final result, proportionally to its performance. XGBoost also uses a technique called gradient boosting, which updates the model's parameters by minimizing the gradient of the loss function. This iterative approach optimizes the model's fit to the data, resulting in a robust regression model capable of handling complex relationships and noisy datasets.

The assessment of model performance typically relies on metrics such as root mean square error (RMSE) and mean absolute error (MAE). These metrics were computed on a test set, resulting in an RMSE of 11.1 s and an MAE of 2.2 s. These values, while relatively small, align with expectations for scenarios without traffic congestion. Estimating travel time under normal, free-flowing conditions is generally straightforward.

However, during traffic jams, accuracy in travel time estimation is challenged by unpredictable events, such as vehicle accidents. Although the XGBoost model successfully identifies all traffic jams, it struggles to provide precise travel time predictions in such scenarios. Consequently, the error metrics are notably higher, with an RMSE of 126.3 s and an MAE of 107.6 s. That also explains why RMSE is higher than MAE because it is more sensitive to outliers.

## 4 Advanced Data Fusion – Hybrid Approach

As explained in Sect. 3, our non-ML approach relies on a pure statistical model to estimate the traffic state and the extent of traffic jam. The travel time and travel delay calculations are averages of travel time samples collected over specific time window. One notable drawback of these methods is their lack of predictive intelligence for anticipating traffic jams and delays. At times, they report travel time delays, which significantly deviates from the real-time conditions. As a result, traffic jams are identified late, and queue lengths are not measured with expected accuracy. Figure 1 illustrates a situation where our statistical method did not yield precise travel-time delay that match the actual conditions. This resulted in discrepancies of up to 30 min when compared to the real time delays experienced. Therefore, to narrow down these discrepancies, we have developed an ensemble strategy that combines our pure statistical model with the outcomes of our ML model. We refer this strategy as the "hybrid approach".

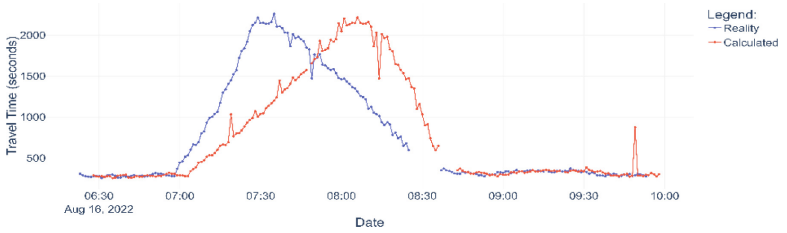



**Fig. 1.** Delay in the estimation of travel time delays

It is important to understand that this approach does not replace our conventional approach (non-ML), instead, it serves as a complementary strategy. Our goals are as follows: 1) Accurately estimate travel time delays, approaching real-time accuracy, 2) Identify the traffic jams at an earlier stage and 3) Enhance the precision of estimating the starting and ending points of traffic congestions.

Reference [7] describes various statistical and ensemble methods to integrate the results from multiple models. In our hybrid approach, we have chosen Bayesian statistics [8] to calculate individual weights for each data source, and thereby include or exclude a

specific data source for traffic jam prediction based on their weightage. The data sources here also include the outcomes of the machine learning.

From the historic traffic data, we have pre-selected the traffic hotspots (sections and time periods). For each of these hotspots we have estimated prior probabilities for the data sources based on the fact whether they have identified the traffic jams within a threshold time or not. Although the data sources are independent, they have a strong correlation due to the similarity of the data that they produce. Therefore, we not only can calculate individual probabilities but also a joint probability of the likelihood of predicting a jam.

### 4.1 The Bayesian's Model for Data Source Selection and Aggregation

In this model, we consider our main data sources Bluetooth and WLAN data (B), toll data (T), and speed sensors (S). To find out the likelihood of each of these data sources detecting a jam, we compute the conditional probabilities of traffic jam (J) given average speeds from speed sensors P(J|S), toll detectors P(J|T) and Bluetooth detectors P(J|B) using Bayes rule. Subsequently, we also calculate the conditional probability of observing measurements from the data sources S, T, and B given the presence of traffic jam J by using the below formula:

$$P(J|S,T,B) = \frac{P(S,T,B|J)P(J)}{P(S,T,B)} \tag{6}$$

where P(S,T,B) represents the joint probability of observing the measurements from the data sources S,T,B, regardless of the traffic jam conditions.

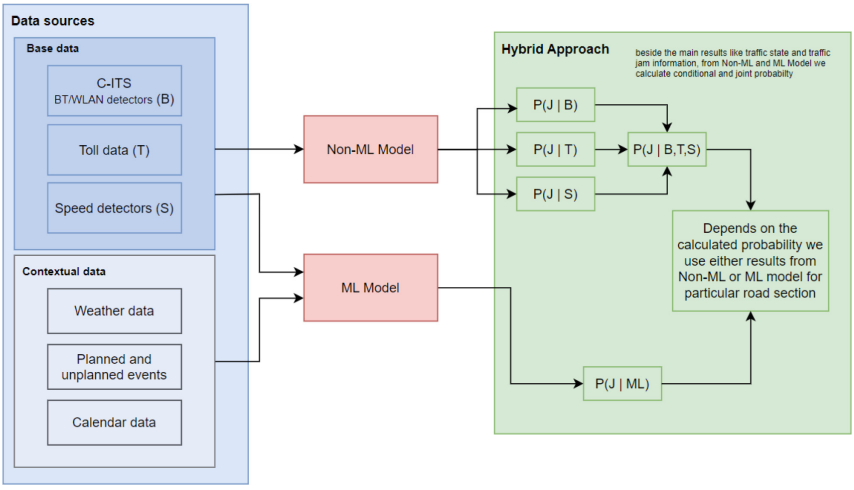



**Fig. 2.** Data Flow Visualization with focus on Bayesian's model for data source selection and aggregation

We first apply the joint probability, to check if it is greater than 0.7, indicating that there is strong likelihood of predicting the jam. In these cases, we assume that the data sources are capable of estimating the jam with less discrepancies to the reality without the help from the ML prediction. However, if the joint probability is less than 0.7 then:

1. We evaluate the conditional probabilities of each data sources to remove those with a conditional probability less than 0.7
2. We calculate the conditional probability of the prediction from ML model *P(J|ML)*
3. Finally, we perform a weighted average of the remaining data sources and the ML predictions.

This way we can dynamically assess and select the most reliable data sources for predicting the traffic jams by considering the outcomes from the ML model when needed.

## 5 Evaluation of Non-ML and ML Model

In this section an in-depth comparison between the outcomes of non-ML and ML models is presented. For this we also used RMSE and MAE metrics. Travel times obtained from non-ML model is rescaled by a constant to compensate a different length between start and end sensors position of ML model. Data from Google maps are utilized for more detailed, accurate comparison to non-ML and ML model.

Table 1 presents the overall metric results, and Fig. 2 illustrates the comparison between the ML model and non-ML approaches. Both approaches predicted the traffic jams and travel times in free flow cases correctly. However, the ML model predicted them earlier. In Fig. 2, we can see that the ML model is the first source to predict the change in the traffic trend. The difference between ML model and non-ML model data could be explained by the fact that for ML model features from BT and speed detectors data are more significant than from Toll transactions and thus is not able to predict travel time specially for trucks but instead predicts travel time for all vehicle classes. On the other hand, non-ML is calculating travel time separately for cars and lorries. The ML model predicted the change in the travel time pattern (free flow to queuing traffic) at least 5–10 min faster than our non-ML model and Google data. Likewise, it also detected the second pattern (queuing to free flow traffic) 15 – 20 min faster than the others (Fig. 3).

**Table 1.** Comparison between non-ML and ML model travel time RMSE and MAE metrics results together with comparison to non-ML and Google data.

| | RMSE [s] | MAE [s] |
|---|---|---|
| ML to Google data | 27.2 | 9.6 |
| non-ML car to Google data | 52.9 | 17.5 |
| non-ML lorry to Google data | 52.9 | 18.7 |
| ML to non-ML car | 26.2 | 7.0 |
| ML to non-ML lorry | 24.7 | 8.7 |

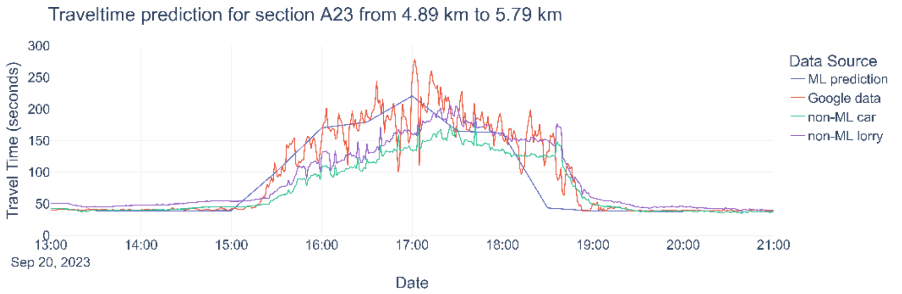



**Fig. 3.** Comparison of the results from ML and non-ML models together with Google data for road section on A23 during selected traffic jam.

## 6 Conclusion

Due to the emergence of various detection technologies, we have an increased diversity of data sources which help us in improving the accuracy of the traffic information. However, to fully leverage the strengths of these diverse data, we need an advanced approach that can effectively ensemble data from all the available data sources. Our paper focused on this important topic, where it presented a hybrid approach to ensemble data from multiple data sources, and furthermore ensembles the outcomes of the ML model when needed. At present we have employed this approach on selected road section. As part of the future work, we shall implement this proposed approach on the entire ASFINAG road network. Furthermore, we shall also research and experiment with other ML and AI models to conclude if they fit better for our use cases. We shall specifically focus on Graph Neural Network to model the whole high-level road network and compare the results with our current approach.

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# Future Mobility Campus Ireland: A Testbed for Advanced and Autonomous Vehicles

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**Abstract.** The Future Mobility Campus Ireland (FMCI) was founded with the sole purpose of creating and delivering future mobility testbed facilities for stimulating research, development and innovation in the area of Autonomous Connected Electric Shared Vehicles (ACES), including Connected and Autonomous Vehicles (CAV) and Advanced Air Mobility (AAM), in Ireland. FMCI focuses on comprehensive mobility technologies that span both ground (autonomous driving, micro-mobility, smart cities, V2X communications) and air (unmanned drones, eVTOL, AAM, UTM) uses.

FMCI supports a range of parties, from individual researchers to multi-national corporations, as well as start-ups and government entities. FMCI assists organisations to conceive, develop, trial, and deploy societally transformative transport solutions both nationally and internationally.

The installation of state-of-the-art connectivity technologies at the FMCI testbed is providing an environment for the automotive industry, component suppliers, telecommunications companies and research institutions with the opportunity to adopt new approaches to develop innovation for future technologies. FMCI has been operational for over a year and is already facilitating various companies and higher education institutes (HEIs) to further their innovation and/or technologies.

**Keywords:** Testbed · Transport · Mobility

## 1 Background

Mobility has a major impact on our economy and our society. Travel of the future will focus on the needs of the individual rather than the operators. It will be multi-modal involving a mixture of cars, buses, trains and planes [1]. Future mobility must be more environmentally friendly, more efficient and overall, much smarter. It will be driven by data and enabled by the latest technological advances. FMCI [2] seeks to facilitate the technological solutions which will enable Ireland to benefit socially and economically from more sustainable and efficient transport systems.

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In 2017 the CAV (Connected & Autonomous Vehicles) Ireland [3] forum was formed with members from IDA, EI, SFI, Lero, Insight, and Intelligent Transport Systems (ITS) working with industry partners from across the island of Ireland. The group focussed on identifying a value proposition for CAV in Ireland and helping to identify policy and regulatory barriers to our adoption of CAV, as well as the need for infrastructure to support the emerging ecosystem of companies involved in the development, manufacturing and testing of products and services related to CAV. The group concluded that an entity such as FMCI would support growth and expansion in these companies while providing opportunities to attract new inward Foreign Direct Investment (FDI) and create new start-up opportunities for Irish researchers and entrepreneurs (Fig. 1).

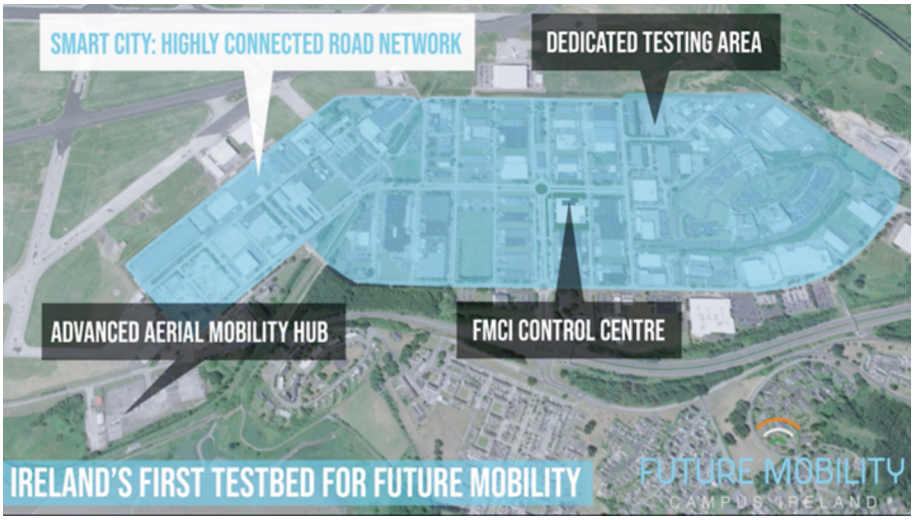



**Fig. 1.** Illustrating FMCI facilities at the Shannon free Zone (Image reproduced with permission from Future Mobility Campus Ireland (FMCI), copyright FMCI, 2024).

FMCI is delivering on the provision of a CAV test facility located in real-world settings, providing technology companies and researchers the ability to test and enhance their innovative solutions. The test facility is a non-for-profit entity and consists of a road network which is retrofitted with interconnected state of the art sensing and telecommunication technologies, all of which are fully accessible and controlled via a dedicated control centre located within the FMCI Headquarters (HQ). Within its first year of operations FMCI has expanded its offering which was initially focused on the provision of CAV text facilities, to also include aerial mobility R&D facilities.

FMCI facilities are available to its users/customers via a rental model with target users/customers of the facility including national and international automotive and technology providers that are interested in testing/validating their technology in real-world settings before the product release phase.

## 2 FMCI - An Automotive Testbed

FMCI's open testbed spans over 4 km of public road network within the Shannon Industrial Estate. The testbed is highly connected with fibre network to our dedicated data centre. It is equipped with multiple sensors, CCTV, a set of traffic lights along with high accuracy location systems, as well as a data management and control centre. FMCI provides its customers access to an advanced control room capabilities enabling insightful and data-driven monitoring as well as visual analytics of mobility data. The control room is fully equipped with an audio-visual system for real-time monitoring of the testbed (Fig. 2).




**Fig. 2. (above left) and 3 (above right).** Demonstrating a selection of FMCIs test vehicles (Images above reproduced with permission from Future Mobility Campus Ireland (FMCI), copyright FMCI, 2024).

At the Future Mobility Campus Ireland headquarters, customers can avail of private and secure workshop bays with all relevant services including high-speed broadband, a private virtual network, and a secure facial recognition access control. Customers are also offered access to a private or a common laboratory for any hardware works, etc. FMCI's fleet includes a Jaguar I-Pace and two Land Rover Defenders. All vehicles are retrofitted with a wide range of sensing and data processing technology which are secured to a flexible and adaptable roof rack, connected to a data logger equipped with large data storage capacity, and fully integrated to our in-house data centre. Recently FMCI has also added a mobile control centre which allows for additional monitoring and data analysis in offsite areas which may not be covered by our fibre connection.

### 2.1 Stimulating Innovation

New technologies and communications systems now embedded in vehicles are resulting in connectivity that opens up new possibilities, redefining mobility and changing public and private transport options [4]. While this is disrupting traditional business models it is also delivering opportunities for new business growth. FMCI facilitates innovation by providing start-ups; SMEs, MNCs as well as researchers with the infrastructure to trial, test, demonstrate and validate solutions for systems and technologies in a "laboratory with real-life conditions."

### 2.2 FMCI Customer Use Case: Provizio

Provizio [5] is an Irish SME who have been based at FMCI for the past 12 months. Provizio's technology fuses radar technology and on-board vehicle camera sensors with AI-on-the-edge processing and SLAM into one affordable, software-enhanced platform which can identify potential hazards with a high level of accuracy and speed. Each sensor is fully software-defined and integrated on an edge GPU - where proven AI-powered imaging techniques further improve their point cloud by more than 10x and in five dimensions. Provizio has been an anchor tenant for FMCI since its inception and utilise all aspects of FMCI infrastructure including, office rental for staff, test vehicle for technology integration, workshop space for hardware testing and vehicle integration as well as the FMCI data centre.

### 2.3 Diversity of R&D Projects

In its first 12 months of operation, FMCI has hosted a plethora of diverse R&D projects across a variety of organisations and research preforming entities, some of which include:

- Jaguar Land Rover: JLR Shannon [6] is at the cutting edge of Jaguar Land Rover's vision for the future and play an important role in developing new technologies to support electrification and self-driving features.
  - FMCI partner and several ongoing technological projects in conjunction with FMCI including V2X using FMCI fleet vehicles and testbed infrastructure.
- Valeo [7]: Vision systems and automated parking, producing physical hardware and generating software intellectual property with artificial intelligence.
  - FMCI partner as well as using FMCI facilities to further develop their technologies.

## 3 FMCI – Facilitating Advanced Aerial Mobility

FMCI Air targets a high growth potential market that is Advanced Aerial Mobility (AAM). From an industry perspective there are good synergies between air mobility and road mobility. Many of the same industry and research partners who are developing products for the future of road transportation will also utilise these products for air

mobility. Users of the FMCI 'Drone port' can also avail of the facilities and infrastructure as listed above including the office space, laboratories, workshops, data centre and control room. The FMCI 'Drone Port' is designed to be scalable and mobile. To support testing and operations, the drone port offers a flight operations centre and a mobile unit to allow flexibility for off-site testing. The flight operations centre is based on a modular container equipped with the necessary radio and communications equipment to ensure flight safety.

## 4 FMCI – Leveraging National Funding

FMCI has also targeted European funding to further develop and demonstrate research projects in a real-world environment while also expanding its portfolio of clients throughout Europe. By leveraging nationally funded infrastructure, FMCI has been successful in a European proposal entitled 'ÉALÚ-AER [8]' which is a three-year project involving Irish and European partners. ÉALÚ-AER is one of the first European Digital Sky Demonstrators to focus on U-space and Urban Air Mobility and aims at accelerating the delivery of an inclusive, resilient, and sustainable Digital European Skies through research and innovation. Over the past 6 months FMCI has also been requested to join 6 European consortia with regard to submitted R&D proposals under the Horizon Europe funding programme, all of which have either an automotive or ariel research component.

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# The More You Know: Digital Twins of Travelers

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**Abstract.** Despite increasing digitalization, rail operators and other mobility service providers often need more real-time information regarding the occupancy of trains and stations. Worse, only general assumptions regarding passengers' specific destinations, individual needs, and current and past experiences can be made. Digital Twins of Travelers (DTT) address the issue by holding real-time digital representations of passengers throughout their journey from start to destination. Being informed about a passenger's route instead of isolated sections enables customized real-time forecasts, accessibility information for each transfer location, and veridical updates about how much time may be spent there. For example, a traveler would benefit directly when parts of a journey must be rescheduled due to delays on the original route. When continuing with means of transportation different from those chosen initially, forecasts and other information can be immediately adapted to the new route. In the same scenario, mobility service providers would benefit by being informed about occupancy changes, allowing them to prioritize scheduled connections if necessary. DTT consist of a real-world twin, its digital counterpart, and an interchange component linking them. The digital twin represents how travelers experience current events, holds information regarding their individual itineraries' progress, and can exchange information with mobility service providers. DDT's purposes range from supporting passengers in real-time by providing information relevant to their journey milestones, analyzing the effect of events such as delays on the travel experience, to helping to align transport services with the existing demand.

**Keywords:** Human Digital Twins · Public Transport · Travel Experience · Demand Forecast · Knowledge Management

## 1 Human Digital Twin Systems

Digital twins were initially conceived in the context of product lifecycle management (PLM), intended as a structured approach to the design, manufacturing, deployment, and maintenance of physical products. [8, 9] argued that successful PLM requires detailed knowledge of the product state at all times and that a continually updated digital representation of the product can provide this knowledge. In this conception, knowing the state of a digital twin equals knowing the state of the represented object. The digital twin allows for complete predictability of its physical counterpart because of a mechanism linking the digital twin's virtual space with the real-world twin's real space. The

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mechanism continuously updates the digital twin, enabling data-generating processes like forecasts and analytics whose results may flow back toward the real space.

The core idea of coupled virtual representations of physical objects has received much attention, particularly in domains where product-related processes generate detailed yet isolated data [12]. However, the purposes of digital twins have been explored beyond their original conceptualization, precluding uniform definitions of what such twins may encompass. [14] suggested a purpose-related classification with two dimensions. The first dimension differentiates between an intended use for exploratory purposes, where no information flows from the virtual to the real space, and an intended use for decision-taking, where such information flows are characteristic. The second dimension differentiates between three kinds of entities the digital twin can represent. The first kind of representation concerns types instead of specific instances, for example, to enable virtual testing. The second kind represents individual instances, such as those required to track the life of a specific resource. The third kind of representation addresses more general system properties like resource consumption.

In recent years, the application of the digital twin concept to humans and human-related processes has been discussed. In their review of human digital twins, [13] discussed use cases in medicine, ergonomics, and sports performance. Notably, the authors suggested an ontology of Human Digital Twin Systems (HDTS) comprising a real-world twin, its digital twin counterpart, and an interchange component linking both. Additional components, such as a visualization engine, can significantly enhance the system's effectiveness, particularly for exploratory purposes such as during the prototyping stages of system development.

Minimally, the real-world twin comprises one human agent, one sensor to collect information regarding the current environment, and one process, such as a manufacturing workflow in which human behavior occurs. In the virtual world, the digital twin contains models of the human agent, the mission or task to be accomplished by the human agent, and performance goals to track how well the task is executed. Further, a prediction engine allows forecasting how changing properties within the virtual world would influence human or system performance, particularly regarding performance goals. Finally, the HDTS interchange component allows for bidirectional communication between the real and the virtual world and data-related functions such as persistent storage, cleaning, and fusion.

A critical difference between the concept of HDTS and PLM-related systems is the need to consider the enormous variety inherent to human experiences, human behavior, and the environments in which they occur. Further, there is an essential difference between measuring physical attributes and human-related constructs. In the case of physical products, many relevant attributes can be represented by measuring physical properties such as temperature. Precluding measurement errors, a user of the digital twin system can safely infer the real-world twin's state based on these measurements. In the case of human-related attributes, that is not necessarily the case. For example, based on an indicator such as a low heart rate, a person's stress level might also be classified as being low. However, such a classification can be substantially misleading without knowing that person's base rate. The relation between the level of indicator variables and the assumed level of human-related attributes is far less certain than for physical

products. As such, mapping the real-world twin's state onto the digital twin's state often amounts to a profound measuring problem. Interpreting human-related measurements often requires extensive context information, primarily if few constraints govern the expected human behavior, like in many mobility systems.

We argue that HDTS can substantially help addressing problems of measuring and interpreting human behavior in open and complex environments. Designing, maintaining, and improving human-centric mobility services requires knowledge of many human-related attributes. Such knowledge does not have to be instantaneous or all-encompassing and should be restricted to the relevant information regarding the represented person. Still, a core tenet in Human Factors Engineering is "to ensure that something goes well, it is necessary to understand what goes on" [10, p. 358]. Achieving such an understanding requires integrating many aspects of travelers' experience during their journey, and what is relevant for an individual traveler may not always be evident from the outside. For mobility providers, travelers are only visible when entering their area of responsibility. For an individual traveler, however, the entire journey is essential, regardless of who is responsible for ensuring the journey goes well.

As such, representing the way travelers take through the various spaces of their journey poses similar challenges as representing physical products in the context of PLM. As a domain-specific application of HDTS, we argue that the concept of Digital Twins of Travelers (DTT) is a promising approach to represent humans as they journey through the traffic system and to integrate multiple data sources indicating their experiences during this time. Crucially, the approach provides a conceptual basis to represent the mobility-related context of the travelers' experiences, holding information about chosen routes or the journey trajectory concerning reached travel milestones [15]. A twin system can help focus on a subset of human-related phenomena and the specific situations in which they occur, for example, to aid in understanding complex issues such as travel mode choice based on real-world data. In short, a DTT provides the framework to implement conceptualizations of mobility as a travelers' journey through time and space [1].

Implementing the DTT concept requires (a) a clear theoretical and empirical basis for the construct of travel experience to know which human attributes can be represented and (b) use cases for applying the DTT concept to know what should be represented. Both aspects will be discussed in the following sections. Finally, open questions regarding data privacy and data ownership will be discussed.

## 2 Travel Experience

As an analogy to the construct of user experience that relates human affective experiences to technical system usage [20], travel experience refers to the collective subjective impressions and evaluations a traveler has in the context of a journey [19]. Travel experience is not restricted to using vehicles such as shuttles, trains, or cars but also addresses travel-relevant infrastructure such as stations, hubs, and technical systems such as ticket vending machines or apps [2, 3, 5, 11]. Further, relevant experiences may include the feeling of pleasantness when looking out of the window in a calm high-speed train, the frustration when learning that a bus has been canceled, or the discomfort caused by standing on a crowded platform.

Unfortunately, when using trains and other public transportation, many passengers regularly experience delays, missed connections, a lack of journey-relevant information, or long waiting times. If the negative experiences outweigh the positive experiences over a sufficient period, the likelihood of using individual modes of transportation, such as private cars, can rise considerably. However, we argue that properties of the public transport system, such as the state of the infrastructure or the number of delays, are only one factor influencing travel experiences and may not always be the most important one. As an affective-emotional state, journey-related experiences are not one-dimensional and do not perfectly correlate with any single measurement [18].

Instead, travel experiences are heavily influenced by a person's goals, resources, and cognitive and physical state. Depending on those factors, a situation such as a train's delayed arrival at the next station could lead to various cognitive and emotional responses. Whereas some passengers may be indifferent because the station is their final destination, others could experience significant stress for fear of missing a connecting train with drastic consequences for the remainder of their journey. Particularly in case of missed connections, travelers with access to relevant information may be able to reschedule their journey quickly and consequently experience much less uncertainty than those relying on outside help to adapt their itinerary.

Ideally, the travelers' digital twin can represent a broad spectrum of emotional travel experiences such as frustration, uncertainty, anger, fear, discomfort, flow, or pleasantness. However, deriving such a wide variety of states from sensors such as fitness trackers, which can plausibly accessed during the travelers' journey, is a considerable challenge. Instead, a lean but robust approach mapping indicators of arousal to positive or negative valence could serve as a more practical first step [16]. Recent work has employed this approach when assessing travel experience, recording valence or similar constructs based on one or two self-report items and arousal using physiological indicators [2–4]. Although this approach provides only a low resolution of the emotional spectrum, it operationalizes the construct traveler experience as an immediately applicable method that yields valuable results.

## 3 Use Cases for Digital Twins of Travelers

The first use case concerns exploring factors influencing passengers' travel experience. Representing attributes of specific persons with known itineraries allows a much better understanding of how they solve the task of traveling to their destination, react in case of unexpected events, and evaluate certain situations along their journey. Crucially, understanding factors influencing the travel experience can be improved iteratively by analyzing the data, formulating hypotheses based on insights gained, and testing those hypotheses by making predictions regarding novel situations. If specific context data is required to understand travel experience, it is possible to add such data post-hoc by querying relevant sources.

A second use case addresses the support of passengers directly during their journey. For example, by improving the digital twin's process model to represent the task-relevant goals of travelers during their journey, providing the real-world twin with relevant information to achieve their next goal becomes considerably more straightforward. Whereas

the construct of travel experience addresses what a journey feels like, a DTT must also represent what needs to be done to complete the journey, i.e., hold a passenger's itinerary. In this view, the digital twin of a traveler is a construct for mapping, updating, and forecasting all relevant individual customer requests regarding their transportation. Specifically, itineraries can be modeled as the essential points or milestones of the service trajectory of the journey. Milestones include the journey's starting point and destination, the means of transportation on each leg of the journey, and, importantly, required transfers and associated waiting times between the legs of the journey [6]. During the journey, the DTT updates arrival and departure times for the upcoming milestones depending on the actual traffic situation and adjusts the transfer times accordingly. Such a real-time itinerary would enable communication of a passenger's progress on their specific travel chain, allowing them to manage delays and disruptions of transport services with much better consideration of individual needs and preferences [17].

As a third use case, a DTT could be a valuable data source for better adjusting supplied services to the actual demands for transportation. Whereas travelers often know in advance the specific relations they will use, mobility service providers do not have access to that information. Thus, decisions regarding offering transport services must be based on forecasts, potentially causing providers to miss business opportunities for relations where an unknown demand exists. In local public transport, ticket options such as transit passes place few constrictions on how customers use existing transport services, making the capacity planning for specific routes challenging. Even if a service has been booked well in advance, it is not certain that the customer will use it. Obtaining insight into current and planned journeys and perhaps individual preferences may allow mobility service providers to provide more targeted services than today, even in day-to-day operations. For example, if passengers miss a connection due to a service failure, the impact will vary depending on the trip's purpose. Taking the aggregated impact of service failures into account could help allocate resources in a more targeted way.

Finally, the fourth use case concerns the predictions enabled by the DTT's process model. Reducing complex journeys to essential milestones discretizes otherwise continuous processes, making simulations of complex relations in the traffic system much more accessible. For example, the approach allows for predicting the effect of travelers' preferences on the usage of buses or trains. Preferences refer to variables such as the time travelers are willing to wait on average for a connection, the price they are willing to pay, or the maximum vehicle utilization they will tolerate. When considering changes to existing transport services, the effect of those changes can be simulated together with varying preference distributions. It may be challenging to validate the veracity of the simulation's outcome. However, we argue that even considering travel experience when planning transport services is a crucial first step to aligning offered services with existing demand.

## 4 Data Privacy and Data Ownership

In a nutshell, the concept of DTT suggests combining data indicating travelers' emotional state with relevant context information underpinned by a powerful abstraction of the traveling task. We have argued that such an approach offers many attractive features supporting a better understanding of human behavior and experiences in complex

environments and solving mobility-related practical issues. However, we also believe that implementing the concept requires further discussions regarding data privacy and data ownership. To be useful, the digital twin must represent its real-world counterpart's highly sensitive personal data, such as physiological data, self-reports, timetables, and traveler trajectories. As described in the use cases, leveraging the DTT's full potential requires sharing parts of the collected data with third parties, like mobility service providers. As such, effective precautions to eliminate, minimize, and mitigate threats to data privacy are indispensable. On the other hand, the EU's General Data Protection Regulation (GDPR) already regulates many aspects of collecting and processing private data. Any implementation and operation of DTT would need to adhere to the GDPR and other data protection regulations.

In any case, we suggest thoroughly addressing data privacy and data ownership already on the architectural level. First, travelers using a digital twin must have complete control over the collected data, especially regarding sharing such data with third parties. Second, if users are unwilling to share some data, they need to be able to use the subset of the DTT's functionality, which is still available. Third, data must be anonymized or at least pseudonymized immediately. For example, aggregated data is likely sufficient if a mobility service provider is interested in how service failures impact traveler experience. Fourth, data ownership at each processing step must be clear. As such, roles and responsibilities ensuring compliance with data privacy regulations must be considered as part of the DTT design phase.

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# Different Facets of Artificial Intelligence-Based Predictive Maintenance for Electric Powertrains

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**Abstract.** Maintenance, traditionally perceived as a reactive cost and a hindrance, poses challenges to efficiency when components succumb to unforeseen breakdowns. In addition to the financial implications, the repair process also incurs substantial time wastage. To overcome these obstacles and achieve enhanced efficiency and cost savings within the manufacturing sector, this paper presents a conceptual study of a technologically advanced predictive maintenance (PdM) approach, particularly in the realm of artificial intelligence-powered digital twins. The effectiveness of these solutions hinges on their data-driven nature, technical feasibility, and acceptance by industry stakeholders.

**Keywords:** Predictive Maintenance · Artificial Intelligence · Electric Powertrains · Performance Optimization · Operational Efficiency · Sustainability

## 1 Introduction

The multifaceted nature of predictive maintenance for electric powertrains entails comprehensive approaches to diagnose the internal physical phenomena of various components within electric vehicle (EV) powertrains. By integrating advanced sensing technologies, data analytics, and machine learning algorithms, predictive maintenance enables real-time monitoring and analysis of key performance indicators, facilitating early detection of faults or abnormalities. This proactive approach not only optimizes the performance, longevity, safety, and reliability of electric powertrains but also mitigates unplanned downtime, lowers maintenance costs, and enhances overall operational efficiency. Through the utilization of multidimensional predictive maintenance strategies, stakeholders in the electric vehicle industry can achieve significant advancements in powertrain maintenance and contribute to the development of sustainable transportation solutions.

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This study aims to investigate the facets and benefits of implementing predictive maintenance strategies, specifically focusing on artificial intelligence-based approaches, in the context of electric powertrains. The European Union-funded ESCALATE and OPEVA approach aims to assure the electric vehicle user reaches its current destination to boost customer satisfaction, as it offers not only a safe journey but also promises no more breakdowns before the destination is reached. By examining the multifaceted aspects of predictive maintenance, including advanced sensing technologies, data analytics, and machine learning algorithms, this research aims to explore how these building blocks are brought together to enhance the performance, longevity, safety, and reliability of electric powertrains. Furthermore, the study seeks to evaluate the impact of advanced predictive maintenance on reducing unplanned downtime, optimizing maintenance costs, and improving overall operational efficiency. Through data-driven insights, this study aims to provide valuable insights and recommendations for stakeholders in the electric vehicle industry, contributing to the development of sustainable transportation solutions.

## 2 State-of-the-Art

Concurrently, extensive research is underway to enhance BMS performance, particularly in terms of predicting battery ageing and ensuring safety. These techniques also aim to predict battery lifespan and detect faults. To address these challenges, James C. Chen et al. [1] propose empirical mode decomposition (EMD), grey relational analysis (GRA), and deep recurrent neural networks (RNN), whilst Y. Che et al. [2] propose optimized health indicators and online model correction with transfer learning for the RUL prediction of lithium-ion batteries.

The practical integration of AI into power electronic applications encompasses deterministic and stochastic environments, data collection and analytics methods, forecasting techniques, and cost-effective algorithms and hardware implementations [3]. In recent years, physics-informed PdM methods aligned seamlessly with the strategy of making AI a frontrunner in e-mobility applications. Among these, Li et al. [4] propose a model to calculate the cumulative fatigue damage of IGBT modules in EVs to evaluate the reliability. Rao et al. [5] propose a novel approach to PdM of power electronics by integrating optical and quantum-enhanced AI techniques.

The electric motor, a pivotal component within the electrical powertrain of electric vehicles powered by batteries, operates under demanding conditions characterized by significant temperature fluctuations, pronounced vibrations and voltage stress stemming from inverter power supply [6]. Wotawa et al. [7] employ model-based, simulation-based and machine learning-based real-time PdM approach for e-motors. Rjabtšikov et al. [8] and Dettinger et.al [9] use a Digital Twin-based approach when dealing with the predictive maintenance of e-motors.

Recent developments [10] employ AIoT-based preventive diagnostic by enabling recommendation and notification prediction for Run-to-Failure maintenance, planned preventive maintenance, and predictive maintenance for EV thermal management system. Yi et al. [11] utilize Long Short-Term Memory (LSTM) based Digital Twin to achieve real-time temperature forecasting and analyze degradation models for lithium-ion batteries. Dettinger et al. [9] introduce a machine learning-based model for fault

detection in EV powertrains, employing a Digital Twin. In parallel, Bhatti et al. [12] advocate the application of Digital Twin technology in EVs through their systematic review.

## 3 Digital-Twin-Powered PdM Services Architecture

Integrating technologies like IoFog, Arrowhead, and Mimosa into predictive maintenance (PdM) for Electric Vehicle (EV) powertrains can significantly enhance real-time data processing, communication, and overall management of maintenance activities by leveraging the capabilities of edge computing, interoperable automation, and standards for enterprise integration respectively. The PdM services are designed to be used as online services, in the form of PdM-as-a-Service, within a digital twin framework as depicted in Fig. 1. The framework has a data acquisition and management module which is built on a secure multi-agent system. This module is implemented as a heterogeneous data flow backbone based on an Arrowhead-ioFog-Mimosa architecture (See Fig. 2). This module is strengthened with cyber security solutions enabling very fast agent data encryption and person/node authentication. The multi-agent system enables effective data acquisition from EVs, grid infrastructure (i.e., charging infrastructure) and environmental data.

The acquired data can be classified as JSON files and stored in a cloud database, such as MariaDB, as proposed in the digital twin framework. There exist auxiliary backend services such as data and query management services, cloud services management, security and privacy management and Identity Management System (IDMS).

A two-way Kafka-based messaging system is designed to feed the Smart Services Modules which are utilized as Docker containers at the righthand side. The Docker containers receive the classified data in JSON format or other messages or requests from the secure multi-agent system and backend services. When the Digital Twin services including AI-powered PdM solutions produce an output, these outputs are also delivered to the visualization and user interfaces layer through a results gateway, or as feedback to the Secure Multi-Agent System (for instance, in case of an anomaly).

The framework is realized through a layered architecture (Fig. 2) that utilizes the combination of Arrowhead [13], Eclipse ioFog [14] and MIMOSA [15] and is composed of i) Edge layer (ioFog), ii) Communication & Automation Layer (Arrowhead), iii) Enterprise integration layer (MIMOSA), and iv) Execution layer.

The **Edge Layer** facilitates decentralized data processing, enabling real-time analysis of powertrain data (such as battery voltage, current, and temperature) directly within the EV or local edge nodes. This layer implements LSTM or other predictive models on the edge for immediate anomaly detection and alerting for powertrain issues. Here ioFog can manage data transmission over the cloud, ensuring only relevant or summarized data is sent, which is vital for efficient bandwidth usage and managing large fleets of EVs. This layer delivers an Edge-AI-based processing that enables localized decision-making, and reduces the need to transmit all raw data to a central server, thus saving bandwidth and enhancing data privacy. Instantaneous actions, such as emergency alerts or minor adjustment suggestions, could be generated directly from the AI models deployed at the edge.

The **Communication & Automation Layer** provides a framework for ensuring interoperable communication between various systems involved in a PdM solution space,

such as between EVs, charging stations, and maintenance facilities. This layer is implemented by deploying an Arrowhead framework which is an open-source technology that establishes a standardized and secure interoperability platform for seamless communication and interaction between diverse services and devices. The Arrowhead-based solution facilitates automated workflows that enhance PdM, like scheduling maintenance activities, based on predictive insights while considering logistic and operational constraints.

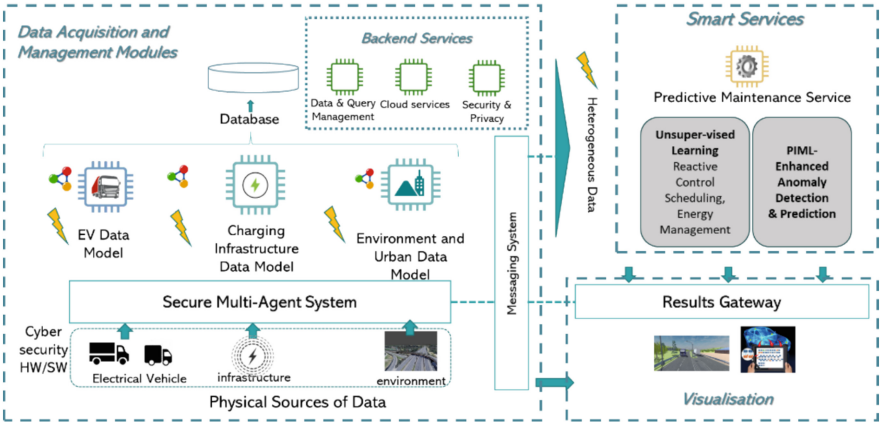



**Fig. 1.** Proposed Digital Twin Framework (Reproduced with permission from AI4SEC OÜ, copyright AI4SEC OÜ, 2024).

The **Enterprise Integration Layer** is implemented by utilizing the MIMOSA framework which is based on the Open System Architecture for Enterprise Application Integration (OSA-EAI) standard. Implementing MIMOSA standards ensures consistent data handling and interpretation across various entities involved in PdM systems, such as service providers, component manufacturers, and operators. Utilizing MIMOSA's OSA-EAI standards for enhanced data sharing and integration between enterprise systems and field-level entities ensures that PdM insights and actions are cohesively managed and executed across the organization (e.g. fleet operator, vehicle manufacturer).

The **Execution Layer** is the highest level of applications that are actively used by the end users such as maintenance service providers, vehicle operators, etc. The bi-directional arrows between this layer and the Enterprise Integration Layer indicate the cooperative work of service maintenance scheduling and coordination.

The four-layer architecture enables an effective data and action flow between layers. Data flow starts with raw data acquired from edge nodes like edge devices, gateways, smart grids, and/or onboard systems. Processed data and initial insights are transferred between the edge and communication layers. The standardized and structured data are propagated to the enterprise layer along with global insights and alerts. On the other hand, action flows can be instructions for actual maintenance activities that are streamed from the enterprise layer to the execution layer. Feedback, status updates and any corrective actions are exchanged between the execution and enterprise layer.

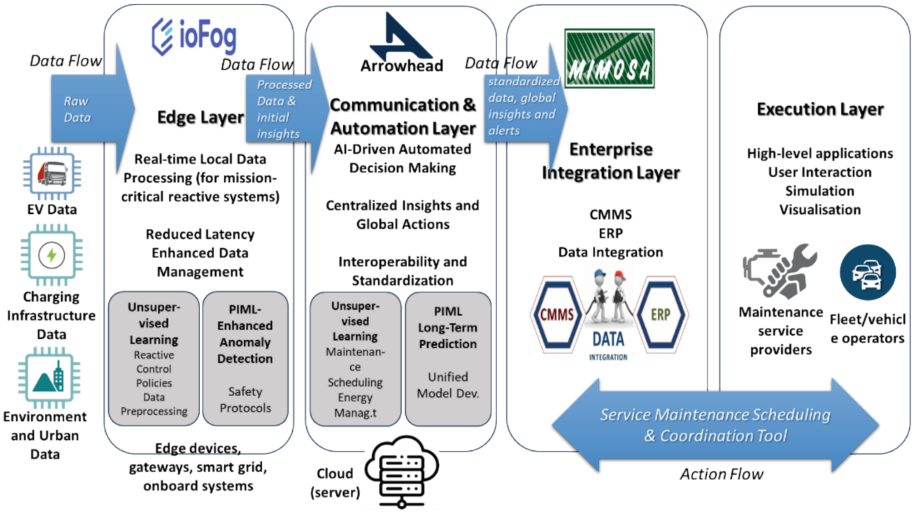



**Fig. 2.** The layered Digital Twin Architecture (Reproduced with permission from AI4SEC OÜ, copyright AI4SEC OÜ, 2024)

In both edge and communication & automation layers, unsupervised learning (UL) algorithms can be deployed for reactive control and data preprocessing as well as maintenance scheduling and energy management. The proposed architecture at the edge layer implements UL algorithms to develop local control policies that react to real-time data, adjusting operating parameters to enhance performance or mitigate anomalies. The edge layer also enables optimal energy management and creating policies that consider both localized powertrain health and broader energy demands, like grid stability or energy prices. Physics-Informed Machine Learning (PIML) for more effective PdM can also be tacked both at the edge and global level. ioFog can be used to implement PIML for real-time analysis, using physics-based principles to enhance anomaly detection in powertrain components, ensuring that the alerts are not just data-driven but also physically plausible. Here, safety protocols leverage PIML to establish safe operating boundaries for the powertrain, using physics principles to prevent settings or actions that might risk component health or safety. At the automation layer, PIML models can be used for analysing long-term physical degradation patterns in powertrain components, ensuring that PdM strategies are aligned with anticipated wear and tear. A unified model can be developed to integrate physics-based principles with data-driven insights, presenting comprehensive models that ensure predictive insights and prescribed actions that are scientifically substantiated.

## 4 Conclusion

This paper presents a digital twin framework based on a 4-layered architecture that integrates Edge (ioFog), Communication & Automation (Arrowhead), Enterprise integration (MIMOSA), and Execution layers. IoFog, Arrowhead, and Mimosa are utilized

for orchestrating physics-informed PdM and UL for EV powertrains so that organizations can create a robust, efficient, and scalable system. This integration not only enhances real-time data processing and communication but also ensures that the maintenance activities are streamlined, standardized, and optimized for the best possible performance and longevity of EV powertrains.

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# Analyzing the Enabling Factors to Implement MaaS in Asian, African and Latin American Cities

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**Abstract.** The EU-funded SOLUTIONSplus project, which aims at kick starting urban e-mobility in developing countries, included the provision of a white label app customizable to the needs of the cities as part of its offer to its 7 demonstration cities in Asia, Africa and Latin America. Despite having the possibility of testing the customized app free of charge for the duration of the project, only 2 out of 7 cities, Quito (Ecuador) and Kigali (Rwanda), started and continued the process. Yet, only Quito was able to test the customized app in real operations. Thus, the paper analyzes the MaaS level and implementation barriers of the 7 cities and conducts an in-depth expert assessment of the technology, organization and environment enabling factors (TOE) to implement the MaaS concept in Quito, Kathmandu and Kigali. The results show that despite some progress towards an intelligent and integrated transport system in the analyzed cities, an important number of conditions that are a given in the Global North (e.g.: formality and integration of PT system), still need to be met in cities in developing countries before MaaS could be realized.

**Keywords:** Mobility as a Service (MaaS) · Enabling Factors · Developing Countries

## 1 Introduction

In an increasingly urbanized world, where more than half of the global population already lives in cities (2/3 by 2050), digital technologies will have a pivotal role in advancing sustainable urban development and formulating effective policies and measures for climate change mitigation. In parallel, the emergence of new mobility concepts and the

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widespread use of smartphones worldwide has brought along the emergence of a significant number of mobility applications aimed at improving the efficiency of urban mobility services both for freight and passenger transport. Local and international mobility (and micromobility) apps such as Uber (Eats), Ola, Gojek, SafeBoda, Glovo, PedidosYA, tembici, Moveo, etc. already operate in Africa, Asia and Latin America, showing the great penetration and potential that app-based mobility services already have in the Global South. The integration of such services under the Mobility as a Service (MaaS) concept could contribute to modal shift and reduced energy consumption [2, 3].

MaaS is a new transport and mobility concept that integrates existing and new mobility services (NMS) into a single digital platform, providing customized mobility options and offering personalized trip planning and digital payment possibilities [1]. MaaS has the potential to improve the travelling experience, reduce travelers' costs, efficiently manage travel demand, and improve environmental and social outcomes [2–4]. MaaS has been gaining popularity in Europe / the Global North and has been implemented in several cities with positive results related to sustainable and low-carbon mobility [2, 3]. However, in developing countries, in contexts of fragmented and often informal public transport systems, lack of data, cash economies, low digitalization levels, the implementation of such a concept comes with a lot of challenges [5]. While important scholarly contributions have been made to understand the barriers and enablers of MaaS [5–8], these studies primarily rely on literature reviews and expert interviews. In this article, we contribute to this body of knowledge–which has mainly focused on the European context– by validating these findings with data from real-world MaaS schemes in the global South.

The EU-funded SOLUTIONSplus project, which aims at kick starting urban e-mobility in developing countries, included the provision of a white label app customizable to the needs of the cities to enable access to the e-mobility services for the end-users as part of its offer to its 7 demonstration cities in Asia, Africa and Latin America [9]. In a MaaS approach, the app offered the integration of all services, payment and information useful for the end-users allowing the possibility of integrating e-bikes, e-3-wheelers, e-taxis, etc. to the existing public transport (PT) system.

Thus, the purpose of this paper is to define and analyze the enabling conditions needed to adopt the MaaS concept in developing countries. The analysis starts by assessing the MaaS level and the implementation process in the 7 SOLUTIONSplus demonstration cities in Asia, Africa and Latin America (Sect. 2.1). The analysis of the enabling factors in Sect. 2.2 focuses on Kigali, Kathmandu and Quito, the 3 cities in which the feasibility of implementation of a MaaS app in the context of the project was further explored.

## 2 Analysis

### 2.1 MaaS Level and Pilot Implementation in SOLUTIONSplus Cities

In an attempt to create a comparison tool for the level of penetration of the MaaS concept in different cities, Sochor et al. (2018) propose a topology that consists of 5 levels based on the degree of integration [10], i.e.: 0 - no integration; 1 - integration of information; 2 - integration of booking and payment; 3 - integration of the service offer; 4 - integration of societal goals. As it can be seen in Table 1, the 7 SOLUTIONSplus cities fall between

the Levels 0 (in transition to 1) and 2. This means that most cities already have access to some sort of route planning app and the more advanced ones are already in the process of integrating the in-app payment functionality.

Regarding the level of implementation under the SOLUTIONSplus project, it is shown that despite having the possibility of testing the customized app free of charge for the duration of the project, only 2 out of 7 cities, Quito (Ecuador) and Kigali (Rwanda), started and continued the process. Yet, only Quito was able to test the customized app in real operations. Nevertheless, it is worth noting that other demonstration cities such as Hanoi, Dar Es Salaam and Montevideo have taken their own path to develop mobility apps for specific needs.

**Table 1.** MaaS level and implementation in SOLUTIONSplus cities

| City | MaaS level | Level of MaaS implementation under SOLUTIONSplus |
|---|---|---|
| **Africa** | | |
| Kigali | L1 | Discussions between the SOLUTIONSplus team and the representatives of the City of Kigali to develop a customized MaaS app took place between July 2021 and May 2023. However, a joint decision not to pursue it due to high constraints and limited time was taken. |
| Dar Es Salaam | L0 in transition to 1 | Dar Es Salaam is developing its own planning and ticketing app for which the SOLUTIONSplus team had an advisory role. The conditions to implement a MaaS app between BRT buses and paratransit modes are not in place yet. |
| **Asia** | | |
| Kathmandu | L0 in transition to 1 | After a prefeasibility assessment conducted by DTU [11], it was determined that the conditions to implement a MaaS app were not yet in place in Kathmandu. In particular, related to the lack of an intelligent transport system, a business model and the regulations to incentivize transport operators to take part in a MaaS platform. |
| Hanoi | L2 | It was decided to put all efforts in the development of a booking app for the e-2-wheelers being implemented in the pilot. |
| Pasig | L1 | The governance of PT in Pasig would have required the involvement of a larger number of stakeholders, including the national government. Due to the complexity, after the assessment it was decided not to pursue it. |
| **Latin America** | | |

(*continued*)

**Table 1.** (*continued*)

| City | MaaS level | Level of MaaS implementation under SOLUTIONSplus |
|---|---|---|
| Montevideo | L1 in transition to L2 | The Municipality of Montevideo declined the offer arguing that they already have their own municipal app called "Como ir", which at the moment only allows trip planning, but is supposed to integrate in-app payment once the ticket validators in the buses are replaced |
| Quito | L1 | A customized MaaS app including a trip planner, in-app payment and e-ticketing was developed in close collaboration with the municipal PTOs (BRTs and subway). In order to address the specific needs of the city, two complements were added: 1) a web app to top up the e-wallet with cash in the ticket booth and 2) A mobile app to validate the e-tickets until the automatic turnstiles are procured and installed in all stations. The 3 apps were piloted in Q4 2022 with 50 university students for a period of 4 weeks in 1 BRT station. The circumstances that led to the pilot implementation in Quito were: 1) the imminent launch of the subway line, by which the city is in the process of modernizing and integrating the PT system, which encompasses the Integrated Payment System (SIR), the Data Exploitation System (SAE) and the User Information System (SIU). The Municipality was reluctant to continue and scale-up the pilot due to the lack of knowledge of the new authorities about the MaaS concept, the regulatory framework for its implementation and the linkage to and benefits for the SIR. The main concerns were related to the business model and costs after the project end, as well as the ownership of the data and the application. |

### 2.2 The Enabling Environment in Quito, Kathmandu and Kigali

A literature review was conducted to investigate the main requirements, but also the barriers that have been defined / identified both in the Global North and South for the implementation of the MaaS concept [5–7]. Based on that and following the methodology applied by Hasselwander et al. (2022), the technology, organization and environment

(TOE) framework was used to classify what from now on will be called enabling factors [5]. A total of 20 number of variables have been identified as enabling factors for MaaS implementation. The elements considered under Technology refer to the level of digitalization in the selected cities. In terms of Organization enablers, policies, plans and the governance structure related to digitalization of transport and intelligent transport systems were analyzed. Under Environment, the enabling factors are related to the integration level of the public transport system and other transport services.

The results of the analysis using the TOE framework are summarized in Figs. 1, 2 and 3. As it can be seen, only very few factors are fully met in the 3 cities. Nevertheless, in most factors the Quito, Kathmandu and Kigali comply partially, which means there is already some level of advancement.

| City | Quito | Kathmandu | Kigali | In summary |
|---|---|---|---|---|
| **Enabling factor** | Expert Assessment | | | |
| Access to smartphones and mobile internet | PARTLY | PARTLY | PARTLY | Access to a smartphone doesn't seem to be a barrier, at least not in the age group expected to use the app, and not in urban areas. Mobile internet access has risen in these cities, but the affordability of data plans still represents a restriction for an important percentage of the population. |
| Availability of payment gateways (e.g.: PayPal) | PARTLY | PARTLY | YES | MTN Mobile Money is widely used for transport services in Kigali. In Kathmandu and Quito there some payment gateways, such us e-Sewa and DeUna, but their use for transport services is limited or non-existent. |
| Penetration of mobility apps (e.g.: Uber)<br>1) Availability and use<br>2) In-app payment (credit card usage, payment gateways, etc.) | YES | YES | YES | There are, however, several mobility apps, local and international, operating in the 3 cities. However, the possibility to pay in-app with credit / debit cards or payment gateways is still limited in most cases. |
| Availability of journey planner (e.g.: Google maps, Waze, municipal apps, etc.) | PARTLY | PARTLY | YES | Global apps such as Google maps work in the 3 cities. However, with different functionalities. While in Quito and Kigali it is possible to see the bus routes and the estimated times, in Kathmandu it only shows the walking route. |
| Users' acceptance and profile | PARTLY | PARTLY | PARTLY | There positive experiences of the widespread use of mobile money and e-wallets in Kigali and Kathmandu. It is expected, as in other contexts, that the primary target group is young people. However, depending on the user friendliness, affordability and benefits of using the app, a larger and more diverse number of users could be attracted. |
| Data collection and standards<br>1) Standardization and aggregation of data, open data or willingness to share data<br>2) Real-time data collected<br>3) GTFS files available | PARTLY | NO | PARTLY | The use of ITS by PTOs is still quite limited / fragmented. (Real-time) data collection, sharing and ownership is still an unresolved issue in the 3 cities.The only city from the 3 with a GTFS available was Quito. |
| Privacy and security of user data is not a limitation for users | YES | YES | PARTLY | Concerns regarding data privacy / security in the general population of these cities is low in comparison with European countries / cities. In the case of Kigali, however, the privacy and security of user data are quite relevant for the national authorities. |

**Fig. 1.** Technology enabling factors in Quito, Kathmandu and Kigali

| City | Quito | Kathmandu | Kigali | In summary |
|---|---|---|---|---|
| **Enabling factor** | Expert Assessment | | | |
| Transport digitalisation policy objectives | PARTLY | PARTLY | PARTLY | The 3 cities analyzed have some type of plan, framework or strategy either at the national or local level, where the use of ICT to improve public transport is mentioned. The MaaS concept, however, is only explicitly mentioned in Quito's SUMP, yet without further detail. |
| General transport authority / degree of centralization / governance | PARTLY | NO | NO | There's not a unique authority. Transport governance is pretty disperse. Quito is trying to create a general transport authority, but the process will take time. |
| Knowledge & capacities<br>1) Experience / Clarity regarding role and responsibilities / expected benefits<br>2) ICT expertise | PARTLY | NO | NO | There's lack of knowledge / clarity about the MaaS concept, its application, operationalisation and benefits. In the case of Quito, however, we counted with the support of a public official that had clarity about the concept and benefits. It was one individual, at the institutional level it's still an unknown concept. |
| Transport authorities structures, fast decision processes, innovative strategies and integrated planning approaches | NO | NO | NO | The complexity of transport governance, including the relationship between public and private actors, and the low speed of processes, makes the introduction of MaaS difficult. |
| Political will and institutionalization<br>1) Top management support<br>2) Public sector engagement / Political support<br>3) Necessity of a window of (political) opportunity / political cycle | PARTLY | YES | YES | In general terms, these municipalities were engaged. The processes in these 3 cities were able to move forward only because of the top management support provided. However, the system and the governance is not mature enough for its full implementation. In the case of Quito, the political cycle played a huge role, as the new authorities were not as supportive of the project as the previous ones. |
| Financial resources and funding | PARTLY | NO | NO | The municipalities didn't have their own resources because MaaS is not yet in their priorities / radar. In Quito, there are resources as the Integrated Payment System (SIR) is being implemented as part of the PT modernization. |
| Clarity about the business model / ownership of app / data collection | NO | NO | NO | Business model and data ownership are among the main concerns when deciding to move forward. There was very little knowledge in the counterparts about how to implement the MaaS concept in the given environment. |
| Enabling regulatory framework | PARTLY | PARTLY | PARTLY | At the moment, the regulations in the analyzed countries are either at a very early stage or very restrictive. In particular, we encountered some regulations that make the collaboration with international companies for the development of MaaS or other mobility applications difficult. In Rwanda, for instance, cloud storage can't happen outside of the country. In Ecuador, on the other hand, the fare collection of PT has to be in the corresponding bank account of the PT authority within 24hours. |

**Fig. 2.** Organizational enabling factors in Quito, Kathmandu and Kigali

| City | Quito | Kathmandu | Kigali | In summary |
|---|---|---|---|---|
| **Enabling factor** | Expert Assessment | | | |
| Integrated and regulated operator landscape<br>1) Form of Route Service contracts between Authorities and transport operators<br>2) Formal, multimodal and integrated PT system (physical and tariff)<br>3) Low informality rate in transport services | PARTLY | NO | PARTLY | In the 3 cities, there is some form of route service contracts that formalises and regulate transport. In the recent years, the 3 cities have tried to improve the processes. However, the PTO landscape is still very fragmented in Kathmandu, and partially fragmented in Quito. Paratransit / informal transport is only relevant in Kathmandu. Thus, the level of integration of the system varies, but is still not ideal in any of the 3 cities. |
| Private sector engagement / Support from transport groups and associations | PARTLY | PARTLY | YES | The development has not reach the level of opposition. However, the level of integration that the proper functioning of the MaaS concept requires will need important negotiations with all PTOs. Thus, in the case of Quito and Kathmandu, where PT integration is not completed, it can lead to some level of opposition. |
| Integrated payment system for PT | PARTLY | NO | PARTLY | Kigali has a smart card that can be used in all PT operators. Quito is currently working on the introduction of an Integrated Payment System, which will include the proper infrastructure, the IT systems and fund reconciliations. In Kathmandu, there have been some failed attempts. In the 2 latter, cash is still the mean of payment in PT, while in Kigali mobile money is used. |
| Existance and integration with other transport services (bike sharing, e-scooter sharing, etc.) | PARTLY | NO | PARTLY | In the 3 cities there are transport services, be it bike sharing, e-scooters or moto-taxi services. Some of them linked to mobility / booking apps. However, there's no proper integration between other services and PT. In Kigali and Quito there are some located close to PT stations, but there's not a proper multimodality strategy. |
| Successful adoptions (in the country/region) serving as blue print | PARTLY | PARTLY | PARTLY | There are some mobility apps in the 3 region trying to start a MaaS service with many limitations. However, so far, in most cities they only have trip planning functionalities. |

**Fig. 3.** Environment enabling factors in Quito, Kathmandu and Kigali

## 3 Conclusions

As it has been shown throughout the paper, the implementation of the MaaS concept require the fulfillment of a set of technology, organization and environment conditions. The MaaS level analysis shows that despite the fact that some of the analyzed cities are still in level 0, they are already transitioning to level 1. Most cities are in level 1, some transitioning to level 2. Thus, the cities analyzed, despite their differences, reveal a slow, but steady progress towards the adoption of the features of an intelligent and integrated transport system that will enable MaaS. There are, however, still a series of barriers that need to be overcome related to the digitalization level, as well as in the transport system and governance, before the MaaS concept implementation is feasible in developing countries. A step-by-step approach could be desirable, starting by the gradual integration of all PTOs into the system in one digital platform and then the addition of other mobility service providers.

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# Designing Mobility Systems-of-Systems

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**Abstract.** In this paper we describe the results of a study on the design of open and co-opetitive systems of systems for mobility. A system of systems (SoS) is a set of independent systems (CS – Constituent Systems) that interact to create capabilities that none of the constituent systems can accomplish on their own. A CS can be simultaneously part of several SoS. The independence of the constituent systems is an important and central ingredient in an SoS, and is often divided into managerial and operational independence.

We argue that the mobility SoS of the future can benefit from being open and co-opetitive (i.e., simultaneously collaborating and competing) to enable combined mobility (MaaS) for real. If competition between CS is not allowed, new entrants will choose to compete with the SoS instead of becoming part of it. If a new entrant develops much better vehicles or better ways to find transport solutions for users, that entrant must be able to become part of the SoS and take market share from other actors.

**Keywords:** Mobility · transport · system of systems · architecture · sustainability · MaaS

## 1 Introduction

Mobility as a service (MaaS) has emerged as a core component of smart city development. There are a number of definitions circulating around the smart city of the future, but basically it is about having a holistic perspective in the construction of a city that is economically, socially and ecologically sustainable with the help of technology.

An important part of the smart city will be smart mobility and transport solutions. In recent years, a vast array of new mobility services have been introduced. For instance, cities have been flooded with electric scooters and a large number of different car-sharing services have been introduced. Despite this, there are no city-wide services that allow residents to easily book a trip from A to B with a combination of several services. Rather, what we see on our streets is

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a hodgepodge of services that often do not survive for very long, while the interconnected system of transport services that would constitute real system innovation is missing. One reason for this is the lack of language with which to formulate a systems of system mobility solution. Although there are many initiatives around smart cities worldwide that deal with transportation, and many research activities in the area, they are usually carried out as isolated projects.

MaaS is also a popular research topic that involves the integration of various mobility services [1,2]. There is a need to take account of different regulatory frameworks, infrastructures, and user preferences when implementing such systems [3]. There are many different actors involved in MaaS, such as vehicle operators, brokers that connect users to vehicle operators, users, and municipal and regional authorities.

Current approaches to MaaS are based in transport systems engineering and mostly consider them as integrated systems, i.e., they envision a system that is tightly integrated and controlled by a central orchestrator. This means that the technical architecture for a MaaS solution must integrate the different transport services tightly into a single digital platform [4]. There are obstacles in the form of data sharing and ownership issues as well as how to avoid silo solutions that lock-in the user to specific companies. From the perspective of companies involved in MaaS solutions, there is an understandable reluctance to cooperate too closely with competitors. But in order for the MaaS to be useful and gain enough market share to make a difference, there must be such cooperation.

Prompted by these possibilities to combine SoS and MaaS, we undertook a project (Maus) that investigated a *systems of systems* (SoS) [5] approach to mobility as a service by considering a scenario in a semi-rural area near a major Swedish metropolitan. In this paper, we describe some of the results of this project. Main results include a design method for SoS [6], a business model evaluation method, SoS architecture patterns [6–9], and processes and methods for governance and management of the SoS, as well as a survey of existing SoS design patterns [10].

The main scientific contribution of this paper is to take a first step towards applying SoS concepts to MaaS.

This paper is outlined as follows. Section 2 introduces key SoS concepts, both standard ones and results of the Maus project. Section 3 illustrates the mobility SoS. We conclude with a summary and discussion in Sect. 4.

## 2 Mobility Systems of Systems

An SoS is a set of independent systems (CS – Constituent Systems) that interact to create capabilities that none of the constituent systems can achieve on their own. A CS can be part of several SoS at the same time. The independence of the constituent systems is a central ingredient in an SoS. An important question when studying and designing SoS is what entities should be considered as the CS. For a mobility SoS, this boils down to the deciding if the CS should be the individual vehicles that carry out the transports or the transport companies

that own the vehicles. For mobility SoS, it is usually the vehicles that should be considered CS, but this can vary depending on which aspects of the SoS that are studied. In addition to the vehicles, a mobility SoS will also need to have support services of various kinds, such as travel planners and payment intermediaries. Such support services are CS of a special kind called mediators. Figure 1 shows this general structure of an SoS. A mediator can be seen as a special case of CS and is something that provides services necessary to organize the collaboration, but does not have the same degree of independence as a CS. In a mobility SoS, someone who manages an intangible service, for example for information sharing, payment transfer or developing proposals for constellations whose combined abilities solve the transport assignments, is a journey planner. An example of a mediator could be to ensure that the trip can be booked and payment can be made.

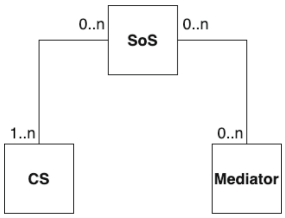



**Fig. 1.** An SoS contains one or more CS and optionally some mediators.

In earlier work, different types of SoS have been defined [5,11], for example depending on how much central control there is in the SoS. In a Directed or Acknowledged SoS, each CS is subordinated to a central control, while in Collaborative SoS the CS retain their control and choose when to collaborate. Here we will focus on Collaborative SoS that are also open and co-opetitive. An open SoS is an SoS which new actors can join. A co-opetitive SoS is an SoS whose constituents simultaneously both collaborate and compete.

## 3 Applying the Mobility SoS to a Semi-Rural Example

What might an SoS solution for mobility look like? In the Maus movie (available at sos-4-mobility.se or https://www.youtube.com/watch?v=e-DdHS5o6yk) we show this for parts of the scenario described here. The Maus project used the area around Harestad, north of Gothenburg, as a concrete case to work with. At the start of the project, a list of specific user stories and use cases was developed.

How would the people solve their transport needs today? Many of them would routinely choose their own car, because “all other ways are so hard”. Some would check out the possibilities of using public transport. Someone would call different taxi companies to get prices. Some would ride bikes. What these solutions have in common is that the people focus on the means of transport instead of the

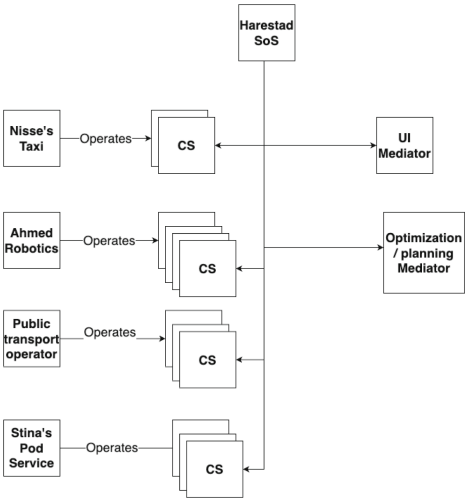



**Fig. 2.** Schematic view of the mobility SoS that could solve the travel needs in Harestad. The SoS has access to a large number of CS from four different companies, and also needs mediators for interfacing to the users, travel planning/optimization, and payment distribution.

transport itself. If you want to make an optimal choice of transport, you need to contact several different transport companies and compare their offers. Many people will then choose to travel with their own car because it is the easiest. The purpose of the Maus project was to show how you can choose transport instead of choosing a means of transport. In the next section, we show what such a solution could look like.

What is required for an SoS solution to be realized? There is a need for a robust payment service that enables the user to pay only once, and then distributes the money to all involved parties in a fair manner. This is one of the necessary mediators in the mobility SoS. Agreements are needed that regulate service levels and services that collect data on the quality of travel and goal achievement [9]. It is also important that all actors who are part of the SoS trust each other and that agreements are in place that regulate, for example, compensation levels and the consequences of delays and other problems.

Solutions are also needed to enable the users of the SoS to formulate their travel needs and for the SoS to match these with possible solutions. Here, it is important to specify what are acceptable waiting times and investigate the balance between cost and goal achievement. The major optimization problem posed by matching can not be solved exactly, which makes it important to study which trade-offs are acceptable. These services are best divided into two different mediators. One is the travel planner service. This mediator takes requests for transports and matches them to the available transport capabilities of the SoS. We have earlier [8] described how this could work. The other needed mediator is

a user interface mediator. This service provides the interface between the users and the SoS.

Figure 2 displays the SoS structure that could be implemented. While we here include only one of each type of mediator, it is important to note that a SoS should be open for innovation and competition also for its mediators. If a new company develops a better travel planning service, it should be free to join the SoS and provide its service as a mediator that competes with the existing mediators.

## 4 Conclusion

In conclusion, we discussed some of the results of the Maus project and how SoS concepts could be applied to mobility and MaaS applications. We introduced some standard SoS concepts as well as new concepts developed within Maus.

The main contributions of this paper are to start the discussion on how to use SoS concepts to overcome some of the barriers currently preventing MaaS solutions and to present a first example of how a MaaS based on SoS concepts could be designed. The focus on the different perspectives that different roles in an SoS entail can contribute to better understanding of the roles and responsibilities within MaaS. By abandoning the idea of MaaS as a single system and embracing the co-opetitive SoS concept, it becomes easier to design solutions that both satisfy the needs of users and municipalities while still allowing the competition between actors that drives innovation.

There are ample opportunities for further research in this area. There is a need to further explore the usefulness of SoS concepts in transport and mobility research and implementing the ideas in demonstrations and pilots. Before this, however, it would be useful to perform large-scale simulations based on realistic travel patterns, to be able to quantify both the costs and the benefits of SoS mobility solutions.

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# Transport Data Sharing

# Towards Integrated Traffic Management for All of Austria: Realtime Traffic Information and Multimodal Journey Planning Beyond Administrative Borders

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**Abstract.** All major players in road operation and traffic management of Austria joined forces in the EVIS.AT platform and developed a harmonized real time traffic information network. It provides a countrywide, comprehensive, and authorized real-time data basis for traffic information, traffic management and traffic analysis. The platform delivers traffic messages for planned and unplanned events as well as for traffic regulations and access restrictions and traffic flow data such as current and predicted speeds and LOS. This is done for all major street levels (highways to rural roads) for all of Austria and is based on sensors, probe data and journalistic data of the authorities. The involved parties committed to long-term operation and provision of real-time data through a public-public cooperation. Thus, the platform EVIS.AT serves as strong basis for road-related traffic data in the context of integrated traffic management as well as comprehensive traffic information. The authorized real-time road data of EVIS.AT is combined with public transport data of all operators, including timetable, real-time and message data in the intermodal routing platform VAO.AT. The platform delivers high-quality intermodal routing and traffic information services, based on the comprehensive data sets of Austria's various public authorities. It is used by partners and b2b customers to create powerful end user applications as well as various tools for administration.

The paper reports on objectives and status for these platforms, what makes them unique in the European data and service landscape and how these data and services are being used in national and international applications.

**Keywords:** Multi modal journey planner · real time traffic information · travel times · standardization · vehicle probe data · incident management

## 1 Introduction

The European Commission passed the Delegated Regulation (EU) 2017/1926 on 31 May 2017 with regard to the provision of EU-wide multimodal travel information services (the revision will be published soon). Even long before this event Austria took the approach to develop a platform called VAO („Traffic information Austria"): a nationwide intermodal traffic information platform that integrates approved traffic information of all modes

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of transport provided by the major traffic infrastructure and traffic service providers. The system includes public transport timetables, stations and other connecting points, a detailed intermodal graph called GIP [1], traffic messages and Level-of-Service data for all major motorways, all addresses in Austria, park + ride and other parking facilities as well as additional data such as points of interest, bike rental stations and short term parking zones. VAO's various services rely on data covering all of Austria, making it a comprehensive toolset for traffic information and end user services. Intermodal routing services are available through a well-defined interface. [2] Currently, VAO is including shared mobility services to its routing and maps database.

EVIS.AT (Real time traffic information on Roads in Austria) on the other hand, aims at providing real time traffic information for roads and besides ASFINAG as Austria's motorway operator, brought aboard the 9 Austrian federal states, ITS organizations, major cities as well as the Ministry of Internal Affairs (police) and the automotive and mobility club ÖAMTC. They joined forces to improve the real time traffic data landscape of Austria significantly and to harmonize data and processes nationally. The project has been an ITS emphasis in the past few years. It ended in 2022 and started a permanent operation of data provision and quality processes to ensure long term support. [3] Subsequent sections of this paper report on objectives, technical and organizational construction as well as provided data and services and use of that data.

## 2 Objectives of the EVIS.AT Platform

EVIS.AT is a nationwide, harmonized and unified platform for all kinds of traffic information for motorized traffic, built by the experts who already developed and operate their existing solutions. The mission of the platform is to harmonize and unify traffic data for motorized traffic, with the goal of providing a better real time traffic data basis for VAO through creation of a data platform as well as processes for all major infrastructure and traffic information [5, 6]. EVIS.AT became the main content platform for dynamic aggregated road traffic information in Austria.

The main objectives of the EVIS.AT platform are:

- As public actors, **create and collect own real-time traffic data** as strong basis for administrative tasks and end user services but also when engaging with the large private mobility service providers (i.e. routing engines, navigation companies,…)
- **Harmonize all data of all public actors** (technically, structural, content-wise) to create a meaningful, national data set. Agree upon standards for implementation formats as well as delivery processes.
- **Collect and provide all data at a single point of contact** (EVIS.AT data platform) to make the data accessible; utilize this for data dissemination within the partners but also towards third parties, i.e. media, routing and navigation providers.

# 3 The EVIS.AT Platform

## 3.1 Development

The EVIS.AT platform (Echtzeit Verkehrsinformation Straße; real-time road traffic information) was established in an implementation project in three phases (planning, technical implementation, operation) and focused content-wise on the two key areas: incident management and real time traffic information (i.e. LOS on the roads).

Launching a project with broad participation of road and traffic authorities was based on the following considerations: *Use local expertise.* (collection of traffic information with respect to local road layouts and topographies but also knowledge of the specific workflows in provinces and federal states). *Therefore, get everybody together*. (EVIS is led by Austria's motorway operator ASFINAG and supervised by BMK. Moreover, most of the administrative stakeholders for traffic in Austria are project partners). *Develop common standards.* (When using local expertise and even varying methods and means to collect traffic information it is a must to agree upon common standards and the quality of service along with data types and formats. This is meant to ensure that a national data aggregation and logical decentralized unit can produce harmonized traffic information and foster the exchange of data to efficiently use them for traffic information and network management. Basis for this are European standards like DATEX2.) [4].

On the technical level, the main approach in developing the platform was to utilize existent well working solutions of the partners (be it systems, data formats, processes,…), select the fittest and deploy them nationally.

The project targeted the whole lifecycle of traffic information: from fundamentals like extending the stationary traffic sensor network throughout Austria, extending the traffic network graph GIP.GV.AT and tendering floating car data and mapping them on the graph. Concerning standards, the partners agreed upon data formats, definitions, message types and minimum standards for message creation. The definition of processes focused on clear responsibilities, local know-how and individual implementation. The partners implemented several tools for common usage (see next section) and in the area of governance, they set up a public-public partnership and contracts.

## 3.2 Technical Implementation

The EVIS.AT platform is structured as a distributed system. On the one hand, there are several local data aggregation and provision services. Following political and administrative conditions, partners from different areas in Austria are responsible for data generation and provision for their respective region. However, they all agreed upon common formats, standards and quality. To bring the data together in a harmonized way, these so called "central services" provide services to all users but are only implemented once. Therefore, each member can use all services implemented by itself or other parties. The following table gives an overview of the services (Table 1).

**Table 1.** Central services of the EVIS.AT platform

| Central service | Tasks |
|---|---|
| Data hub | The **Data Hub** (data collection and distribution service) receives and distributes data between partners and 3rd parties like Verkehrsauskunft Österreich VAO and the free market |
| Clearing service | The **Clearing Service** is responsible for the collection of incident data and for the conflict free distribution in terms of location and content |
| Geo-Services | **Geo-Services** translate different versions of the above mentioned GIP format into the newest. They also translate the GIP system into other location referencing systems like WGS84. |
| FCD Services | The **Central FCD Service** collects and tenders nationwide probe data, processes them from raw data to speeds and travel times and makes the data available to partners |
| Traffic Message Acquisition Tool | The **Traffic Message Acquisition Tool** provides a tailored web front end for the input of traffic messages for authorities and supports the GIP as well as DATEX2 output and is integrated in a national identity provision and authorization framework and administration processes |

### 3.3 Legal and Organizational Implementation

Legally, the EVIS.AT platform is constructed as a public-public cooperation of public sector stakeholders based on respective agreements. This allows for a cooperation agreement, where each partner provides services, data and licenses to the consortium while avoiding to found a corporation or directly providing cash.

The main parts of the cooperation agreement include:

- Governance and steering of the operating platform;
- Central Services and responsibilities of the respective responsible party and operator within the distributed system EVIS.AT, for details see Sect. 3.2;
- Provision of real-time traffic data of the respective responsible authority;
- Consummation and rights of use of real-time traffic data of other parties;
- Technical sales and distribution of data services to third parties;
- Public relations and external communication of the platform EVIS.AT.

Goods and services that can not be provided from within the consortium are tendered on the market – where one or several of the partners tender the respective services for the whole platform. As of summer 2023, there have been two major tenders:

- Clearing services: the objective of the central service “Clearing” is to receive, process, quality check and provide all traffic messages of more than 60 regional message

providers (local public authorities); most of these checks are automated but manual checks are performed as well.

- Floating car data: dynamic procurement system established by Salzburg Research and the federal states of Salzburg, Tirol and Vorarlberg where tenderers bid to demonstrate their qualification and eligibility based on legal and commercial terms as well as data specific KPIs [7] to enter the procurement pool and deliveries are requested based on available funds from the pool [8].

The technical but also legal and organizational implementation of the platform has been operating for over a year now and is working well.

## 4 EVIS.AT Data and Service Offering

Through the EVIS.AT platform, Austrian road authorities can provide their respective real-time traffic data to third parties at a one-stop-shop, harmonized and comprehensive for all of Austria: motorways but also the lower-level network and several cities.

ASFINAG is the distributor of all EVIS.AT real-time traffic information data, i.e. not only for motorways but also for the lower-level network. This is based upon respective agreements with all 9 federal states of Austria, several cities, the BMI (Ministry of the Interior/Police), the BMK (Ministry of climate and traffic) and ÖAMTC (Automotive Club) and several cities via the operating agreement.

The data streams included are listed in Table 2.

**Table 2.** Data streams of EVIS.AT

| Data stream | Data description | Data format |
|---|---|---|
| Traffic messages of planned events | i.e. constructions, closures, events, winter equipment,… | DATEX2 |
| Traffic messages of unplanned events | congestion, accidents, bad weather,… | DATEX2 |
| Seasonal conditional access restrictions | closed off-ramps of highways (for through-traffic in Tirol and Salzburg) | DATEX2 |
| Traffic State | level of service, current speeds | JSON |
| Traffic State Prognosis | level of service, speed prognosis | JSON |
| Yearly average speeds | Yearly average speeds | JSON |

All data is accessible via a secure https REST interface. Authentication and authorization are implemented via OpenID Connect.

To access the data, interested organizations need to sign a license agreement with the distributor ASFINAG. A license fee applies that reflects on the cost of providing the real-time data interfaces, clearing services and SLA. The data itself is free of charge.

All data is listed on Austria's National Access Point mobilitaetsdaten.gv.at as requested by the ITS directive [9].

## 5 Application of EVIS.AT Traffic Data

EVIS.AT traffic data is being used in a variety of end-user applications but also for internal tools in traffic management.

Verkehrsauskunft Österreich (VAO) is providing white-label multimodal end-user applications as described in the introduction and implemented all EVIS.AT data as reference service. This means, that through the EVIS.AT and VAO eco system, public authorities are now able to push traffic messages and measures in about 30 apps and websites within minutes.

Internal tools of the various partners that implement EVIS.AT data and utilize it to optimize operation and traffic management include:

- **GIS and maps tools**: they are used for strategic planning but also for traffic management to get an overview of adjacent networks and traffic situations; see Fig. 1 for an example of ASFINAG's Maps application.
- **Winter service**: EVIS.AT data is used in winter service applications. In return, they feedback traffic information from winter services to EVIS directly, i.e. snow closures, avalanche warnings and the like.
- **Abnormal load management**: abnormal loads (width, height, weight) need to be admitted by road authorities who take traffic, road and weather conditions into consideration. These authorities now also use EVIS.AT data to better evaluate and assess the suitability of certain routes (i.e. constructions)
- **Operation planning and routing for emergency vehicles**: certain traffic conditions or regulations (i.e. closures) are taken into account for route planning

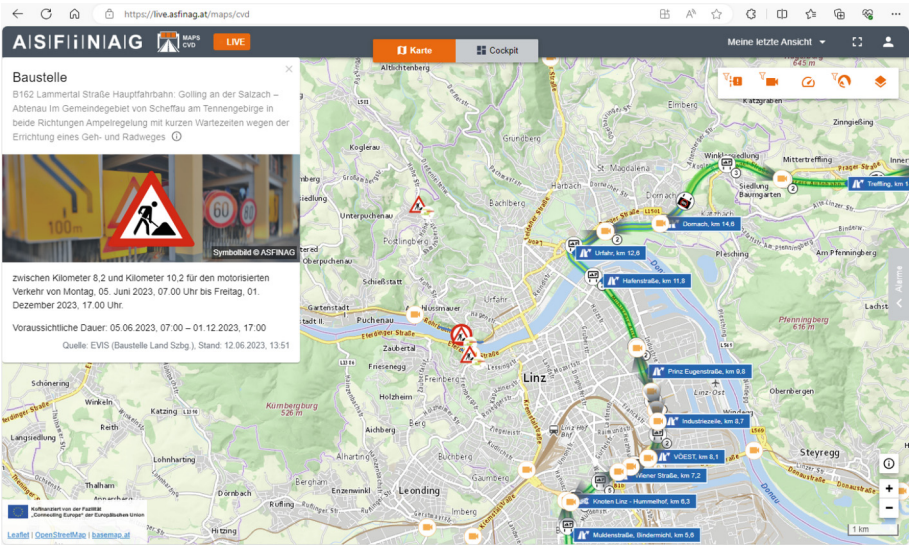



**Fig. 1.** Live.asfinag.at – ASFINAG's internal maps application for strategic traffic management and operations. EVIS.AT data of partners is implemented so that operators have an overview of the traffic information on adjacent networks. Reproduced with permission from ASFINAG, copyright ASFINAG, 2024.

Currently, there are also major efforts in place, to move towards Integrated Traffic Management in Austria to allow for policy making. Integrated Traffic Management is more than just integrating different data sources into a data hub. Main requirements are precise strategies and traffic management goals of politics and authorities as well as the legal delegation of traffic management duties to a capable platform that oversees the different networks and modes of transport. Additionally, the inclusion of several modes of transport, i.e. public transport and new mobility services will be included. In fall 2023, several projects on this topic were started by the major infrastructure and traffic information providers. The projects builds on EVIS.AT, VAO and other Austrian ITS platforms and datapools. Their main objective is to lay out a set up plan to introducing integrated traffic management in Austria.

The platform EVIS.AT will take on several roles in an "Integrated Traffic ´Management Austria": it will provide harmonized base data for KPIs and road traffic overview to be gathered by traffic operation centers; the consortium will serve as a platform for policymaking and strategic decisions of the road operators; EVIS.AT will also serve as data distribution hub to disseminate the policies and traffic regulations of operative ad hoc traffic management to various end user services.

## 6 Conclusion

We showed that EVIS.AT established a platform and legal framework that includes the motorway operator, federal states, cities, automobile club and police, addressing much-needed harmonization issues with respect to real-time traffic data for a whole country.

The novelty of the approach lies in the strong and legally binding cooperation of all major stakeholders beyond administrative borders and harmonization for a whole country. While most European countries have "national access points" in place, that allow data owners and administrations to list or publish their data, these data sets are hardly harmonized and come in an abundance of data formats, dialects, extensions, semantics, update characteristics and bundling. The data sets are also not complete for larger regions and therefor very hard to use in wider services.

The EVIS.AT partners agreed upon data formats, definitions, message types and minimum standards for message creation. The definition of processes focused on clear responsibilities, local know-how and individual implementation. The cooperation agreements ensure complete coverage for all of Austria.

EVIS.AT has become an important and established part auf Austria's ITS landscape, enabling administrations to publish data and generate end user and internal applications as well as third parties to use the real time traffic data in their services. The next step will be to utilize the platform for policymaking in the context of integrated traffic management – as data basis for road traffic as well as dissemination platform.

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# Enhancing Accessibility and Interoperability of Mobility Data: MobilityDCAT-AP, a Metadata Specification for Mobility Data Portals

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**Abstract.** This paper introduces a formal metadata specification for mobility data portals as an extension of DCAT-AP, called mobilityDCAT-AP. It addresses a scenario in which mobility data is offered on a data portal, and is intended to be found, assessed and reused by data users. Unlike in other domains, a structured and community-based metadata for the wider mobility domain has not been established yet. With such specification, an agreed usage of metadata among different portals; easier access to mobility data; improved interoperability in the mobility data ecosystem; and the leveraging of semantic technologies are envisioned. In addition, the Resource Description Framework (RDF) as a de-facto standard for metadata, is applied to model the metadata vocabulary. The paper elaborates on the overall goals, previous works on metadata specification and harmonisation, the working process, concrete deliverables and future prospects of mobilityDCAT-AP.

**Keywords:** Mobility Data · Data Portals · Metadata · National Access Points · Data Harmonisation · Data Interoperability

## 1 Introduction

### 1.1 Context and Motivation

How to make different data assets from different actors in the mobility system discoverable and accessible? This is the role of internet portals for mobility data which have been developed all over the world in recent years. These portals often have specific spatial or thematic coverage, e.g., providing public-transport timetable data for a specific region. In addition, legal obligations, such as those established through the European Union's National Access Points (NAPs) [1], mandate the creation and population of such portals.

This work aims at supporting potential data users during the discovery and assessment of data offerings in NAPs and other mobility-related data portals. Metadata can

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be particularly helpful in understanding the features and options of corresponding data, especially in complex and ever-changing ITS environments [2]. Thus, this work enables to describe data offerings via metadata, answering questions such as what data are offered, by whom they are published, what access conditions apply, etc. More specifically, the work structures and harmonises such descriptions in the form of a formal metadata specification called mobilityDCAT-AP. This specification provides precise and unambiguous metadata designations for any mobility related data offerings, facilitating harmonised, platform-independent metadata descriptions both in human-readable and machine-readable formats.

An important driver for such metadata specification is found in the context of interoperability. The mobility data ecosystem consists of different elements that complement and relate to each other. For example, a single data set may be bound to a single use case or a single region. To get a complete picture, multiple data sources from multiple portals may need to be combined. However, handling multiple data sources requires that the corresponding metadata are interoperable in terms of semantics and syntax. Interoperability depends on domain-specific metadata specifications or standards [3]. They aim to provide an agreed and uniform way of describing metadata, regardless of the metadata origin or user. They precise formal structures, vocabularies and agreements on their use. Another driver is the need for efficient ways of storing and sharing metadata, giving a key role to Resource Description Framework (RDF), which is also a prerequisite for Linked Data and Semantic Web concepts [4]. As a result, many of the established metadata standards and specifications are based on RDF.

This work has been carried out in the context of NAPCORE, an EU-cofunded Programme Support Action under the GRANT AGREEMENT No MOVE/B4/SUB/2020-123/SI2.852232 [5].

### 1.2 Previous Works

One well-known framework for defining metadata and specifications is the Data Catalog Vocabulary (DCAT), as an RDF vocabulary designed to describe data catalogues [6]. DCAT Application Profile (DCAT-AP) specifies DCAT as a basic profile for data portals in Europe to facilitate the aggregation, exchange, search and auto-mated processing of metadata [7]. DCAT-AP scope is cross-border and cross-domain, and thus further specified in different, domain-specific extensions like GeoDCAT-AP for spatial data [8] and StatDCAT-AP for statistical datasets [9]. In the field of mobility, some extensions such as TransportDCAT-AP in the domain of public transport, as created in the OASIS project [10], and spsDCAT-AP in the domain of Smart Parking Systems are based on DCAT-AP [11].

The Shift2Rail IP4 SPRINT project provided an automated solution for ingesting and harmonising metadata from selected NAPs to enable cross-border multimodal journey planning [12]. Similar work was carried out in the LOD-RoadTran18 project [13], which includes a specific metadata model to represent road-traffic information datasets. Both projects again rely on the DCAT-AP vocabulary.

Besides such DCAT-AP-based approaches, there are some proprietary metadata specifications, i.e., approaches based on proprietary metadata models and ontologies. The Coordinated Metadata Catalogue of the EU EIP project was a first common blueprint

for metadata structures for NAPs in Europe [14]. It defines a common minimum set of metadata, including descriptions, formatting constraints and obligation levels. However, these definitions are only available in a proprietary, human-readable format.

This review identifies some previous approaches to metadata specification and harmonisation. However, many of these have not been developed for the generic domain of mobility. Moreover, some seem to be at an experimental level, not ready for community-wide and long-term application. Finally, some did not fully address interoperability and conformance with semantic technologies via RDF. Therefore, the presented work is a first approach towards a domain-wide, application-ready and RDF-compliant metadata specification in the domain of mobility data. It adds the mobility domain to the DCAT-AP extension family, with an own extension called mobilityDCAT-AP.

## 2 Development of a Metadata Specification

### 2.1 Preparatory Works

As a starting point, the NAPCORE Metadata Working Group [5] defined a roadmap for the design, implementation and publication of the envisaged metadata specification. A first action was a detailed requirement analysis involving experts and mobility-data stakeholders [15]. Based on this, a conceptual model was developed, which translates the before-formulated requirements into a technology-independent data structure. We focused on essential information about a mobility data offering on a data portal, and analysed common practice in NAPs and other mobility portals, harmonisation exercises, and feedback from experts. Figure 1 shows an aggregated view of the essential aspects identified.

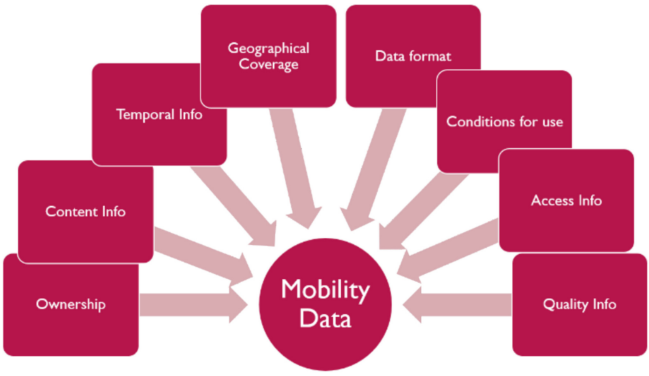



**Fig. 1.** Essential aspects of mobility data – Basis for the conceptual model of mobilityDCAT-AP

Such essential aspects were then disaggregated in much more detail, also considering mobility-related characteristics. For example, the aspect "Content info" was specified by the transport mode, the part of the transport network and other details covered by the data offering. The final conceptual model was developed iteratively in a tabular format, listing essential metadata elements including definitions, obligation levels, and usage notes.

### 2.2 RDF Vocabulary

The elements of the conceptual model were then mapped to corresponding RDF elements. RDF data representations are based on a data model architecture that includes classes and properties. As mobilityDCAT-AP is planned as an extension to DCAT-AP [7], the first step was to check if and how existing elements from the DCAT-AP vocabulary correspond to the elements of the conceptual model. In fact, many existing elements could be reused, although some definitions and usage notes had to be rewritten, and some obligation levels had to be changed. Further, additional classes and properties from other vocabularies were incorporated. For example, the quality description of a data offer, being an essential aspect to be provided via metadata, was considered by reusing the established Data Quality Vocabulary [16], which is another RDF vocabulary.

In cases where neither DCAT-AP nor any other known RDF vocabulary provided applicable elements, mobilityDCAT-AP added its own vocabulary elements. These additions aim at capturing some specific characteristics and features of mobility data. This is done by creating a separate namespace "mobilitydcatap:" and individual class/property declarations. Among other things, a property "mobilitydcatap:transportMode" has been introduced this way. MobilityDCAT-AP has also re-moved some optional properties from DCAT-AP. The reason for this is the rather broad scope of DCAT-AP, and the aim to keep the vocabulary size of mobilityDCAT-AP as compact as possible.

The final data model, comprising all RDF elements representing the conceptual model, was visualized as a Unified Modelling Language (UML) diagram. Figure 2 shows central classes from this diagram, and selected properties, as embedded within such classes.

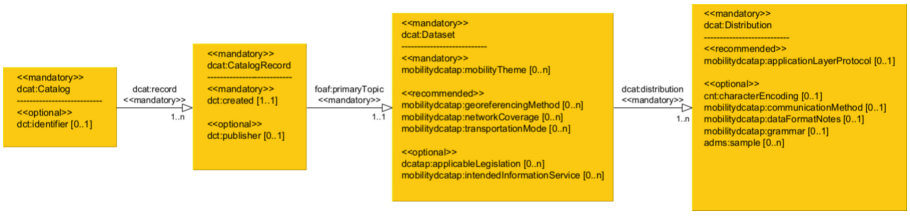



**Fig. 2.** UML Diagram of mobilityDCAT-AP

Accordingly, four central classes represent a hierarchical concept when describing metadata via mobilityDCAT-AP. Firstly, the Catalogue as such is described, i.e., being the metadata register in a data portal. Secondly, there is the Catalogue Record, which describes the metadata entry, including its publication date. Thirdly, the Dataset is described. In fact, most metadata elements are covered here, including the content theme; the spatial and temporal context; quality information and others. Finally, the distribution describes a technical and organisational way to access the Dataset. In addition to the data format (e.g., a machine-readable syntax standard), the licensing terms are described here. Some additional classes (not shown above) act to support these general classes.

Some of the vocabulary elements are restricted in such a way that the possible expressions of the vocabulary are bound to predefined value lists. Such value lists are stored under Controlled Vocabularies. For example, the Controlled Vocabulary of the above-mentioned property "mobilitydcatap:transportMode" contains the values "car, truck, bike, pedestrian, etc.". Such predefinitions aim at the unambiguous use of frequently used terms. In addition, Controlled Vocabularies are also expressed as RDF vocabularies and allow interoperable processing. For example, a Controlled Vocabulary could be provided in multi-lingual versions.

### 2.3 Documentation and User Support

There is online documentation of the mobilityDCAT-AP specification [17], including a human-readable vocabulary description; a set of usage notes; a set of machine-readable serialisation formats to allow IT systems process the vocabulary; and schemas for automated conformance validation. In addition, user support is provided via a dedicated GitHub repository where users can interact with the editors, for example by raising questions and issues.

Finally, there is an Accompanying Guideline that serves as a practical orientation for users of mobilityDCAT-AP. This includes additional explanations and examples for specific vocabulary elements; recommendations for metadata handling and exposure on individual IT systems; and advice on metadata quality and validation processes.

## 3 Outlook

Following its release in autumn 2023, this specification is promoted for wide-spread use in mobility data portals. Some NAPs are interested in implementing mobilityDCAT-AP in their systems as early adopters. The NAPCORE Metadata Group supports such adopters through direct support and feedback. In addition, the development of a cross-border metadata directory using mobilityDCAT-AP will be demonstrated as a proof-of-concept.

Lastly, a maintenance and governance organisation will take care of future versions of mobilityDCAT-AP. These versions will consider, among others: a refinement of class and property definitions; further precision of controlled vocabs; alignment with other DCAT-AP extensions; and the adoption of progress in the DCAT(-AP) super-specifications. Such maintenance and governance structures will ensure the long-term acceptance and sustainability of mobilityDCAT-AP, and ensure safeguards are in place for a responsible use of metadata in the mobility field. Lastly, efforts will be made to care about privacy to prevent and mitigate the risk of misuse, related to metadata exchange [18].

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# The PRESORT Project: Improving the Use of Third-Party Data by National Road Authorities

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**Abstract.** PRESORT is a research project funded by the Conference of European Directors of Roads (CEDR) through the CEDR Transnational Road Research Programme (Call 2022). The aim is to improve the use of third-party data by National Road Authorities (NRAs).

NRAs are seeing increasing levels of digitisation and are open to the potential opportunities through the utilisation of third-party data – that is, data aggregated from multiple sources – to support them in the delivery of their core business services in traffic management, asset management, and construction.

PRESORT will eventually deliver practical, implementable, easy to use online guide to support NRAs to make better decisions regarding HOW and WHEN to acquire and use third-party data, which will assist their core business activities.

The initial phase of this project involved capturing the current state of third-party data use by NRAs. Part of this phase explored the challenges and barriers NRAs face regarding use of third-party data through a literature review and engagement with data providers and crucially, the NRA end-users. This paper reports on the results of this engagement.

**Keywords:** Third-party data · Cooperative ITS · Road safety · Road user charging

## 1 Introduction and Development of Questionnaire About NRA Use of Third-Party Data

Third-party data is aggregated or collated by a provider not involved in the original collection of the data. The data is then provided to a National Road Authorities (NRA).

PRESORT completed a broad literature review to understand current use of third-party data by NRAs. Given the nature of the subject, the search was restricted to identifying evidence from recent years – with over 280 separate articles discovered. This

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literature review provided the background to an online questionnaire designed to engage key individuals from NRAs and third-party data providers.

Prior reporting highlighted data accessibility, data quality, data interoperability, legal matters such as GDPR considerations, and a general lack of the skills required to address these issues. There appears to be limited or no data flow between three data eco-systems in the transport system – cooperative ITS, data for road safety, and road user charging.

## 2 Questionnaire Respondents

A questionnaire was sent out to 79 targeted individuals working in NRAs or data providers, as well as to stakeholder representatives and independent experts. Participants were also encouraged to forward the questionnaire to others whom they deemed appropriate. A total of 34 individuals completed the questionnaire.

The questionnaire contained 24 questions related to the current and future use of third-party data by NRAs, the risks and challenges of using such data, and the preparedness of NRAs and their workers. This paper provides a report about the challenges and barriers to third-party data use by NRAs.

Questionnaire respondents reported they worked across 16 different countries or regions, as shown in Fig. 1, and many worked globally or across multiple countries. The majority (22) work either for or on behalf of an NRA, and most (30) reported their organisation used third-party data.

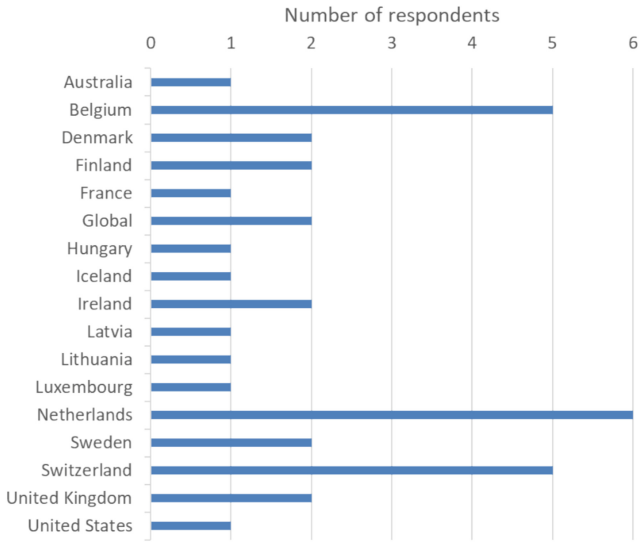



**Fig. 1.** Countries from which the questionnaire respondents operate.

## 3 Use of Third-Party Data by Questionnaire Respondents

Questionnaire respondents were also asked what type of third-party data they use. Their responses are summarised in Fig. 2, although it is worth noting this cannot be used as representative of the entire industry and only helps to qualify their other responses. However, it is a reflection of the types of third-party data that are available from data providers and partly a reflection of the previous demand for such data.

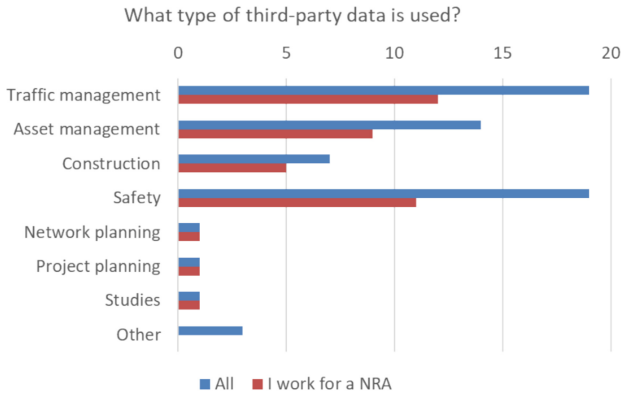



**Fig. 2.** The types of third-party data used by the questionnaire respondents.

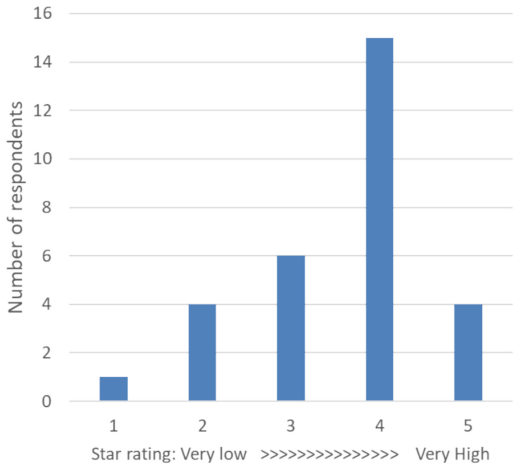



**Fig. 3.** Questionnaire respondents' estimation of their organisation's maturity level in using third party data.

The questionnaire also asked respondents to rate their organisation's maturity level in using third-party data. Generally, the respondents believed their organisation was mature

(as shown in Fig. 3, their data management systems were ready, and the people in their organisations have the skills to use third-party data.

## 4 Challenges and Barriers to Third-Party Data Use by NRAs

Participants were asked what challenges there are to using third-party data. They were given several options to tick as well as the option to identify additional issues. Table 1 summarises the challenges and barriers identified by participants and a description of the issues.

**Table 1.** Challenges and barriers to third-party data use by NRAs identified by questionnaire respondents.

| Challenge | Description |
|---|---|
| Privacy and security | GDPR (and similar) apply if the data has not been anonymised. Anonymisation is reversible for very small datasets or sections |
| Data sharing | Parties may be reluctant to share data or have little incentive to share |
| Practical applications | A common issue is the existence of seemingly useful third-party data without a specific application. A solution in search of a problem |
| Incompatible data formats | This may result either from the data type, or from the method used to collect it, for example different timeslots, leading to the need for interpolation |
| Data maintenance | Use of third-party data relies on the third-party, with no control over its consistency or indeed continued availability |
| Trust | Many respondents identified trust in third-party data's integrity and continuity as possible issues |
| User skills and training | Extra training will take time and resources away from the main functions of NRA.<br>Extra recruitment may be needed |
| Business models | Building the business case for the use of third-party data and investment needed to enable the use of third-party data |
| NRA culture | Uptake of new ideas can depend upon the culture within the organisation. The need for extra data may not be obvious to the relevant decision-makers |
| Data use restrictions | NRAs may want to re-use or re-purpose the data for other needs. Often there are restrictions on such activities |

As can be seen in Fig. 4, *Privacy or security* was the most selected issue by respondents, although the small questionnaire sample size and characteristics of the respondents does not make this a quantifiable finding. Notably, the results of this question highlight the broad range of challenges to the use of third-party data for NRAs. Participants took

the opportunity to highlight issues related to business models, NRA culture, and data use restrictions.

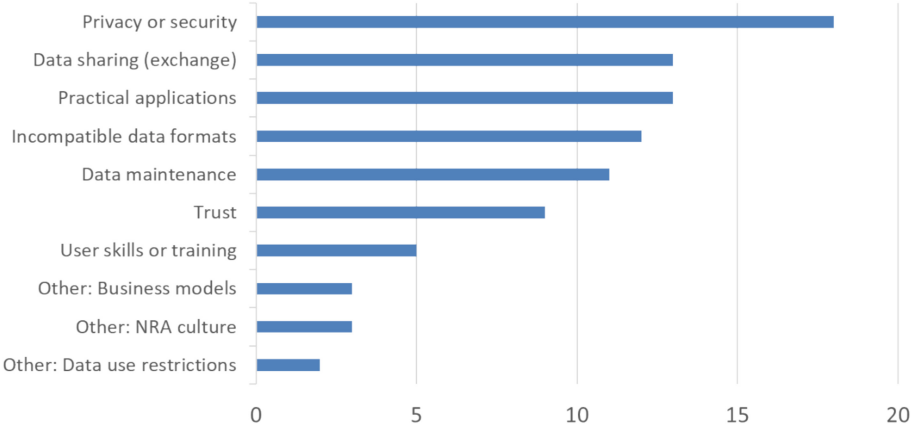



**Fig. 4.** Histogram showing the challenges to third-party data use selected by questionnaire respondents.

## 5 Scale of NRA Third-Party Data Usage

A wide variety of national and international bodies have drawn up strategies and roadmaps for the coordination, promotion, and implementation of digital roads including the use of third-party data. For instance, the EU Data Strategy [1] includes the creation of common European data spaces in key sectors, including mobility. Data spaces bring together the governance and infrastructure to facilitate the pooling and sharing of data in a controlled and secure way. The first stage involves gathering and coordinating all data already available. The creation of NAPs (National Access Points) is a key part of the strategy. More aspects of this strategy, including the relevant actions, are detailed on the site *EU Transport – Road* web page [2].

Some notable strategies include:

- The national vehicle authority in the Netherlands, RDW, have a three-pillar strategy [3]: innovation based on continuity; customised service, and collaboration in networks. This includes regard of ICT and connected and autonomous vehicles.
- In Germany die Bundersregierung Strategy for Automated and Connected Driving [4] has objectives specific to connectivity. These are to remain a lead provider, to become a lead market, and to implement connectivity on the road network.
- Belgium has separate strategies for Flanders and Wallonia.
- In the UK, National Highways' Digital Roads Strategy [5], involving construction and asset management and operation of the Strategic Roads Network (SRN) was announced in 2020. This includes the delivery of *Digital Roads 2025*, the relevant sections of which are *Single view of the network*, *Every customer has an option (ECHO)*, and *Enabling a connected and autonomous future*.

– EU-wide, the Network-Wide Road Safety Assessment Methodology [6] sets out the method to ascertain road network rating and ranking for all strategic roads throughout, specifying what data needs to be collected.
– The EU-wide initiative Data For Road Safety [7] (DFRS) provides the dissemination of live information throughout the European Union and the UK.

There are also cross-border initiatives such as the C-Roads Platform [8] that may involve the use or third-party data. The C-Roads Platform brings authorities and operators together to harmonise the deployment of C-ITS across Europe. Objectives include the effective exchange of data.

## 6 Conclusion

Individuals working in relevant positions have highlighted a broad range of challenges to the use of third-party data by NRAs, which warrant further detailed exploration and documentation.

PRESORT will carry out consultations and workshops with stakeholders (NRAs and third-party suppliers) to explore data needs and use cases, as well as generating interest in data sharing between the C-ITS, data for road safety, and the road user charging data ecosystems. It will also identify the key technical, commercial, legal, and organisational challenges of NRAs and third-party data service providers with regards to acquisition, use, and maintenance of third-party data.

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# Cross-Border Data Exchange to Improve Traffic Management and End-User Information Services in Central Europe

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**Abstract.** In the European vision of a free movement of people and goods, it is obvious that traffic management strategies must not be limited to national borders. Due to the fact that Austria is a small country within an important transit area it is necessary to have a close cooperation with the neighbouring countries. Data is an important basis for modern traffic management, and it became apparent that motorway operators already have many relevant management strategies available. Therefore, ASFINAG has ever since pursued the coordination and harmonisation of Member-State specific approaches, on at technical and organisational level, by aligning topics such as traffic information and management at cross-border level.

The ASFINAG solutions are in principle quite easy with mainly list views beside map based information delivered. Therefore similar operators might have no problems in establishing a similar service at low costs as well as in short term. However the content delivering backend systems need to be at hand in order to fuel the customer service.

**Keyword:** Cross-Border · Data exchange · End-user services

## 1 Motivation

Traffic and transport across main corridor routes hold great potential for substantial improvements in efficiency and fluency. With that however come risks of disturbances, either on regular (e.g. holiday traffic congestions) or exceptional basis (e.g. heavy weather conditions).

Especially during the last years, additional draw backs have been experienced due to increased cross-border waiting times, related to control procedures in conjunction with applicable COVID-19-regulations. This is a possible risk for commuters and truck drivers, who have to cross borders on a regular basis – often several times a day. Beyond that, situations such as increased traffic during holiday seasons or harsh weather events, although more predictable, can quickly lead to major delays, accidents and frustrated road-users.

In the past, activities from the involved ministries, police and operators were often focussed on quickly restoring traffic flow. This was merely about combating the symptoms but not properly addressing the core of the problem, which was a lack in cross-border coordination and appropriate access to data and information. As transport is not

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ending at organisational borders, it is all the more important to draw the links to adjacent urban areas here. While acknowledging the efforts of the previous years, the need for further development of common initiatives reaching beyond borders is still present in order to include real-time events and information that could reach drivers, commuters, HGV drivers or tourists equally.

## 2 Objectives

As for tourist travelling seasons, there are lot of travellers going from the Northern part of Europe to the seaside in Italy, Croatia and Slovenia during the summer period. To coordinate the mass of traffic going through Austria it is necessary to have a close cooperation between all affected road operators. First TMPs (traffic management plans) for the summer season were already agreed in past years between Italy, Croatia, Austria, Hungary and Slovenia. But it is important to continue this cooperation and to develop additional cross-border TMPs to handle the traffic during the summer period.

The most pressing issues are ongoing coordination and harmonisation on technical and organisational level in line with European legislation. In this way operators and service providers can draw from improved access to data and offer the best possible services to end users. Due to different stakeholders (public/private motorway operators, public authorities, other infrastructure/logistics operators) being responsible for their respective infrastructure segments, a special focus must be on addressing and harmonising the link between high-level corridors and adjacent infrastructure (urban areas, ports, etc.).

## 3 Data Collection

The cross-border data exchange focus on provision of EU-wide real-time traffic information related to priority action b), on provision of traffic data related to priority actions c), on the provision of information services for safe and secure parking places for trucks and commercial vehicles related to priority action e) and on the provision of multi-modal traveller information related to priority action a) of the ITS Directive (2010/40/EU). The partners are heavily committed to a corridor-based approach and the coordination necessary to ensure long-term relevance and high quality.

Due to the efforts in terms of data exchange and DATEX II profiling, a solid basis has already existed. All the more important it was to focus on the details, e.g. parameters to consider when describing a detected event, the process of detour selection as well as exact and harmonised location referencing.

## 4 ASFINAG B2C Solutions Towards Requirements of ITS Directive

### 4.1 ASFINAG Smartphone App

In 08/2011 the first version of the ASFINAG Smartphone Application “Unterwegs” was introduced in the Apple App Store and the Android Play Store (by 2021 a Huawei version was established). Since then a professional ITSM/ ITIL based process management was

established to manage the lifecycle of the product leading to an ongoing improvement of the product and the provided information. Because it is now more than ten years old, a general upgrade of this smartphone app was necessary. The new ASFINAG app contains up-to-date information on traffic and road conditions on the Austrian motorway network according the requirements of the ITS Directive. Following main features are available with the new smartphone application (Fig. 1):

- **Personalised homescreen** - a personalised homescreen by adding personal destinations, routes, or webcams.
- **Webcams** - Access to over 1800 live webcam images along with the motorway network including the webcams of the neighbouring countries.
- **Traffic information** - overview of all events and road works along with the motorway network including a push-message function for personalised routes
- **Rest areas** - Overview of all rest areas along with the motorway network including the rest areas of the neighbouring countries.
- **E-Charging station** – Overview of charging stations for electric cars in Austria
- **All about tolls** - purchase of digital vignette or digital route toll via the ASFINAG toll shop, Austria-wide overview of all vignette and GO-Box sales points.
- **Planning & Navigating** - Intermodal Route Planner (Central Europe-wide) with the help of Traffic Information Austria
- **Languages** - ASFINAG App is available in 12 languages

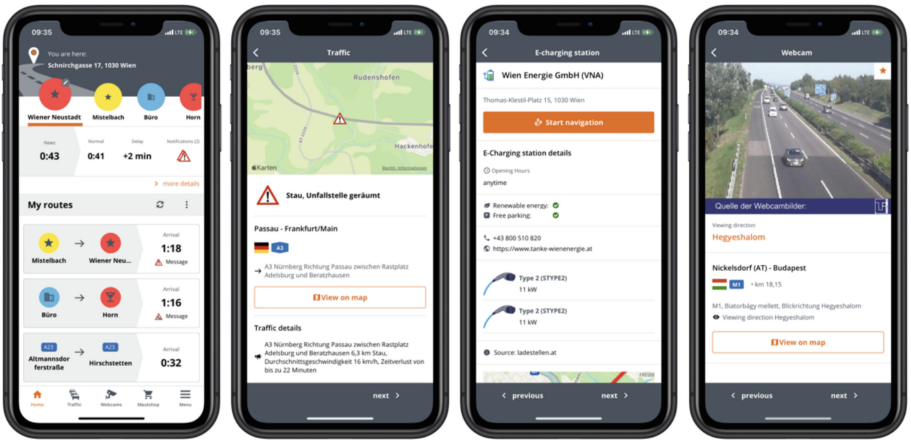



**Fig. 1.** ASFINAG Smartphone App (https://www.asfinag.at/asfinag-app/)

## 4.2 ASFINAG Website

The ASFINAG website provides information by means of maps widgets. The focus is on the needs towards requirements of ITS Directive (incl. E-Charging points) and information from neighbouring countries (e.g. Webcams, rest areas, traffic messages…). The update cycle takes place in four regular updates per year and is regularly extended to include data from neighbouring countries (Fig. 2).




**Fig. 2.** Rest Areas (https://www.asfinag.at/parken-rasten/rastanlagensuche/)

### 4.3 Common Cross-Border TMP Tool

Together with DATEX II and the exchange of event information, that is relevant for road conditions in neighbouring countries, the digitalisation of traffic management plans (TMPs) has become one essential achievement in terms of harmonised cross-border traffic management pursued in Austria.

Although a mature status on TMPs on national level has already existed, a connection on transnational level was needed. Besides the obvious language barriers, missing automatisms and a unified way of displaying information (both internally and to drivers) were major obstacles when updating existing TMPs or adding new ones.

Therefore, operators from Austria, Croatia, Hungary, Italy and Slovenia have established a common process for this coordination of TMPs. In order to properly present the information from those neighbouring motorway operators, Slovenian motorway operator DARS conceived an interactive road map and integrated it into its central system for displaying and entering traffic information throughout the entire Slovenian road network. The system was built in a centralised way, allowing to enter and review information for all Slovenian (and neighbouring countries') roads from a single tool.

The TMP application consist of an interactive map, where users can see TMPs and active events for the CROCODILE corridor region.

Events can be added if the section is covered by a TMP and then add according information, e.g. type of event and duration. For already existing events, all involved parties will receive a notification and are also able to select TMPs and rerouting strategies. For every event only one strategy can be selected. Parties not involved in the certain plan or strategy can view them, but not select or edit (Fig. 3).

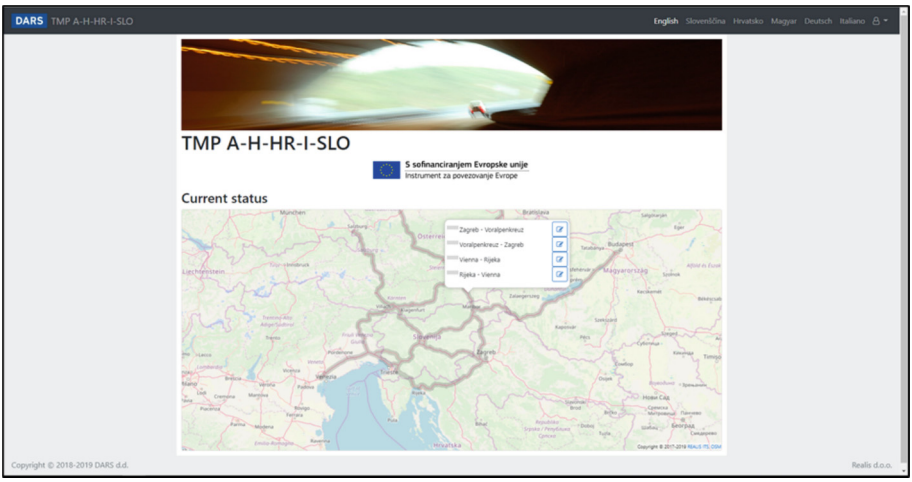



**Fig. 3.** Common TMP tool (https://tmp.dars.si/tmp/app/default)

## 5 Results and Evaluation

As Austria is situated in the heart of Europe, special challenges arise to the transportation network as:

- High percentage of foreign drivers (especially during holiday seasons)
- High percentage of the Austrian motorway classified as critical infrastructure in terms of road safety. The total length of the network is per 2020: 2.249 km; 400 km of the network is situated in tunnels (166 tunnels). In addition 5.818 bridges are located on the Austrian motorway network.
- Due to topographical reasons in some areas are only limited rerouting possibilities.

The ASFINAG solutions are in principle quite easy with mainly list views beside map based information delivered. Therefore similar operators might have no problems in establishing a similar service at low costs as well as in short term. However the content delivering backend systems (in Austria's case e.g. webcam system, roadworks management tool, event database or the Austrian wide route planner) need to be at hand in order to fuel the customer service.

Major findings of the provision of ASFINAG end user services (since beginning in 2011):

- Transparency: delivering real time information pushes the level of data transparency (of course not necessarily bad). With that increase, customers will raise data and service issues, additional ideas and wishes as well as difficulties they experience. Service providers need to be prepared for a high volume of customer contacts in order to satisfy the customers.
- Multilingualism: the provision of the ASFINAG App (now in 12 languages) resulted in reduced flexibility when adding new features as a translation agency has to be consulted for each change request. Additional costs - beside initial costs – for each change are also o be calculated. But the overall feedback show positive response by customers using the service in their preferred language.

## 6 Conclusions

The past years have shown that cooperation is important to find common solutions. Especially since traffic does not end at organisational borders.

While acknowledging the efforts, the need for further collaboration beyond borders is ever more present. The most pressing issues in this regard are the ongoing coordination and harmonisation at technical and organisational level in accordance with European legislation. In this way operators and service providers can draw from improved access to data and offer the best possible services to end users. Due to different stakeholders (public/private motorway operators, public authorities, other infrastructure) being responsible for their respective infrastructure segments, a special focus must be put on addressing and harmonising the link between high-level corridors and the adjacent transport network (urban areas, secondary road network, multi-modal nodes etc.).

Other issues include the harmonised implementation of the ITS Directive and its supplementing Delegated Regulations. While basic principles are set out as mandatory provisions, the technical and organisational details often remain unclear and subject to Member-State-specific approaches. To ensure a common European and corridor-based strategy, it is essential to further foster the alignment of the previously mentioned topics such as DATEX II profiles as well as traffic information and management at cross-border level. This approach has been successful in the past and should be pursued further for sustainable and long-term corridor benefits.

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# AI-Assisted Services for Content Acquisition and Creation Interlinking in Transport Research

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**Abstract.** This paper presents the gateway of the domain-specific Knowledge Graph (KG), which was built based on related data sources and by exploiting the OpenAIRE ecosystem and EOSC services. These enabled it to offer services for integrated KG smart browsing based on impact and reproducibility using AI by also serving several categories of stakeholders. Following the current trends and stakeholders' needs, the areas of highest interest were identified and gaps in data and knowledge were also detected. On top of that knowledge space, transport research-inspired information retrieval scenarios were implemented by tuning the use of individual AI-assisted services or combinations of them. More specifically, scenarios were built around different use case directions including reproducibility/reusability reports for publications and/or datasets in the transport research sector which were automatically identified and they included information about the ease to reproduce/reuse them and the extent to which the work has already been reproduced by meta-analysis studies.

**Keywords:** Knowledge Graph · OpenAIRE · Reproducibility · Data sets · Software PoCs · Open Science

## 1 Introduction

Transportation research sector involves different modes of transport (i.e., road, rail, water, air, cross-modal) and different types of mobility (i.e., passenger and freight) producing innovation uptakes that could enable users and societies to be better informed and make safer, more coordinated and 'smarter' use of transport systems. More specifically, information processing is combined with engineering studies, technologies and human sciences producing research data span multiple domains (e.g., algorithms, software Proof of Concepts (PoCs), methods for technological impact, user acceptance, inputs to draft standards and regulations of newly introduced technologies, etc.). In addition, several domain-specific knowledge bases (i.e., TRID, ERTRAC, ERTICO, ECTRI, IRU, WEGEMT, EASA, ERRAC) are exploited to enhance scientific quality, identify remarkable knowledge and share research activities across national boundaries.

In this context, a domain-specific Knowledge Graph (KG) developed by relying on related data sources and exploiting the OpenAIRE ecosystem and EOSC services. These

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enabled it to offer services for integrated KG smart browsing based on impact and reproducibility using AI by also serving several categories of stakeholders (i.e., researchers, developers, regulators). The areas of highest interest were identified and gaps in data and knowledge were also detected. On top of that knowledge space, transport research-inspired information retrieval scenarios were implemented by tuning the use of individual AI-assisted services or combinations of them. More specifically, scenarios were built around different use case directions including reproducibility/reusability re-ports for publications and/or datasets in the transport research sector which were automatically identified, and they included information about the ease to reproduce/reuse them and the extent to which the work has already been reproduced by meta-analysis studies.

The remainder of this paper is organized as follows: Sect. 2 provides an overview of the key developments and trends in the field of knowledge graphs up to the present day. The followed domain-specific Knowledge Graph in the context of transport research and the derived results of its implementation are presented in Sect. 3. Finally, in Sect. 4 conclusions are drawn and pointers for future research are provided.

## 2 Literature Review

Knowledge graphs have emerged as a fundamental tool for organizing and representing structured knowledge in a graph-based format (Hogan et al., 2021). They have gained significant attention in recent years due to their wide-ranging applications in various domains, including natural language processing, data integration, semantic web, recommendation systems, and artificial intelligence (Chen et al., 2020). The concept of knowledge graphs can be traced back to early AI research, but it gained substantial traction with the advent of the Semantic Web initiative (Chaudhri et al., 2022). Researchers recognized the need for a standardized, machine-readable representation of knowledge to enable machines to understand and reason about information on the web.

The key components of Knowledge Graphs (KG) involve nodes and edges with semantics underlying, and they could be represented as Resource Description Framework (RDF) or Web Ontology Language (OWL). The KGs consist of nodes representing entities (e.g., people, places, concepts) and edges representing relationships between these entities (Hamilton et al., 2018). This graph-based structure allows for the representation of complex relationships and hierarchical information. In addition, the RDF and the OWL (Gutiérrez and Sequeda, 2021) are commonly used formalisms for representing knowledge in a structured and machine-readable way. RDF provides a simple, flexible format for expressing subject-predicate-object, while OWL allows for more complex ontology modeling.

The application of KGs varies as they could be used in (i) semantic search (Li, 2017) allowing users to retrieve relevant information and answer complex queries, (ii) in recommendation systems (Dongliang et al., 2022) to help in understanding user preferences and item attributes, (iii) in question answering (Chakraborty et al., 2021) for extracting relevant information from vast knowledge bases to provide concise answers to user queries, and (iv) in natural language processing (He et al., 2022) for entity recognition, sentiment analysis, and text summarization by incorporating semantic context.

In recent years, several techniques have been developed to learn continuous vector representations of entities and relationships in knowledge graphs, enabling better

reasoning and link prediction (Ali et al., 2021). Moreover, large-scale KGs (such as Wikidata and Google Graph) created and offer vast, interconnected knowledge bases covering a wide range of domains. KGs also integrated with Graph Neural Networks (GNNs) to improve the performance in various applications, such as entity linking, node classification, and recommendation (Park et al., 2019). Finally, KGs are used to provide explanations for AI decision-making processes, increasing transparency and trust in AI systems (Lecue, 2020).

## 3 Knowledge Graph in Transport Research

### 3.1 Knowledge Graph Structure

The KG consist of five entities, i.e., 1) Results that represent the outcomes of research activities, 2) Data Sources that are the sources from which the metadata of graph objects are collected, 3) Organizations that correspond to companies, research institutions, and public authorities involved in projects, 4) Projects that are research project, and 5) Communities that are groups of people with a common research intent, such as the Transport Research Community. Furthermore, the OpenAIRE research graph is utilized to develop various services offered to three distinct categories of organizations within the Transport Research Community. These categories are: 1) Content Providers, 2) Research Organizations, and 3) Public Authorities.

Regarding Content Providers, OpenAIRE offers validator services to automatically verify compliance of exported records with set guidelines. Additionally, full-text mining algorithms utilize the full-texts of Open Access publications to enhance metadata records by linking them to projects, publications, datasets, software, organizations, research infrastructures, and terms from standard classification schemes. For Research Organizations, the services aim to support the adoption of Open Science publishing practices and monitor the implementation of Open Science practices by their researchers. In cases where an official Open Access repository is unavailable, any organization can easily create a dedicated community and encourage affiliated researchers to deposit their research outputs there. Within the user interface, users can access content reports and project lists. The content report provides information about the research outcomes associated with the organizations, while the project list outlines the projects the organization is involved in and their respective research outcomes. Lastly, Public Authorities, such as national and international research funding organizations, can access services to monitor the impact of their funding within the Transport research community.

The gateway for the Transport Community is provided in the https://beopen.openaire.eu/ focusing on promoting territorial and cross border cooperation and contributing to the optimization of open science in transport research. Integrating the described services and leveraging the OpenAIRE Graph, the Transportation Research community benefits from enhanced publication deposits and tools for in-depth exploration.

### 3.2 Results

The studied scenarios of transport research sector following the aforementioned gateway of the OpenAIRE, and the derived results are presented below.

(i) The first scenario studies the use case of researchers that are interested in replicating experiments and verify algorithm's performances on benchmark datasets utilizing open access algorithms/software. Therefore, the developed KG offers a **benchmark reproducibility report of algorithms/software** (Fig. 1) that addresses complex logistics problems by specifying "open access" in the Access category and using as keywords "optimization", "algorithms" and "logistics". Further results with closed access are also found and could be presented by altering our research.

(ii) The second scenario studies the use case of datasets that used for optimization purposes in the logistics sector. The developed KG offers a **benchmark datasets report** (Fig. 2) that used to assess algorithms performance by utilizing the keyword "optimization". This keyword is used by the KG to deliver relevant research data sets as it is specified in the Type category selecting "research data". The results are referring only to the open ones as "open access" was selected in the Access category.

(iii) The third scenario studies the use case of generalization, retrieving information about research publications that study "automation" in different transportation domains. The developed KG offers a **generalization report of publications** (Fig. 3) including information on studies and experiments, such as how an algorithm's performance varies with problem conditions or complexity. The keyword "automation" is utilized for searching the KG and open results are presented as "open access" is selected in the Access category.

*Figure 1 reproduced from the* https://beopen.openaire.eu/*, developed within the BE OPEN and SCILAKE projects.*

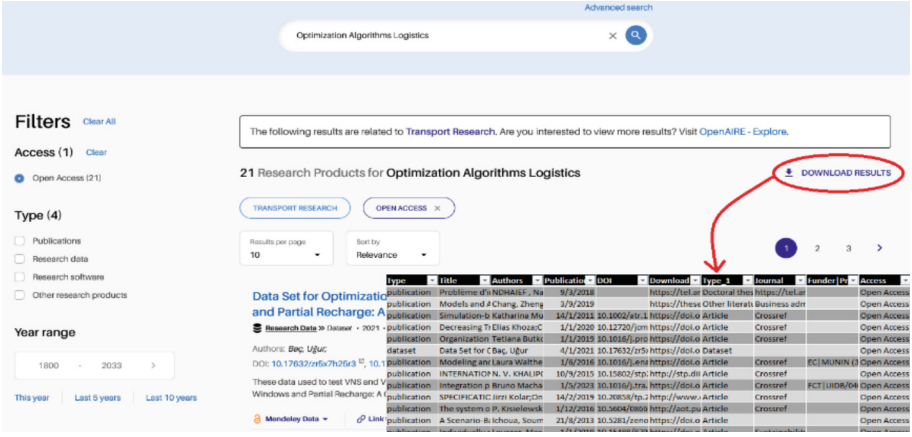



**Fig. 1.** Benchmark reproducibility report.

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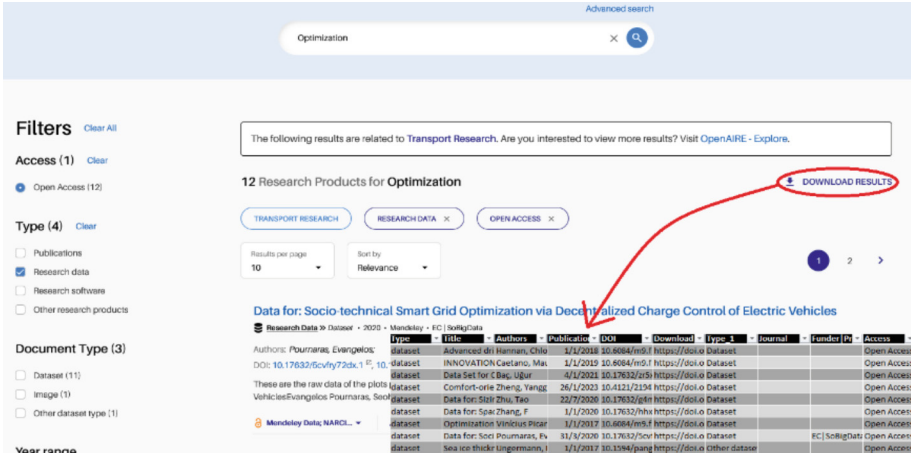



**Fig. 2.** Benchmark datasets report.

*Figure 3 reproduced from the* https://beopen.openaire.eu/*, developed within the BE OPEN and SCILAKE projects.*

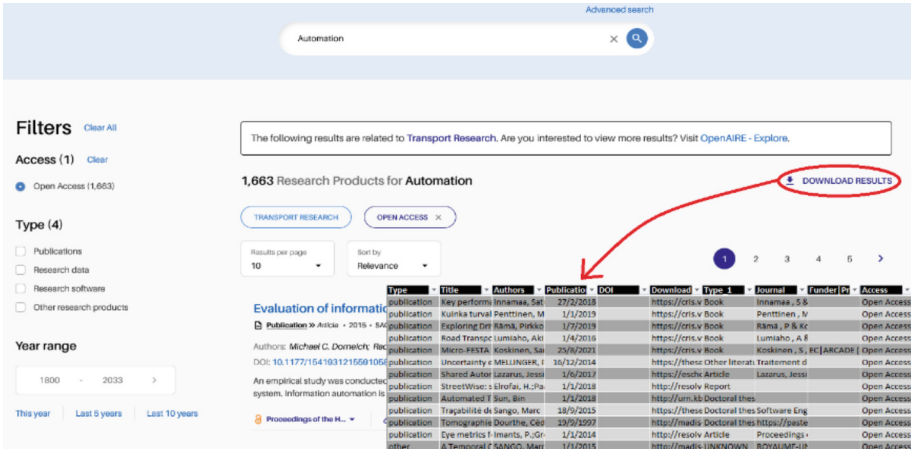



**Fig. 3.** Generalization report of publications.

### 3.3 Next Steps

The developed AI-assisted services could be further enhanced by allowing algorithms comparisons and reproducibility to demonstrate improvements of new algorithms. This should include the code for the baseline algorithms, configuration settings, and clear instructions for conducting fair comparisons in order to enable others to verify the reported performance gains. In addition, parameter tuning is another future step for improvement. Optimization algorithms often have hyperparameters that significantly impact their performance. Thus, reproducibility reports that can outline the process of

hyperparameter tuning, including the range of values tested, the criteria for selecting the best configuration, and the scripts used for this purpose could contribute to the advancement of knowledge and the development of more robust optimization algorithms.

## 4 Conclusions and Future Research

AI-assisted services in the transport research sector introduced to promote science and foster collaboration among research community and other relevant stakeholders. Towards this direction, this paper presents and analyses the services of the gateway for the Transport Community that exploits OpenAIRE Graph. According to the derived results, an open and sustainable scholarly communication is established monitoring and providing all research outcomes in the transport research sector. The presented scenarios and future steps reflect a commitment to advancing research in the sector and optimizing algorithm performance, with a strong emphasis on open-access resources and reproducibility. Consideration is also given on future research and directions are drawn. Ethical and legal considerations should be examined related to AI-assisted services and open access initiatives by exploring issues such as data privacy, intellectual property, and responsible AI deployment in scholarly communication.

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# MBSE Approach for Railway Digital Continuity

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**Abstract.** Railway systems are known as Safety Critical Systems (SCSs). In this kind of system, safety measures derived from the dysfunctional analysis used to be expressed in an informal way. This latter has several gaps in the context of the one going numeric transition: in the early phase of SCSs design, there is a need to link these safety measures to main safety goals. A first step provides a knowledge structure, where the considered knowledge is composed by a set of data and a set of engineering rules. These rules, including safety measures, correspond to a knowhow built through information sharing between actors during previous industrial system life-cycle. From this structured knowledge, models using main concepts can be designed. As concepts come from ontology, the system models are naturally high-level ones and directly linked to the source needs. Indeed, source needs are expressed on the basis of the structuring concepts of the ontology. Obviously, obtained models are abstractions of the real systems. Model based system engineering (MBSE) allows a systematic reasoning and tooled conformance checking and it is possible to assign a meaning to measured data during the whole life cycle of the railway system. A fundamental assumption is the validity of models used during this life cycle. As an abstraction is a partial point of view, the relevance of this partiality must be monitored during the system life cycle in order to avoid ambiguous interpretations. In this paper, the semantic interoperability is tackled to avoid ambiguities and to ensure the railway digital continuity.

**Keywords:** MBSE · Digital Continuity · Railway · Ontologies · Safety

## 1 Introduction

Railway system's design, operation and maintenance require the involvement of several stakeholders such as system engineers, safety engineers, railway experts etc. Indeed, in the system design phases, actors and needs are raised and requirement engineers identify functional requirements, their allocation to stakeholders, flows and interfaces between physical objects. Each phase of the system development involves multi-disciplinary experts that share heterogeneous data and collaborate without an unambiguous terminological guide about exchanged concepts. Actual practices are mainly based on sharing specification and documents in textual form in order to communicate about system

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related choices. Furthermore, models are built independently and refers to different levels of Model-Driven Architecture (MDA), such as Computational Independent Model (CIM), Platform Independent Model (PIM) and Platform Specific Model (PSM) [1]. In the railway domain, different tools are used for each phase of the development process from the industrial needs specification to the prototype implementation. These tools does not generally allow a digital continuity in the information, model or data life-cycle. In order to ensure models traceability and to facilitate the communication between stakeholders, Model-Based System Engineering (MBSE) approaches are adopted in critical systems development, like railway systems [2]. These approaches allow a robust documentation of models and improve their reuse in different contexts. Nevertheless, MBSE does not allow to deal with semantic heterogeneity and to share a common terminology during the whole system development process. From this context, the following Research Question (RQ) is identified: How to ensure semantic interoperability in such multidisciplinary ecosystem, like the railway domain?

In this paper, we introduce a MBSE approach which is able to help decision making and to have an efficient collaboration between actors. This approach is based on the integration of ontology as a structured and shared representation which is maintainable during the system life-cycle [3]. This knowledge representation has been widely used in order to disambiguate different domains. In the next section, the articulation between knowledge engineering and system engineering is introduced with the aim to meet railway issues.

## 2 The Proposed Approach

The proposed approach is illustrated by Fig. 1. It is based on three domains of interest:

1. Knowledge engineering,
2. System engineering and
3. Deployment.

This approach is structured in a top-down way from the abstract level which represents the need's specification until the implementation level. Knowledge structuring using ontologies is proposed as a crucial step in the system development, especially in complex operational activities related to system performance evaluation. Indeed, an ontology is defined as "a formal, explicit specification of a shared conceptualisation" [4]. It is considered as the basis of the whole process since it disambiguates the domain terminology and provides a common and shared representation between all stakeholders.

A domain ontology is formalised using the Web Ontology Language (OWL) and represents CIM level which is crucial to represent the domain view. In order to fulfil the critical needs of railway systems and to federate the railway data models representing heterogeneous subsystems of the railway infrastructure, an upper ontology, Unified Foundational Ontology (UFO) [5], is used. Upper ontologies provide foundational concepts and relations and their definition, such as space, process, situation, etc. [6]. Domain ontologies that are grounding in upper ontologies are more reusable since this practice facilitates the semantic alignment between heterogeneous knowledge domains. Conceptual models are considered as lightweight ontologies represented in Unified Modeling

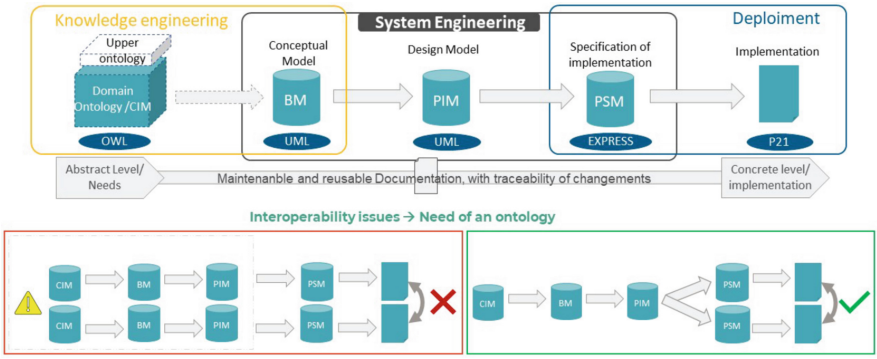



**Fig. 1.** The proposed MBSE approach for railway digital continuity

Language (UML) [7] and are a common part of both knowledge and system engineering. They are also used to be Business Models (BM) which represent the most pertinent concepts of the domain.

Using MBSE foundations, model-driven approaches and related standards, the conceptual model is then extended and refined in design model (PIM) to represent system features and attributes. Design models include several system properties as design constraints in the system architecture models for example. Therefore, these models are transformed into PSM to provide models in a specific language/format. At this level, the implementation/serialisation is performed to have a concrete prototype.

The whole process is supported by a documentation process which is required to maintain and manage changes traceability during the system design. Furthermore, the key aspect of this approach is the digital continuity between all system design phases since the ontology is the essence of the common semantic interpretation. This methodology is as generic as possible to ensure semantic interoperability in the design of the railway system assets. In the next section, the validation of this MBSE approach in the railway domain is presented.

## 3 The Approach Application and Validation

In previous work, an ontological approach was proposed with the aim to integrate dysfunctional analysis into the system design process of railway systems [8]. Then, this approach is illustrated and validated by real railway accidents. The key contribution of this approach is to ensure a semantic link between the safety measures and safety requirements in the railway system. This approach helps the safety-decisions making process and enhances the collaboration and communication.

Several initiatives have been developed as railway reference models that represent the infrastructure, such as Rail System Model (RSM) [9], IFC Rail[1] and EULYNX[2] that are built independently in UML. However, there is a digital discontinuity and a lack of

[1] https://www.buildingsmart.org/standards/rooms/railway/ifc-rail-project/.
[2] https://www.eulynx.eu/.

interoperability between these standards. The proposed MBSE approach is successfully used to deal with this semantic heterogeneity and to ensure digital continuity between the railway ontology and the system architecture. The developed railway domain ontology aims to avoid semantic ambiguities of railway concepts, such as Track, Signaling, Energy and Telecom and relations between them [10]. Then, this railway ontology is used to help decisions making in maintenance activities.

In order to ensure the digital continuity in the development of new systems with high performance, the proposed approach is validated and applied in the autonomous train development, namely the Autonomous Train Map (ATM) subsystem [11]. An ontology was developed in order to represent the ATM concepts and relations. Then, conceptual and design models were built, transformed in PSM and then serialised in code to be integrated in the final system.

## 4 Conclusions and Perspectives

The proposed top-down approach has powerful and generic capabilities to be applied in different fields and use-cases for the whole life-cycle phases from the design to operation and maintenance of systems. In the railway domain, this approach is used to ensure digital continuity. Indeed, the ontology layer is integrated as a knowledge basis to establish the semantic interoperability between railway actors. This MBSE approach improves collaboration and helps decisions-making process during the system life-cycle. It has been widely used and validated in the autonomous train development process and to ensure digital continuity in the railway domain.

In future work, we intend to adapt this approach for the development of railway digital twins (DT) with the integration of a digital representation layer, such as Building Information Modelling (BIM) [12]. Therefore, the integration of ontologies, Machine Learning (ML) algorithms and BIM in the DT development for the railway domain should meet scientific and industrial challenges related to data interoperability and integrity regarding the multiplicity of data sources. Finally, we plan to validate it by real use cases of predictive maintenance of track components using its BIM models.

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# Effect of Different Weather Elements on the Delay Prediction of Trains

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**Abstract.** Estimation of train delays is crucial for customer information. One cause of the train delays can be easily blamed on the weather. The effect of weather on signaling and dispatching can be indirectly articulated from the arrival and departure delays at the stations. The study uses Norwegian delay data from 2021, 2022 and parts of 2023. This data contains scheduled and actual departure and arrival times of trains on the Dovre line between Oslo and Trondheim. This article talks about acquiring freely available weather data using APIs at the stopping station and checking the effect of weather elements on the departure delay. Weather elements correlated with the departure delays were rainfall (precipitation) and temperature. This study attempts to articulate the quantitative nature of the effect of these weather elements on the departure delays of the trains. The delay prediction model uses different neural network algorithms. The prediction results from different algorithms are compared to provide a deeper insight into the effect of weather on the delay characteristics.

**Keywords:** Delay prediction · railway operations · neural networks · weather effects · predictive modeling · transportation management

## 1 Introduction

Due to the unpredictability of weather conditions, transportation networks are experiencing unprecedented challenges. The railway system is thought to be the least weather-sensitive of the transport modes, often expected to run when other forms of transport are disrupted [1]. However, weather conditions can influence the railway traffic and cause delays. Additionally, extreme weather can affect the train operator's performance directly or indirectly through disturbances in the railway infrastructure.

It is hard to identify the best implementation options to lessen the negative effects of disruptions. However, it is widely acknowledged that transportation planning and management organizations must increase system resilience to minimize losses and disruptions [2]. This is partly caused by an inadequate knowledge of how various weather phenomena and specific extreme weather occurrences affect the functionality of transportation systems. Uncertainty exists over

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how effects vary across various event types and geographically and temporally for various means of transportation within the same event. Therefore, providing a comprehensive picture of their effects is crucial, mapping all essential steps toward increased network robustness and resilience and finding chances for mode substitution [3].

As stated by [4], weather and climate are frequently treated as synonyms even though they differ. Weather is the short-term state of the atmosphere at a specific time and place. On the other hand, climate is the long-term manifestations of weather and other atmospheric conditions in a given area during a period long enough to ensure that representative values are obtained. Weather refers to the daily variation in the atmosphere, including the temperature, relative humidity, cloud cover, precipitation, and wind. In contrast, climate refers to the general conditions over a long period in a given location. More studies on climate change and its impact on the transport sector have been published in the 21st century, hence the railway system [5].

There are several ways to examine the impact of the weather conditions on the transport mode, according to [2]. The differences in performance can compare transport systems between regions with very different weather conditions. According to [4], the weather influences individual travel demand. Travelers have availability to information on the exact weather conditions and advanced weather forecasts, which seems to have an impact on their choice of transportation mode.

Each railway system has its particular challenges related to the local weather. While the cold weather is unfamiliar in the southern nations, it isn't easy in the Northern countries. The weather-related issues can be solved in a variety of ways. The British railway system has its own *Leaf Fall Timetable Changes* [6]. Thousands of tonnes of leaves fall across the railway network during the autumn. The leaves on the track are compressed by passing trains, producing a thin, black coating that affects train braking and acceleration. Timetables are modified throughout the autumn to prevent unforeseen delays to journeys.

There has been some recent research on how weather conditions affect disturbance in the railway industry. However, the examination of published literature has a heavier emphasis on other modes of transportation [7,8]. Yet, as [9] pointed out, the literature has begun to pay more and more attention to the need to comprehend how weather and climate change affect railway delays and punctuality.

Including weather variables in the train delay prediction models has been shown to improve the overall accuracy of the models. [10] developed a dynamic train delay prediction system that uses state-of-the-art tools and techniques to combine heterogeneous data sources and interact with dynamically changing systems to provide meaningful information to traffic management and dispatching operations. These models are further enhanced by including exogenous meteorological data [10,11]. [12] attempted to comprehend the trends in weather and railway delays. According to the study, train delays in severe weather are most influenced by poor weather. Still, delays in fair weather are primarily influenced by the duration and frequency of previous train delays. Further, [12] found that

infrequently occurring weather, such as snow in southern cities, has a stronger influence and causes longer train delays.

The impacts of weather phenomena, including wind, temperature, and precipitation, on railway operators' performance of passenger train services are estimated by [1]. The study concluded that 4–8% of all train disturbances were caused by bad weather conditions. [13] discovered that trains frequently display the same delay patterns as in the past and that adverse weather frequently results in longer delays. [14] found that 60 % of late arrivals in Finland between 2008 and 2010 were connected to winter weather by modeling the co-variation between harsh weather and freight train delays. The weather factors that influence the punctuality of trains on the Norwegian railway Nordland Line were examined by [8]. The study demonstrates that extreme winter cold is a significant influencing factor that leads to delays and poor punctuality. Moreover, snow depth is the meteorological factor that most explains changes in passenger train punctuality daily and weekly. [15] investigated the impact of weather on railway punctuality. As the temperature drops below 0°, punctuality reduces exponentially; at –5°, it drops by 7.5%, and at –30°, it drops by 50%. The temperature variation was highly correlated with the travel distance. [16] introduced a train delay prediction model that included a fully connected neural network with two LSTM components. The study highlighted the importance of considering the interactions between trains, stations and weather-related factors regarding prediction accuracy.

The present study tries to provide data-driven insights into delay modeling by including weather elements. This research specifically targets the existing delays and the effect of different weather elements on the departure delays of the trains.

This research is a part of an EU-funded project "FutuRe". The flagship project FP6 – FutuRe (GA 101101962) [17] under Europe's Rail Joint Undertaking) aims at providing new innovative technical requirements, methods, solutions, developments and services based on the latest leading-edge technologies to make regional rail cost-efficient while meeting safety standards and improving the reliability, availability and capacity of the railway system. The work presented here is related to the FutuRe project area Regional Rail Customer Services, focusing on customer service and aiming to develop highly accurate multimodal passenger information on-board and/or at stations for passenger and freight management.

## 2 Methodology

The data was acquired from Bane NOR for the arrival and departure delays of long-distance trains running on the Oslo-Trondheim line from 1 January 2021 to 28 February 2023 at the stopping and non-stopping stations. The data was acquired from different sources into TIOS database as shown in Fig. 1. The data includes trains starting from Oslo and trains starting from Trondheim. Machine learning model, specifically the long short-term memory (LSTM) algorithm of

the neural network domain, was used for prediction modeling. Three weather features (temperature and precipitation) were acquired from the Norwegian Meteorological Institute for the corresponding dates. Correlations were established between the effects of different aspects of weather. These results were compared to the predictions without considering the weather effect. The data was cleaned and analyzed using Python modules.

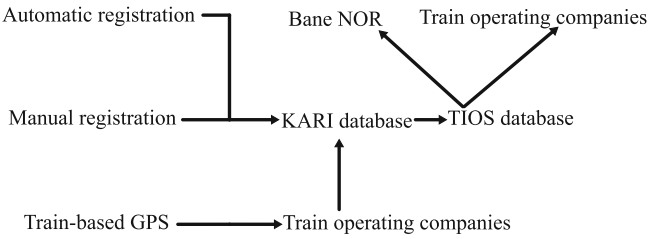



**Fig. 1.** Illustration of the data flow of the train record information (reproduced from [18])

The delay data was selected between the interquartile range (IQR), a statistical measure of the spread of a data set, as shown in Eq. 1. It is calculated as the difference between the third (Q3) and the first quartile (Q1) of the data distribution, which is the range between the 25th and 75th percentiles of the data. The IQR method for identifying outliers is used by setting up a "fence" outside of Q1 and Q3, or minimum and maximum values. Values outside of these boundaries are considered outliers.

$$lower_boundary = Q1 - 1.5 \cdot IQR; upper_boundary = Q3 + 1.5 \cdot IQR \quad (1)$$

The delays, temperature, and rainfall values (parameters) were graded using a formula in Eq. 2 to derive additional features for the prediction model. The value of variable *grad* ranges from 1 to 4 while the values v1, v2 and v3 are changed as per the parameter.

$$Parameter = \begin{cases} < v1 & \text{grad} = 1 \\ \geq v1 < v2 & \text{grad} = 2 \\ \geq v2 \leq v3 & \text{grad} = 3 \\ > v3 & \text{grad} = 4 \end{cases} \quad (2)$$

There were negative delays at some non-boarding stations in the dataset, which were ignored in this analysis. The Entur Geocoder API was used for getting the latitude and longitude of the stations to connect them with the nearest weather stations. The FrostMET API was used to get historical data on temperature and rainfall from weather stations nearest to the train stations.

Entur Geocoder API is free to use and requires no credentials. However, bulk requests are blocked by the server. The application of FrostMET API requires duly formed credentials, which can be overcome by web scraping. However, there are some unresolved issues regarding bulk requests and multiple weather elements. These issues will be resolved in the future research.

## 3 Analysis and Results

The effect of gradation as a modeling feature is shown in the form of Pearson coefficient values ($R^2$), mean absolute error (MAE, in minutes) and root mean square error (RMSE, in minutes) of the LSTM prediction model (as per Fig. 2) in Table 1.

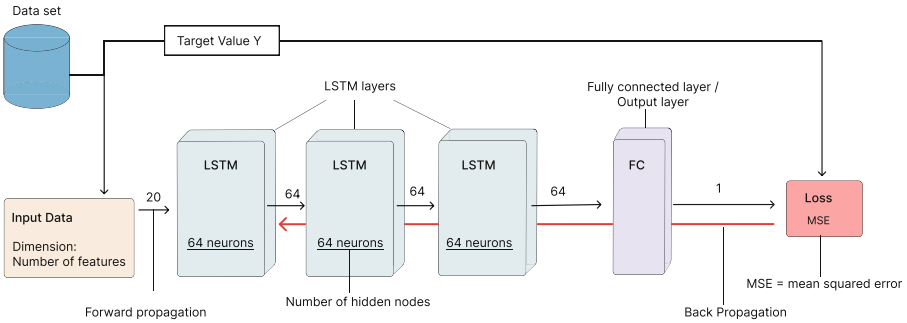



**Fig. 2.** LSTM model architecture (adopted from [18])

The general gradation of delay values was present in all the datasets by default unless stated in the table. It can be seen that gradation increases the $R^2$ values while keeping the error values in check. It can be seen that without gradation, the weather data correlation becomes much weaker [19].

**Table 1.** Statistical inferences from different prediction models

| Models | MAE | RMSE | $R^2$ |
|---|---|---|---|
| Weather without gradation (delay gradation absent) | 2.0231 | 2.5375 | 0.0109 |
| temperature and rainfall data without gradation | 0.9358 | 1.4162 | 0.6919 |
| temperature and rainfall data with gradation | 0.9813 | 1.2976 | 0.7414 |
| Only temperature data with gradation | 0.9528 | 1.2730 | 0.7500 |
| No weather data at all | 0.9712 | 1.3205 | 0.7312 |

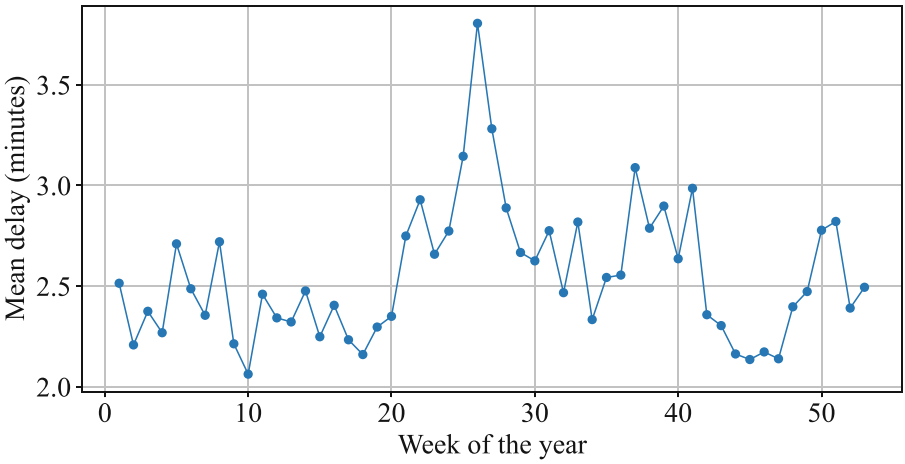



**Fig. 3.** Delay averaged over the weeks of the year (1 is the first week and 53 is the last week on the x-axis)

The delay averaged over the weeks of the year is shown in Fig. 3. The delays can be related to two factors, i.e., congestion-based delays due to increased demand and weather-based delays. The peak delay is in the middle of the year, specifically the 26th week. This coincides with the peak of the holiday season in Norway, and people travel during this time. The second-highest peak is at 37th week, around the arrival of the fall season in Norway. This requires more maintenance at the railway tracks, thus causing delays on single-line tracks.

## 4 Conclusions

The major conclusion that can be drawn from the study and the literature studied in the present study are:

1. The application of weather elements to the prediction model surely increases the quality of the results. However, clustering and gradation as a feature are more helpful in bolstering their application.
2. The peak delays can be related to two major factors: congestion due to increased demand and maintenance due to extreme weather.

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**Data Availability Statement.** The data used in the present research is made available on https://github.com/pranjalm/Future_Europes_rail.

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# An Analysis of Dock-Less Bike Sharing Service in Dublin, Ireland

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**Abstract.** Cycling promotes a healthier lifestyle and alleviates traffic congestion and air pollution. The present study focuses on the dockless bike sharing system in Dublin, Ireland and identifies the socio-economic and built environment factors that affect the dwell time. The origin- destination and timestamp databases obtained from Bleeper Bike are used to estimate the dwell time. The data is analysed using Uber H3 hexagonal zones, and non-spatial and spatial regression models (both spatial lag and spatial error models) are developed. The spatial error model was found to provide a better fit to dwell time. The study identified that key factors such as the presence of public transport stations and car ownership impact dwell time significantly.

**Keywords:** Bike sharing · dwell time · spatial regression models

## 1 Introduction

Cycling is an environmentally conscious form of transport that promotes a healthier lifestyle and helps alleviate traffic congestion and air pollution [1, 2]. In the past two decades, bike-sharing systems, which allow for flexible and environmentally friendly travel, have been gaining popularity in many cities worldwide. Recently, dockless bike sharing systems that allow users to park their bike anywhere is growing across the world. Bleeper bikes [3], is the first to introduce dockless bike sharing systems in Dublin, Ireland.

Bike sharing research areas include identifying factors that influence the demand, analysing the use of bike sharing schemes to solve the last mile problem, and repositioning of bikes [4, 5]. Most earlier studies focused on docked bike sharing systems to identify the factors influencing their demand [6, 7]. These studies have found that socio-economic characteristics, built environment factors, and weather affect the demand. Recently, dockless bike sharing systems have been introduced all over the world. The analysis of these systems and identification of factors affecting their demand is still in the nascent stage, and more studies are essential.

Earlier studies have employed various regression models. These range from Bayesian structural time series model, geographically weighted regression, autoregressive model

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with exogenous variables, spatial lag model, graph regularisation technique, negative binomial regression, machine learning models, and semi-parametric methods [8]. All the above studies have modelled bike sharing trip counts. None of the studies have analysed the effect of built environment factors on dwell time, particularly in Ireland.

In this study, we have developed regression models for dwell time by spatial zones. To evaluate the presence of and consider spatial dependence in dwell time, we developed spatial lag and error models and compared them with the non- spatial model. The present study contributes to the literature by modelling dwell time, in contrast to earlier studies modelling bike trip counts. The study findings reveal various factors that affect dwell time and provide initial evidence of the need for repositioning. The findings provide valuable information that could be used to understand and improve the bike sharing systems.

The rest of the paper is organised as follows. Section 2 presents the data and descriptive statistics. Sections 3 and 4 provide details on the methodology employed and the study results. Finally, Sect. 5 presents the study conclusions.

## 2 Data and Descriptive Statistics

The data utilized in this study has been sourced from Bleeper, which is the first dockless bike-sharing system established in Dublin, Ireland. This system operates within a defined service area known as the "purple zone", which is 100 $km^2$. Users can both access and return bikes only within this zone. The origin and destination (OD) database and the timestamp database are used in this study. The timestamp database contains the location data of the bike every 5 minutes. Since these dockless bikes can be parked anywhere, for the purpose of the analysis, the study area was divided into zones using Uber H3 hexagons [9] (Fig. 1). The resolution used is 9, implying each hexagon has an area of 0.10533 $km^2$.

For each zone, dwell time was calculated as the time between the destination of journey A and the time of the origin of journey B, where journeys A and B are consecutive trips made by the same bike. If the time at destination A and the time at origin B occur on different days, the dwell time was readjusted to account for the five hours (12.00 am to 5.00 am) that the bikes cannot be unlocked. In the present study, dwell times exhibited considerable variability, ranging from 0.26 to 46,234 h, with a mean value of 4,132 hours and a standard deviation of 6,248 h for the H3 zones. This is because of the variation in bike supply and usage by H3 zone. The number of bike trip origins from each zone ranged from 0 to 290. Figure 1 compares bike trips and dwell time. A few H3 zones with more bike trips have shorter dwell times and vice versa.

We obtained the data on the socio-demographic characteristics and built environment from multiple sources. The socio-demographic characteristics such as the number of households, population by age and ethnicity, employment by sector, and car ownership were obtained from the Central Statistics Office (CSO) public datasets [10]. This information is available at a resolution of 20 $m^2$ as small area population statistics and was remapped to estimate different variables for the H3 zones. The built environment variables were counted as the number of bus stops, bike stations, bars and restaurants, and others using their geolocations obtained from OpenStreetMaps.

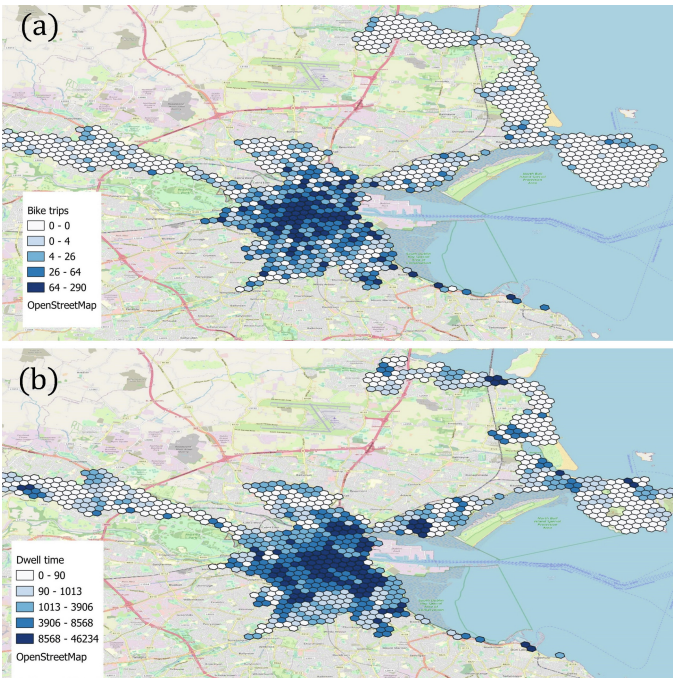



**Fig. 1.** Study area showing the (a) bike trips and (b) dwell time (hr) variation with resolution 9 Uber hexagons. (Basemap source: Google Maps™).

## 3 Methods

In the present study, non-spatial linear regression models (NS), spatial lag models (SLM) and spatial error models (SEM) are developed for dwell time. The NS model is estimated using the ordinary least squares estimator. Spatial models are considered to capture spatial dependence and understand the neighbour inter- actions, utilising a spatial weights matrix. The spatial weights matrix chosen is the 6-nearest neighbour matrix, similar to [11]. This matrix differs from the contiguity weights matrix only in the case of boundary zones. SLM and SEM are estimated using the maximum likelihood estimator (Fig. 2).

### 3.1 Spatial Lag Models

Spatial Lag Models (SLM) capture the spatial correlation in each cross-sectional unit's dependent variable as a spatially weighted average of dependent variables of other cross-sectional units. The weighted average is the spatial lag ($\boldsymbol{WY}$), with its parameter known as the spatial lag parameter ρ. While $\boldsymbol{X}$ is a matrix of independent variables, $\boldsymbol{\beta}$ is a vector of parameters to be estimated. The corresponding reduced-form version of Eq. (1), given by Eq. (2), reveals a global range of spillovers, with $\boldsymbol{A^{-1} = (I - \rho W)^{-1}}$ being the spatial multiplier or the Leontief inverse [12].

$$Y = \rho WY + X\beta + \varepsilon \tag{1}$$

| Variable | Min | Max | Mean | SD |
|---|---|---|---|---|
| Dwell time (hr) | 0.26 | 46234 | 4132 | 6248 |
| Bike origins (#) | 0 | 290 | 25 | 43 |
| *Socio-demographic characteristics* | | | | |
| # households | 51 | 1560 | 590 | 275 |
| *Population by age - proportion* | | | | |
| Age < 10 | 0.00 | 0.28 | 0.11 | 0.04 |
| Age < 20 | 0.01 | 0.57 | 0.09 | 0.05 |
| Age 20-25 | 0.02 | 0.52 | 0.08 | 0.05 |
| Age 25-30 | 0.03 | 0.28 | 0.10 | 0.05 |
| Age 30-35 | 0.01 | 0.25 | 0.10 | 0.05 |
| Age 35-40 | 0.01 | 0.18 | 0.08 | 0.03 |
| Age 40-45 | 0.00 | 0.16 | 0.07 | 0.02 |
| Age 45-50 | 0.00 | 0.13 | 0.06 | 0.01 |
| Age 50-55 | 0.00 | 0.14 | 0.06 | 0.02 |
| Age 55-60 | 0.00 | 0.12 | 0.06 | 0.02 |
| Age 60-65 | 0.00 | 0.14 | 0.05 | 0.02 |
| Age > 65 | 0.00 | 0.55 | 0.15 | 0.08 |
| Age > 50 | 0.00 | 0.71 | 0.32 | 0.11 |
| *Population by ethnicity* | | | | |
| White Irish | 32 | 2771 | 1090.71 | 484.82 |
| WI Traveller | 0 | 191 | 3.53 | 12.63 |
| Other whites | 7 | 1336 | 216.32 | 196.62 |
| Black Irish | 0 | 229 | 23.07 | 31.09 |
| Asian Irish | 0 | 626 | 65.3 | 77.17 |
| Other race | 0 | 412 | 45.15 | 46.49 |

| Variable | Min | Max | Mean | SD |
|---|---|---|---|---|
| *Number of people employed by sector* | | | | |
| AFFT | 0 | 12 | 1.5 | 1.7 |
| BCT | 0 | 85 | 21.6 | 13.8 |
| MIT | 0 | 144 | 41.7 | 22.4 |
| CTT | 1 | 755 | 231.9 | 129.1 |
| TCT | 0 | 486 | 103.5 | 70.0 |
| PAT | 1 | 166 | 44.0 | 25.8 |
| PST | 1 | 513 | 180.4 | 93.9 |
| Others | 2 | 1574 | 197.6 | 205.0 |
| *Car ownership proportion in total households* | | | | |
| 0 cars | 0.01 | 0.8 | 0.25 | 0.19 |
| 1 car | 0.08 | 0.65 | 0.39 | 0.09 |
| 2 cars | 0.01 | 0.58 | 0.24 | 0.13 |
| 3 cars | 0 | 0.14 | 0.04 | 0.03 |
| >3 cars | 0 | 0.27 | 0.06 | 0.04 |
| *Built environment* | | | | |
| # Bus stops | 0 | 31 | 2.05 | 2.87 |
| # Bike stations | 0 | 19 | 1.01 | 2.18 |
| # Bars and restaurants | 0 | 94 | 2.4 | 6.73 |
| # Entertainment and cinema | 0.00 | 5 | 0.16 | 0.58 |
| # Educational institutions | 0.00 | 5 | 0.16 | 0.53 |
| # Financial institutions | 0 | 9 | 0.29 | 0.92 |
| # Health centres | 0 | 8 | 0.47 | 1.1 |
| # Government institutions | 0 | 8 | 0.61 | 1.16 |
| # Luas stops | 0 | 1 | 0.03 | 0.17 |
| # Parks | 0 | 4 | 0.05 | 0.3 |
| # Rail stations | 0 | 1 | 0.03 | 0.18 |
| # Schools | 0 | 2 | 0.02 | 0.15 |
| # PT stops | 0 | 31 | 2.11 | 2.93 |

*Note: AFFT - Agriculture, forestry and fishing; BCT - Building and construction; MIT - Manufacturing industries; CTT - Commerce and trade; TCT - Transport and communications; PAT - Public administration; PST - Professional services*

**Fig. 2.** Descriptive statistics of the dependent and independent variables.

$$Y = A^{-1}X\beta + A^{-1}\varepsilon \tag{2}$$

where, $\boldsymbol{Y}$ is the dependent variable. $\boldsymbol{I}$ is an identity matrix. $\boldsymbol{W}$ is the spatial weights matrix. $\varepsilon$ is normally distributed with mean 0 and variance $\sigma^2$.

$$Y = X\beta + u \tag{3}$$

where,

$$u = \lambda Wu + \varepsilon \tag{4}$$

## 4 Results

The effect of neighbourhood characteristics on dwell time are presented in this section. Table 1 presents the different models developed in this study. The R2 and AIC of the models are also shown in the table. The best model is the SEM model in terms of AIC. The spatial dependence is present in both the dependent variable (SLM) and the residuals (SEM). In both the spatial and non-spatial models, the socio-demographic characteristics such as population by age and ethnicity, employment by sector, and car ownership are found to affect the dwell time. Similarly, built environment variables also affect the dwell time.

A few variables were found to be insignificant in each of the models. Dwell time did not differ for the populations aged 25–30 and 35–40 in the SLM model. Further, the proportion of white Irish employed in the building and construction, commerce and trade sectors and the proportion of households with either 1 or 2 cars are found to be not significant. The number of Luas stations also did not affect the dwell time of a zone. Similar results are also observed in the case of SEM, except for the number of households with either 1 or 2 cars, which are found to influence the dwell time.

The SEM model is only interpreted here for the sake of brevity. The results show that zones with a higher proportion of households owning either 1 or 2 cars have shorter dwell times. This is perhaps because these zones have higher usage of bikes mixed with a lower supply. Further, zones with more bus stops and rail stations tend to experience longer dwell times, perhaps because most bike trips in these zones are for park-and-ride trips that result in higher dwell times. Additionally, zones with more bike stations, bars and restaurants, and financial institutions have higher dwell time. On the other hand, zones with more educational institutions have shorter dwell times. Further, zones with a higher proportion of black Irish population aged 55–60 have shorter dwell times. This is perhaps because the younger population and black Irish tend to rely more on bikes for their mobility than other population groups.

**Table 1.** Non-spatial and spatial regression model results for dwell time

| Variable | NS | SLM | SEM |
|---|---|---|---|
| (Intercept) | 9881.00 (6.35) | 1183.91 (1.74) | 6249.44 (5.20) |
| *Population by age* | | | |
| Age 25–30 | −15460.00 (2.30) | | |
| Age 35–40 | −15400.00 (1.62) | | |
| Age 55–60 | −33400 (3.36) | −26637.39 (2.96) | −28209.33 (2.62) |
| *Population by ethnicity* | | | |
| WI | −2.41 (3.80) | | |
| BI | −32.88 (4.58) | −23.76 (4.55) | −27.90 (4.46) |
| *Employment by sector* | | | |
| BCT | 30.26 (1.50) | | |
| CTT | 8.29 (2.56) | | |

(*continued*)

**Table 1.** (*continued*)

| Variable | NS | SLM | SEM |
|---|---|---|---|
| TCT<br>*Car ownership*<br>No cars | 18.26 (3.63) | 15.95 (6.40)<br>2187.65 (1.88) | 20.59 (7.25) |
| 1 car | −4906.00 (2.21) | | −7101.25 (3.36) |
| 2 cars<br>*Built environment*<br>Bus stops | −8817.00 (4.49)<br>207.20 (3.25) | 178.92 (2.90) | −4591.75 (2.68)<br>165.70 (2.63) |
| Bike stations | 764.20 (6.75) | 787.58 (7.19) | 844.99 (7.69) |
| Bars and restaurants | 240.40 (6.50) | 213.53 (5.92) | 247.14 (6.73) |
| Educational institutions | −797.90 (2.23) | −891.32 (2.58) | −996.18 (2.94) |
| Financial institutions | 400.70 (1.71) | 581.10 (2.60) | 485.74 (2.21) |
| Luas stations | 1239.00 (1.40) | | |
| Parks | 1227.00 (2.51) | 1049.71 (2.21) | 944.02 (2.00) |
| Rail stations | 1615.00 (2.01) | 1270.81 (1.63) | 1148.50 (1.51) |
| *Spatial parameters*<br>$\rho$ | NA | 0.23 (5.75) | NA |
| $\lambda$ | NA | NA | 0.29 (6.09) |
| No of observations<br>*Model fit* | | 704 | |
| $R^2$ | 0.64 | NA | NA |

## 5 Conclusions

The present study considers the spatial dependence in the bike dwell times by hexagonal zones. Our findings show the presence of spatial interactions in both the dependent variable and the residuals, and considering spatial effects produces a better model. The spatial error model provides the best fit. Notably, zones with a higher proportion of car ownership have a high bike usage conditional on the supply. Bike supply can be increased in these zones. Zones with more public transport stops experience higher dwell times due to a predominant share of park-and-ride trips. Further, the analysis shows specific locations exhibiting longer dwell times, indicating potential oversupply issues or a need for bike repositioning.

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# Mobility Data Harmonisation: The TANGENT Solution

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**Abstract.** Data interoperability is a challenging objective to enable different stakeholders to communicate and exchange information effectively and with unambiguous meaning. Indeed, stakeholders adopt different (legacy) systems for managing and exchanging data that cannot be directly integrated. The H2020 TANGENT project needs to face data interoperability issues to enable the development of innovative tools for multimodal transport network management and for optimising traffic operations. This paper describes the design and the development of the TANGENT solution for data harmonisation and fusion, realised to face heterogeneous interoperability issues related to data discovery, access, harmonisation, integration, and extraction.

**Keywords:** Mobility Data · Data Interoperability · Data Harmonisation

## 1 Introduction

The TANGENT project[1], funded by the European Commission under the Horizon 2020 Programme, is developing new complementary ICT tools for optimising traffic operations in a coordinated and dynamic way from a multimodal perspective and considering automated/non-automated vehicles, passengers, and freight transport.

Data coming from intermodal mobility (transport schedules, transport network, traffic flows, etc.), captured by sensors deployed to monitor the transport network (trains, road traffic, ferries, etc.) or generated by users and vehicles will feed the TANGENT tools to determine the traffic conditions and to deliver warning and recommendation services. One of the project's main objectives is gathering data sources related to the TANGENT case study cities (i.e., Athens, Lisbon, Greater Manchester, and Rennes Metropole) and enabling their usage in the TANGENT tools. The definition of a proper solution is not straightforward and should face the following challenges: (i) **discover** the data (*Which data are available and where?*), (ii) **access** the data: (*How to obtain access to the data?*), (iii) **harmonise** the data: (*How to convert the data according to a reference data model?*), (iv) **integrate** the data: (*How to merge data from different sources?*), *and* (v) **extract** the data: (*How to consume harmonised/integrated data?*).

[1] https://tangent-h2020.eu/.

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The analysis of the proposed challenges considering the TANGENT case studies has highlighted several metadata and data interoperability issues to be addressed. As shown in Fig. 1, data are available in different data catalogues, i.e., web portals that describe and often host a set of data sources (datasets and data services). Considering different data catalogues, each of them may contain:

- datasets in different formats and/or using different data models (A, B, C);
- data services relying on heterogeneous specifications and technologies (I, II);
- data sources described according to different metadata specifications (d,e).

Identifying a single solution to the abovementioned challenges is impossible since a single interoperability problem cannot be formulated. Indeed, the identified data interoperability issues are widely heterogeneous and pose various requirements that can be possibly faced only by considering a set of tools appropriately configured [4].




**Fig. 1.** Metadata and data interoperability issues

The following sections describe the design and the TANGENT solution for data harmonisation and fusion, realised as a set of tools to address the various data interoperability requirements elicited by the project.

## 2 TANGENT Solution for Data Harmonisation and Fusion

This section describes the components of the TANGENT solution identified to face each of the mentioned challenges: discover, access, harmonise, integrate, and extract.

The European Commission is also addressing the first two challenges (discover and access) by implementing National Access Points (NAP) for transportation data. The concept of NAP leverages the one of Data Catalogue, i.e., a digital platform to facilitate the sharing of data sources and their findability by other stakeholders. However, even in the case of NAPs, each Member State adopted different approaches to implementing their NAP, thus creating interoperability issues at the European level. For this reason, the NAPCORE[2] project is currently working on coordinating and harmonising such platforms around Europe. One crucial objective is supporting the findability of data in each mobility data platform and defining a uniform mechanism to access the data sources. Adopting structured metadata descriptors according to well-known vocabularies (e.g., DCAT-AP [2]) is extremely important to facilitate the implementation of searching functionalities within one or multiple data catalogues. Moreover, proper data governance must be defined to regulate the usage of the catalogue between the different involved

[2] https://napcore.eu/.

stakeholders. Finally, data catalogues should support the harmonisation of technological modes to access the data sources and/or provide detailed documentation to assist the data user.

For these reasons, the first two components of the TANGENT solution for data harmonisation and fusion are:

- The **TANGENT Data Catalogue**: a digital platform (i) describing uniformly all the relevant data sources collected for the TANGENT case studies according to the TangentDCAT-AP metadata specification, and (ii) implementing governance mechanisms according to the TANGENT Data-Sharing Governance model. A complete description of the metadata specification and the governance model is available in [1].
- The **TANGENT Data API**: a uniform API to access data sources and define integrations with the overall TANGENT solution. The basic idea of the TANGENT Data API is to make it easier for the final user to access the data without locating and accessing several data portals. The user can access a data source by knowing the endpoint at which the TANGENT Data API is located and by retrieving the identifier of the data source to be accessed from the TANGENT Data Catalogue. The TANGENT Data API handles authorisation mechanisms for the different data sources. Moreover, in cases where a data source that is published online should be filtered according to the specificities of a case study, the TANGENT Data API is already configured for providing access only to the relevant data (e.g., adding parameters to filter data according to a defined temporal/geographical scope).

The remaining three data interoperability challenges (harmonise, integrate, and extract) require a flexible solution that can be configured to address heterogeneous requirements in terms of: (i) *schema and data transformation* to obtain syntactic (structural) and semantic interoperability and (ii) *integration with existing information systems* as data sources (i.e., components generating or storing the data) and/or data sinks (i.e., components consuming or archiving the data).

Different approaches can be exploited and implemented, spanning from ad-hoc solutions targeting a specific scenario to more general and scalable solutions supporting multiple stakeholders and data representations. Into the last approach falls the any-to-one mapping, which reduces the number of mappings, i.e., translations from one representation to another, needed to implement interoperability by different stakeholders [1, 4]. This approach selects a reference model for the domain of interest (e.g., the Transmodel[3]), and each stakeholder is responsible for defining mappings from their own data representation to the reference model and vice versa.

A specific application of any-to-one mappings relies on using Semantic Web technologies and defining the central model as a reference ontology. The main advantage of this approach is the definition of an interoperable and integrated Knowledge Graph, modelled according to a formal reference ontology, as an additional valuable product of the conversion procedure [4].

The implementation of the semantic any-to-one mapping approach requires the definition of two procedures: (i) a ***lifting*** procedure from the source data representation to

[3] https://www.transmodel-cen.eu/.

the reference ontology and (ii) a ***lowering*** procedure from the reference ontology to the target data representation.

Different approaches for lifting and lowering can be suitable considering a specific scenario. Moreover, the harmonisation, integration and extraction process may require the definition of custom pre- and post-processing to manage interoperability issues. Therefore, composing and configuring different components should be possible considering the specific requirements for integrating certain data sources.

Semantic-based ETL (Extract, Transform and Load) tools are proposed in the literature to address the problem of defining composable procedures considering Semantic Web technologies. Chimera[4] [2] is an open-source solution based on Apache Camel[5], enabling the definition of semantic data transformation pipelines by composing different components for knowledge graph construction, transformation, validation, and exploitation. The advantage of Chimera is that the integration with Apache Camel provides a wide set of production-ready components to integrate pipelines with heterogeneous systems. Moreover, custom components can be easily defined and integrated within a pipeline (e.g., to implement custom extraction/filtering approaches). For these reasons, Chimera has been selected to implement the semantic any-to-one mapping approach, considering the integration requirements of the TANGENT project.

Accordingly, two additional elements are identified to support the TANGENT solution for data harmonisation and fusion:

- The **TANGENT Reference Conceptual Model**: a model defining a reference ontology for the transportation-related data handled within TANGENT.
- The **Semantic Harmonisation and Fusion Pipelines**: a set of workflows defined with Chimera to fulfil the integration requirements associated with the TANGENT data sources.

## 3 A Prototype of the TANGENT Solution for Data Harmonisation and Fusion

This section discusses a set of illustrative semantic conversion pipelines developed within the project, considering real data sources from case studies and enabling the harmonisation of traffic data according to a uniform output format.

The following data sources from two different case study cities (i.e., Greater Manchester and Rennes Metropole) are considered:

- MANCH_DATA_01: a data service exposing real-time journey times data for the Greater Manchester case study area in a custom JSON format.
- MANCH_DATA_02: a data service exposing the position of sensors measuring the journey times in MANCH_DATA_01 in a custom JSON format.
- RENN_DATA_01: a data service exposing real-time road traffic data for the Rennes Metropole case study area in a custom CSV format.

[4] https://github.com/cefriel/chimera.
[5] https://camel.apache.org/.

The three custom formats are different but represent similar data associated with real-time traffic measurements. The three data sources contain travel times data, while only REN_DATA_01 includes additional information regarding average speeds and traffic status.

The harmonisation requirement identified is to represent the information of the three data sources using a uniform JSON format based on DATEX II[6] semantics that can be interpreted by other TANGENT services. The resulting data flow should contain the real-time measurements and the position of the sensor that carried out the measurements.

The three data sources are described in the TANGENT Data Catalogue, using a uniform metadata descriptor, and exposed through the TANGENT Data API that filters the incoming data according to the case study areas. The two data sources from Greater Manchester should be merged to obtain the needed data, while the Rennes Metropole data source already integrates both measurements and the position of the sensors. The data in the selected data sources should be lifted to their RDF representation (according to the TANGENT Reference Conceptual Model) by defining a set of declarative mappings. A single lowering mapping is needed to extract data from the produced knowledge graph and lower the information to the common DATEX II-based JSON format. This example shows the advantage of the any-to-one mapping approach: only the lowering mapping should be modified if a modification is introduced in the expected target format since the lifting operation is completely decoupled. Moreover, the intermediate representation through an RDF graph facilitates the possibility of merging different data sources and querying an integrated dataset.

The implementation of the designed pipelines was done following these steps:

- Analysis of the TANGENT Reference Conceptual Model to identify the relevant class and properties to be used for the mappings of concepts specified in the input data sources.
- Encoding the lifting mappings from the input JSON format to their RDF representation according to the identified class and properties.
- Definition of the lowering mappings from the RDF representation to the output JSON format relying on DATEX II-based semantics. The harmonised and possibly fused data are accessed from the knowledge graph and lowering mappings are defined according to the expected output format.
- The semantic harmonisation and fusion pipelines are defined and configured using the Chimera components and Apache Camel.

The pipelines can then be executed and exposed as a data service listed in the TANGENT Data Catalogue and integrated with the TANGENT Data API.

## 4 Conclusions

This paper has described the design of the TANGENT solution for data harmonisation and fusion to address heterogeneous interoperability issues related to data discovery, access, harmonisation, integration, and extraction. The solution has been realised as a set

[6] https://www.datex2.eu/.

of tools (i.e., the TANGENT Data Catalogue, the TANGENT Data API, the TANGENT Reference Conceptual Model, and the Semantic Harmonisation and Fusion Pipelines) to address the various data interoperability requirements elicited by the project. Considering the state-of-the-art and best practices, the solution has been designed by applying the any-to-one centralised approach for semantic interoperability solutions, enabling data conversions and exchange with unambiguous and shared meaning.

The solution has been released, and its integration with the overall TANGENT solution is ongoing.

**Acknowledgements.** The presented research has been supported by the TANGENT project (Grant Agreement no. 955273), co-funded by the European Commission under the Horizon 2020 Framework Programme.

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# Towards Privacy-Preserving Connected Vehicles: A Blockchain Approach for Vehicle Identity Management and Data Sharing

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**Abstract.** As vehicular connectivity and digitisation surge, escalating data transmission to Original Equipment Manufacturers (OEMs) and public authorities is vital for the digital transition, for applications from legal compliance to traffic management. Amidst burgeoning data-sharing ecosystems, ensuring secure, private data transmission and General Data Protection Regulation (GDPR) compliant user control over vehicle identity and data-sharing permissions becomes pivotal, barring legal and enforcement exceptions. This research explores employing blockchain technology to safeguard privacy and security within a Vehicle Identity Management system, using $CO_2$ emissions monitoring as an exemplar. Utilising an emulation-based environment, replicating vehicle interactions with European authorities and the European Commission (EC), the study demonstrates that blockchain systems, specifically for $CO_2$ emissions monitoring, can meet transaction rate and latency demands of large-scale transport applications, accommodating 280 million vehicles reporting annually. This inquiry not only amplifies understanding of blockchain's applicability in connected transportation systems and secure data exchange among vehicles, authorities, and stakeholders but also lays groundwork for future advancements in trustful, efficient, and secure data interchange, potentially benefiting authorities, industry, and end-users alike.

**Keywords:** Sustainable Transport · Digital Identity · Data Integrity · Security and Privacy · Vehicle Connectivity · Regulatory Monitoring · Blockchain

## 1 Introduction

[1]European policy increasingly emphasises the importance of connectivity and interoperability of various systems in the road transport sector. Hundreds of millions of vehicles are projected to interact on a daily basis with people, automated systems and each other. The deployment of new mobility solutions that will improve the sustainability, effectiveness and energy efficiency of the transport sector will rely on connectivity and secure data exchange between entities.

[1] The views expressed in this document are purely those of the authors and shall not be considered as an official position of the European Commission under any circumstance.

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One technology suitable for this purpose are distributed ledgers, and particularly blockchain (BC) systems. At their core, blockchain systems are a type of distributed ledger technology that enables secure and transparent documentation of digital transactions. They are comprised of a series of blocks, each containing a group of validated transactions, which are cryptographically linked to the previous block, thereby creating an immutable and tamper-proof record.

Blockchains could revolutionise how real-world data and assets are connected to their digital counterparts in several ways:

- **Smart Contracts**: Automate transactions for predefined conditions.
- **Identity Management**: generate secure and easily verifiable digital identities for entities, that may be used to control access to data.
- **Data Sharing and Interoperability**: secure data sharing, fostering collaboration and interoperability.

This paper builds upon previous research [1], which investigated the application of BC technology for secure and reliable data communication in the road transport sector. This research changes the network structure to more accurately reflect the real-world. The key research questions addressed are the plausibility of using blockchain in a wide scale application covering large portions of the fleet, and what would be a possible system architecture for doing so. In this paper we investigate the communication of vehicle emissions data to European authorities. Such data retrieval directly from the vehicles is foreseen by existing EU regulations for $CO_2$ emissions [2–4] and have been proposed for the monitoring of regulated $CO_2$ and pollutant emissions.

In the context of emissions monitoring of vehicles, the crucial element for preserving privacy is ensuring the Vehicle Identification Number (VIN) is hidden while verifying that it is both a valid and unique VIN registered at one of the EU27 Vehicle Registration Authorities. Centralised access management of identities raises concerns, such as security risks due to a single point of failure, performance issues from technical problems or Denial of Service (DoS) attacks, and privacy breaches following database leaks [5–7].

## 2 Methodology

This research explores the application of BC technology for securely managing emission data from vehicles, targeting a throughput capable of handling the EU27 fleet of 280 million vehicles. A comprehensive description of the hardware and software utilized is documented in the JRC Science for Policy Report [1].

*Infrastructure and Experimentation:* Utilising JRC's EPIC cluster, we emulated a realistic blockchain (BC) network for simulation purposes, involving the deployment of 80 EPIC nodes connected via a 1 Gbps line, each facilitated with 6 GB of RAM and 40 GB of storage [8]. Hyperledger Fabric (HLF) 2.2 [9] was employed for its modular and private architecture on Ubuntu 18.04, and experiments were executed within an orchestrated environment utilizing Kubernetes atop EPIC to efficiently handle network layers, storage allocation, and scaling.

*Blockchain Network and Data Privacy:* The Hyperledger Fabric employs Private Data Collections (PDCs) to assure data privacy by ensuring only authorized entities access sensitive data, enabling GDPR compliance via irreversible data deletion, and offering adjustable access control to safeguard data while promoting secure sharing among organizations on the channel. A detailed breakdown of PDCs and Hyperledger terminology is available in referenced sources [9–12].

### 2.1 Experimental Setup

Changes were made to the endorsement policy from previous experiments [1] to:

1. require approval only from the Vehicle Registration Authority (RA) and the EC endorser, thereby reducing traffic and conserving storage, and
2. transition to a realistic model, where clients connect, transmit transactions, and disconnect, more closely mimicking real-world operational circumstances.

Vehicles, upon registration with the relevant RA, are assigned an X.509 certificate and a VIN recorded in the RA's global state database, enabling them to transmit emissions data to the pertinent EC organization. Vehicle data is stored on the peers of each RA and the EC, accessible only to these entities, while others receive a hash of the emissions data.

In a network emulating real-world scenarios, 100,000 VINs per RA were registered and then used to generate transaction processes involving connect-discover-authenticate-disconnect procedures, ensuring an extensive engagement of the entire system. A script enabled five connections, each representing a vehicle transmitting data, to mimic a genuine scenario involving multiple vehicle connections to the network. The GNU parallel tool was utilized to manage a substantial number of connections and execute multiple script instances concurrently [1].

## 3 Results

The successful simulation of a comprehensive network, including 27 Member State organisations and the EC, is depicted in Fig. 1 and Fig. 2. The system managed to support 200 clients per Member State (5400 total clients connected simultaneously), handling 2.7 million transactions while maintaining stability and reasonable performance. A saturation point of around 250 Transaction Per Second (TPS) was consistently reached, regardless of the number of organisations, indicating the maximum throughput achievable with the current configuration. Figure 1 shows that when there are only a few Member State organisations with a limited number of clients, the system does not reach saturation. For both 3 and 5 Member State configurations, saturation is achieved with 200 clients per Member State, as shown in Fig. 1 and Fig. 2. With 100 clients per Member State, the network reaches its peak performance at around 280 TPS and a latency of approximately 0.5 s. However, increasing the number to 200 clients per Member State results in a lower TPS of 245. The constant latency, as seen in Fig. 2, indicates that "this reduction is due to an increase in CPU utilisation caused by the larger number of clients" [1].

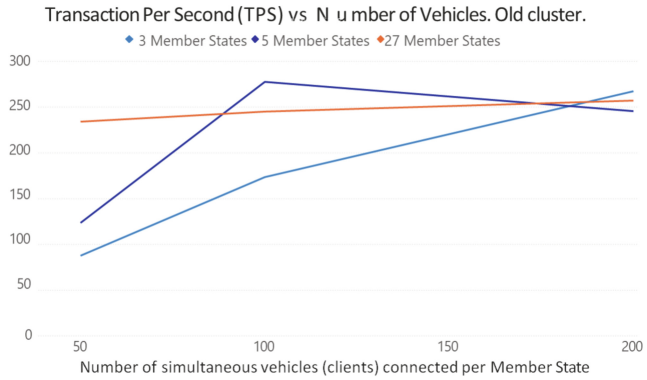



**Fig. 1.** Experiment 2: "*Transactions per second for 3, 5, 27 Member States + EC with varying numbers of simulated vehicles*". Source: JRC, 2022 [1].

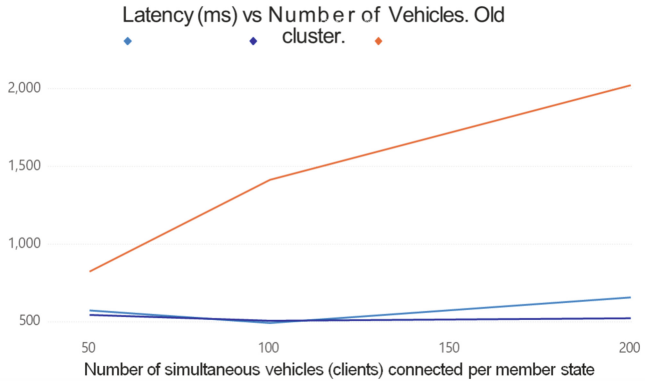



**Fig. 2.** Experiment 2: "*Latency in seconds for 3, 5, 27 Member States + EC with varying numbers of simulated vehicles*". Source: JRC, 2022 [1].

Despite the BC network performance remaining stable, full utilisation each of the virtual CPUs was observed for all endorsing peers. The system with 27 Member States reached saturation even with a small number of clients. When 50 clients were connected simultaneously, "*latency was significantly higher than in the 3 and 5 Member State configurations, increasing to almost 2 s with 200 clients. It is important to note that the system remained stable and no transaction failures or timeouts were observed on the client side*" [1]. However, trials with 300 simultaneous clients, which are not shown in the figures, revealed increased instability across all Member State configurations, mainly due to timeouts and connection failures.

This research builds upon the initial experimental setup findings described in [1, 13], incorporating a modified consensus approach and client configuration to more closely resemble real-world scenarios. By mandating signatures solely from the endorsing peer of the RA in which the vehicle is registered and the endorsing peer of the EC, the

new consensus approach addresses the concerns of maintaining data integrity and audit ability, reducing storage footprints and lowering network traffic.

The updated client configuration, which incorporates 100,000 VINs per RA and simulates a more intricate connect-discover-authenticate-disconnect process, provides a more accurate and comprehensive representation of real-world use cases. This enhanced approach captures the complex aspects of vehicular connections within the blockchain network, offering valuable insights into the network's performance under realistic conditions.

In this experiment, the system was able to support a significant number of clients (200 per Member State, totalling 5400 simultaneous clients) while maintaining stability and reasonable performance. The saturation point of approximately 250 TPS was consistently reached, regardless of the number of organisations involved. This result indicates that the current configuration has a maximum achievable throughput, which may need further optimisation to accommodate higher transaction rates.

However, the experiment also revealed some limitations, such as increased latency and resource constraints with higher numbers of clients. These findings indicate that further optimisation of the network design, consensus approach, and hardware resources may be necessary to improve performance and accommodate larger numbers of clients.

The primary limitation of the system was its ability to accommodate a large amount of clients. "*The system could not handle more than 200 simulated vehicles for each Member State organisation. When the number of vehicles in the simulation*" [1] exceeded this limit, the system experienced difficulties. There was a dramatic increase in the number of transactions that timed out and clients that were disconnected from the system. This suggests that the system has a limited capacity to manage a high volume of clients at the same time.

In conclusion, this research demonstrates the potential of the modified consensus approach and client configuration for handling real-world use cases involving vehicular connections to the blockchain network. The results highlight the scalability and robustness of the proposed architecture while also identifying areas for further optimisation and refinement. Future work should focus on addressing these limitations and further improving the network design to ensure its suitability for large-scale emissions monitoring and other related applications.

## 4 Conclusion

This research aimed to evaluate the technical feasibility of sharing vehicle data through a blockchain-based system, utilising current technology. "*Real-world fuel consumption monitoring served as a representative use case, involving a fleet of 280 million vehicles*" [1], where each Member State is legally obligated to report $CO_2$ emissions from road vehicles to the EC annually. Optimisations in the experimental setup enabled the system to successfully support 5400 concurrent clients (vehicles) distributed across 27 Member States. Each vehicle completed a full life cycle, taking approximately three seconds, achieving a maximum throughput of 257 TPS while maintaining system stability and responsiveness.

Ideally, processing the 280 million required transactions per year would take approximately 12.6 days for all EU vehicles. Although this result may not reflect real-world

conditions with non-optimal timing and variable demand, it does indicate that the system can "*meet the legal requirement of one transaction per vehicle per year*" and even has the potential to reach the experimental goal of one transaction per vehicle per month. However, this work also identified significant HLF limitations, such as considerable "*transaction overhead in terms of disk usage for each endorsement*" [1] and managing numerous open client connections simultaneously. By addressing these limitations, the project team observed substantial performance improvements in the new experimental setup detailed in this research.

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# A Methodology for Planning and Executing Mobility Data Labs: Fostering Collaboration, Data Sharing, and Innovation

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**Abstract.** Data plays a pivotal role in modern mobility research, and data labs have emerged as powerful platforms for promoting collaboration, innovation, and data sharing in the mobility sector. This paper presents a comprehensive methodology designed to plan and execute data labs in the mobility sector, along with its successful implementation within the EU-funded MobiDataLab project context. Central to the methodology is the identification of critical stakeholders, the precise delineation of objectives and challenges, ensuring alignment with genuine mobility issues. It staunchly adheres to a user-centric approach, actively engaging end-users, entrepreneurs, developers, researchers, start-ups, and SMEs with data expertise through a systematic, replicable strategy. Additionally, this paper seeks to introduce the technical infrastructure that was designed and deployed to facilitate these endeavors. The methodology emphasizes the establishment of robust data management systems, protocols, and privacy safeguards. Simultaneously, the methodology advocates for the promotion of interoperability standards and open data formats to facilitate seamless access to diverse data sources. Advanced open data catalogues and data enrichment processors, with anonymization features, further enhance data collaboration and privacy. Capacity-building initiatives enhance stakeholder skills, supported by an Open Knowledge Base for sharing best practices. The methodology's efficacy is finally illustrated through case studies which underscore the concrete benefits of data labs in advancing formal innovation and collaboration within the mobility sector.

**Keywords:** Mobility Data Sharing · Urban Transport · Data Science · Data Labs · Living Labs

## 1 Introduction

In the rapidly evolving landscape of mobility solutions, harnessing the power of data has become the cornerstone for driving innovation, enhancing user experiences, and making transport systems more efficient and sustainable. Data labs have emerged as

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dynamic hubs where stakeholders from various domains converge to co-create, experiment, and leverage data-driven insights for mobility solutions. This paper outlines a robust methodology for orchestrating the creation and operation of mobility data labs, fostering collaboration among diverse stakeholders, facilitating data sharing, and igniting innovation.

In the upcoming sections, we will delve into the core elements of our methodology. Within the methodology section, we emphasize the significance of a user-centric approach and delve into how we seamlessly integrate the quadruple helix model and the Plan-Do-Check-Act (PDCA) tool. As we progress, the implementation in the MobiDataLab project section provides concrete evidence of our methodology's success. Here, we explore the ambitious goals of the MobiDataLab project, its holistic design principles, and the indispensable role played by stakeholders in propelling innovation forward. Concluding our exploration, we delve into the crucial role of FAIR principles in enhancing the efficacy of mobility services, detailing how the MobiDataLab project has successfully integrated these principles into its framework. Finally, through reflection and iterative refinement, we have forged a methodology that paves the way for progress in the realm of mobility data labs.

## 2 Methodology

To embark on the journey of establishing and operating mobility data labs, it is paramount to establish a user-center methodology that not only leverages the expertise of diverse stakeholders, but also prioritizes the real-world needs and challenges of the mobility sector. This paper, therefore, seeks to provide real-world evidence and insights into the establishment and operation of mobility labs based on the findings of the EU MobiDataLab research project.

### 2.1 Living Labs and the Quadruple Helix Model

The Living Lab approach, along with its adaptations like the mobility labs, operates on the concept of the quadruple helix model of innovation collaboration. In this model, government, industry, academia and the general public join forces, collaboratively generating innovative solutions [1]. This approach aligns seamlessly with the mobility data lab framework, as it actively involves these key stakeholders, promoting a holistic approach to mobility innovation. Schaffers et al. (2007) underscores the significance and promise of engaging (end) users actively and consistently throughout the development process, through a collaborative co-creation approach with the developers [2]. The shift in living labs towards emphasizing early-stage innovation like user research and co-creation holds promise for enhancing user participation in ICT innovation and unlocking their innovative potential [3].

### 2.2 Beyond the State of the Art

As a notable advancement beyond conventional practices, the MobiDataLab project has forged a groundbreaking methodology for the inception and execution of mobility data

labs. This innovative approach seamlessly integrates the well-established Plan Do Check Act (PDCA) tool, bolstering it with invaluable insights distilled from the iterative experiences of MobiDataLab living labs. These lessons learned from real-world iterations have profoundly enriched our methodology, elevating it to a new standard of effectiveness and practicality.

The PDCA cycle involves planning, executing, evaluating, and refining solutions iteratively. It ensures that innovations are not only ideated but also rigorously tested, refined, and aligned with real-world challenges. This methodology, rooted in the living lab concept, takes innovation a step further by actively involving a diverse range of stakeholders, including end-users, in each phase of the PDCA cycle (Fig. 1).

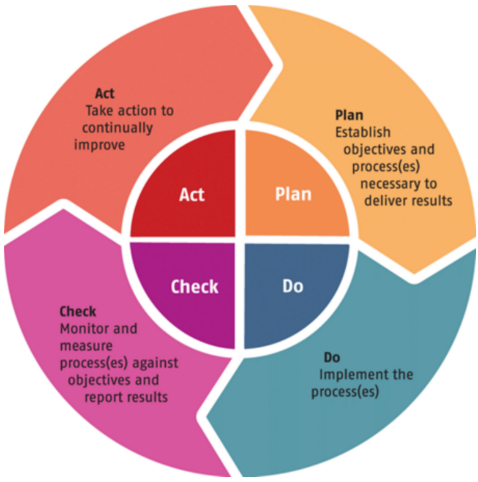



**Fig. 1.** The Plan Do Check Act Cycle [4]

## 3 Implementation in the MobiDataLab Project

The MobiDataLab uses the PDCA approach to guide the project stakeholders: project partners (10 project partners from industry, research, academia, consultancy and governance sectors, located in 7 countries), the reference group, the living labs attendees and external participants to pave the way for successful mobility data sharing.

The execution of the approach did start with an overview on the state-of-the-art, the implementation of the transport cloud, the execution together with the stakeholder group within the three living labs (the Datathon, the Hackathon and the Codagon) and the review of domain expert along the path to reflect and integrate the feedback.

The efficacy of our methodology is rooted in its ability to actively involve stakeholders across the mobility spectrum. Entrepreneurs, developers, researchers, start-ups, and SMEs, armed with data knowledge, become essential participants, equipped to tackle the challenges posed by data providers. Figure 2 shows the five stakeholder groups with their motives and needs as a result of a comprehensive stakeholders' analysis within the mobility sector, coupled with an extensive literature review of successful implementations of mobility living labs.

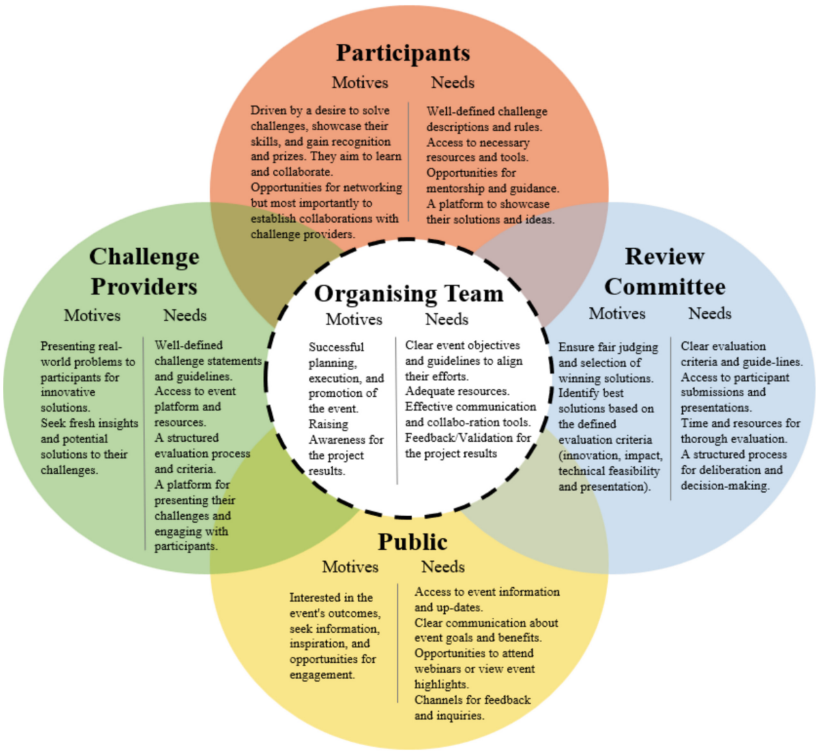



**Fig. 2.** MobiDataLab Living Labs Stakeholders Analysis

*Organising Team:* Project partners involved in the planning, execution and evaluation of the MobiDataLab living labs.

*Challenge Providers:* Municipalities of Leuven, Eindhoven, Milan and Paris.

*Review Committee:* Consisting of project members and external domain experts.

*Participants:* Innovators (SMEs, start-ups, researchers, developers etc.).

*Public:* End-users who use mobility services (e.g. commuters, residents, and citizens) and indirectly affected population groups.

The Virtual Lab platform, a significant component developed within the MobiDataLab project, plays a pivotal role in the realisation of the project's mobility labs. Virtual Lab is a digital counterpart to the traditional living lab concept and contains various functionalities that support discussion and promotion of solutions throughout their inception life cycle, from challenge to idea to a prototype [5].

## 4 FAIR Data and Services

Effective open innovation hinges on the accessibility and availability of open data. As a result of the project and improved by the living labs, the Virtual Lab platform is following the FAIR principles (findable, accessible, interoperable and reusable) [6] and

provides access to mobility metadata catalogues and a service catalogue. The practical application of these catalogues is exemplified through the various challenges tackled during the MobiDataLab Living Labs, demonstrating the platform's ability to address real-world mobility issues and catalyze innovative solutions[1].

In the context of the data labs, it is necessary to make mobility data easier to find, discover and reuse. This is achieved using data catalogues, which enable a more efficient search on the key aspects of each dataset, i.e. descriptive metadata. In the open data ecosystem, a number of software systems can serve this purpose, for example CKAN, GeoNetwork, OpenDataSoft, Socrata [7]. The first difficulty is choosing a solution. In MobiDataLab, the CKAN solution has been elicited due to its modularity, the number of available extensions, and their variety. In particular, the CKAN harvesting extension functionality was implemented, allowing to add datasets on demand into the MobiDataLab data catalogue, from data portals corresponding to the local area of referring municipalities. A future challenge for the MobiDataLab platform is overcoming organisational mistrust, rooted in fears of granting competitors an unintended advantage. Usability by data consumers across the European union remains a challenge since European citizens speak different languages. Harvesting metadata in the local language and translating them in real time into the consumer or most spoken language requested the implementation of dedicated extensions, resulting in MobiDataLab's contribution to open-source software. Not only the MobiDataLab platform improves findability, but also reusability, offering anonymization techniques to data providers, such as microaggregation for anonymising large mobility datasets [8].

Today's mobility services are very diverse and distributed. The FAIR principle is less established and implemented. Catalogues to register services and make them findable are becoming more requested but are not yet stablished. Also, standards for interoperable interfaces are not available or still in discussion. Within the MobiDataLab project, a catalogue with an easy interface to register OpenAPI (https://www.openapis.org/) described services is part of the Transport Cloud ecosystem. The catalogue allows the registration of REST APIs and makes them findable. Further demands are easy access, interoperable interfaces (e.g. aligned and agreed by service providers) to fulfill the reusability as the fourth step to make mobility services FAIR.

## 5 Conclusion

The methodology we present here is a blueprint for harnessing the full potential of data labs in the mobility sector. By bringing diverse stakeholders to the table, setting clear objectives, and fostering user-centric innovation, we enable the co-creation of solutions that address the pressing mobility challenges of our time. The PDCA approach implements the agile principle and aligns and supports all stakeholders on the way to a FAIR approach for mobility data sharing. The provisioning of data and services and connection of data producers and data and service consumers in the context of the Living and Virtual Labs improves the alignment and enables the connectivity between stakeholders through communication and collaborative solution enablement.

[1] Details of the challenges can be accessed at: https://labs.mobidatalab.eu/challenges/.

The MobiDataLab project stands as a testament to the effectiveness of this methodology, demonstrating that by working together, we can create a future of more efficient, sustainable, and inclusive mobility solutions.

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# Data Sharing at the Edge of the Network: A Disturbance Resilient Multi-modal ITS

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**Abstract.** Mobility-as-a-Service (MaaS) is a paradigm that encourages the shift from private cars to more sustainable alternative mobility services. MaaS provides services that enhances and enables multiple modes of transport to operate seamlessly and bringing Multimodal Intelligent Transport Systems (M-ITS) closer to reality. This requires sharing and integration of data collected from multiple sources including modes of transports, sensors, and end-users' devices to allow a seamless and integrated services especially during unprecedented disturbances. This paper discusses the interactions among transportation modes, networks, potential disturbance scenarios, and adaptation strategies to mitigate their impact on MaaS. We particularly discuss the need to share data between the modes of transport and relevant entities that are at the vicinity of each other, taking advantage of edge computing technology to avoid any latency due to communication to the cloud and privacy concerns. However, when sharing at the edge, bandwidth, storage, and computational limitations must be considered.

**Keywords:** Shared mobility · Mobility-as-a-Service · Decentralized Systems · Data sharing · Edge Computing

## 1 Introduction

The concept of Mobility-as-a-Service (MaaS) is gaining interest due to increased awareness of sustainable mobility and the adoption of Intelligent Transportation Systems (ITS) [1,2]. MaaS aims to shift people from cars to more sustainable modes of transportation, relying on ITS for efficient infrastructure use, real-time data provision, and user-guided routing. Presently, public transport (PT) systems commonly use ITS for real-time data on arrival times and vehicle locations. Similarly, bike/scooter-sharing services provide device location data, and traffic signals can optimize intersection throughput based on traffic conditions. These ITS systems often lack cooperation among different transportation modes, limiting their effectiveness particularly at the times of disturbances. Multimodal ITS (M-ITS) [5] can enhance MaaS, where different modes can support or substitute

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one another [3,4,7]. This paper provides an overview of transportation modes, networks, and their interactions, focusing on disturbances and how M-ITS can mitigate them. M-ITS concept can incorporate edge computing paradigm [6] to place the processing of data closer to its source. This will address privacy concerns, reduce data processing delays, enable decentralize computation, and eliminate costly centralized systems. Using edge computing paradigm, decisions are made in a decentralized manner, relying on data from the local transport network, onboard vehicle sensors, and information from nearby vehicles and infrastructure. Identifying data-sharing needs, and the data flow among systems and vehicles during disturbances is essential. This paper outlines such possible disturbances and their impact on different modes and suggests coordinated impact-mitigation strategies for the M-ITS-based MaaS system.

## 2 Transportation Modes and Networks

To facilitate data sharing between multiple modes of transport, we first need to understand their dependencies and how they interact with one another. This paper focuses on transport in urban areas, although most modes can operate beyond. Expanding M-ITS and MaaS to intercity or interstate levels would involve considering additional modes, especially air transport that are out of scope for this paper. To do so, first, we model the dependencies between transportation modes and their infrastructure networks in urban areas.[1] Transport modes can operate on various networks, some shared and others exclusive. Networks often share infrastructure, for example roads are shared between cars, buses, and cyclists. They can be modeled collectively, with parameters defining mode usage. Multimodal modes indicate possible mode transitions. Figure 1 presents an overview of the modes noted as $M_i$ and the networks they use, noted as $N_i$.

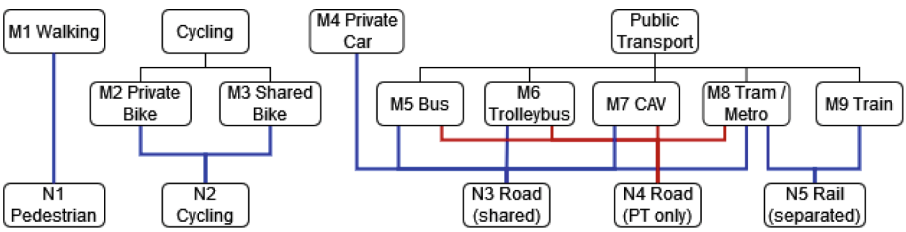



**Fig. 1.** Overview of fundamental transportation modes and networks employed. The indices $M_i$ and $N_i$ are employed for mode and network respectively and specifying the pairings between the two in Fig. 2.

[1] The commonly available transportation modes provided is not exhaustive – each category can represent multiple modes of similar nature.

## 3 Service Disturbances to Mode-Network Combinations and M-ITS Adaptation Strategies

Unplanned events can disrupt normal traffic operations, impacting system performance and requiring adaptations to limit such impacts. Data sharing and collective intelligence can inform about and address the challenges related to such disturbances. Five main causes of disturbances are identified, impacting various mode-network combinations (see Fig. 2). Here, only cases of possible direct impacts (need to re-route) are considered. Secondary impacts due to possible relocation of transport demand are considered later for individual disturbance scenarios. In Table 1, we present a comprehensive overview of individual disturbances, providing further insights into potential data sources for detection, strategies for adaptation, and special cases that might necessitate specific responses.

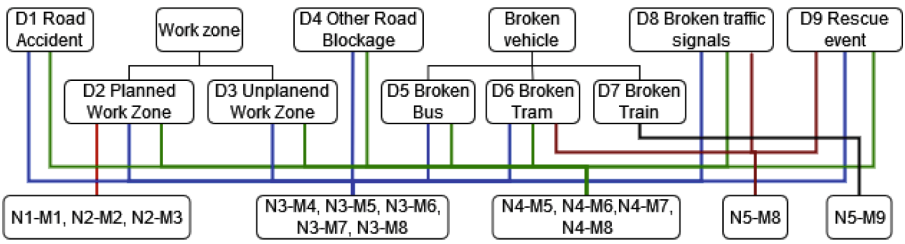



**Fig. 2.** Effects of different sources of disturbance on different combinations of modes and networks.

Below we provide some examples of disturbances and scenarios to handle them. For example, "Planned Work Zone" along the pedestrian network (N1-M1) might result in disturbance for users with wheelchairs. Such work zones are not commonly recorded in a machine-readable format. This is especially true if they are unplanned, hence this case is omitted in the schema in Fig. 2. Pedestrians and cyclists have the advantage of being very agile and can bypass most obstacles on the network with acceptable delay and they are not connected to any ITS service, except shared bikes. Therefore, except for planned work zones, they are not considered primary stakeholders. These modes are considered here mostly as transition modes and as an adaptation strategy in case of disturbance.

Additional causes of disturbance include major sport or cultural events, and gatherings, that significantly increase (or decrease) traffic demand within certain areas of the networks. Therefore, a registry of such events, including information about the event, time, location, affected area, and possibly expected number of visitors should be included. Some disturbances, especially the external ones mentioned above, can be observed and identified centrally. Then only the warnings with relevant information can be shared with relevant individual edge devices to be evaluated individually. This includes the processing of information about

**Table 1.** List of detection options, adaptation strategies, and specific cases for the basic identified disturbances.

| D | Detection Options | Adaptation Strategies | Specific Cases |
|---|---|---|---|
| **D1 - Road accident D4 - Another Road blockage** | • User feedback apps (Waze)<br>• C-ITS data from vehicles (V2I)<br>• Traffic information centers (API, C-ITS DENM, RDS TMC, ...)<br>• Integrated rescue system dispatching<br>• Video detection (AI image processing)<br>• Traffic flow (TF) data from sensors | • Warn road users nearby and with routes via the disturbance location<br>• Info + guidance at affected stops to MaaS alternatives<br>• Busses temporarily adjust routes if taxi/CAV can serve bypassed stops, if favorable<br>• Intelligent traffic signs, VMS and other devices adjust to changes in traffic – warnings, guidance, change signal plan | • Other networks affected<br>• Reserved road lanes are affected<br>• Reaction varies based on road blockage<br>• Treat D4 as D2 when extended |
| **D2 – Planned Work zone** | • Digitized registry of planned work zones with temporary traffic management measures<br>• Intelligent "first/last cone" or contractor updates* | • Temporarily adjust networks for all affected modes and react aptly | • Adjust duration through regular detection means if not updated dynamically |
| **D3 – Unplanned Work zone** | • Integrated rescue system**<br>• User feedback apps (Waze)<br>• C-ITS data from vehicles<br>• Intelligent "cone"*<br>• Traffic information centers<br>• TF data from sensors | • Mostly the same as D1<br>• For long-lasting work zones, treat as D2 once details are available | • Mostly the same as D1<br>• Response varies depending on expected duration |
| **D5-D7 – Broken vehicle Rail block** | • C-ITS data from vehicles (V2I)<br>• Railway or public transport (PT) operator dispatching<br>• Otherwise treat as D1/D4 | • Inform passengers about alternatives within the MaaS<br>• Inform M-ITS about the obstacle and react accordingly (mix of D1 and D3)<br>• For D6, D7, replace operation with busses/CAVs | • Certain PT routes (e.g. airport line) have higher priority<br>• Follow train/metro safety standards |
| **D8 - Broken Traffic signals** | • C-ITS (I2I) from the device<br>• Device operator<br>• TF data from sensors | • Inform police to regulate traffic at the intersection<br>• Warn relevant road users<br>• Optimize nearby traffic signals for changed traffic<br>• Adjust routing for MaaS | • Warn trams, if affected, and react suitably |
| **D9 - Rescue event** | • C-ITS data from vehicles<br>• Integrated rescue system dispatching | • Warn nearby road users<br>• Re-route vehicles or adjust signal plans for smooth rescue | • Consider operation size and duration |

*C-ITS-equipped "traffic cone" or mobile app to update WZ start/end time.
**Police should know first, communication with M-ITS may vary among countries.

detected disturbances from the edge devices and transport users in cases where the impacts of the disturbance exceed the communication range of the local edge devices.

**Other Impact Mitigation Suggestions are as Follows:** –For damaged CAVs, inform its users about nearby replacements and send warnings if blocking the road. –For broken shared bikes and scooters, notify users of alternatives; other modes are not affected. –Temporarily adjust service limits for space-limited services when intermodal nodes near the borders are out of service. –Warn users at affected PT stops and guide them to nearby alternatives or other MaaS services. –Empty bike-sharing nests provide info about nearby nests with available bikes and PT alternatives. –Notify taxis and CAVs of disturbances and areas with increased demand. –Provide (multimodal) route change suggestions for users with planned routes. –General control measures for improved performance: Integrate (multimodal) navigation apps into M-ITS; Increase C-ITS systems and OBU penetration; Establish disturbance detection information systems; Implement VMS and variable LED signage; Use intelligent traffic lights, including cooperation, PT prioritization, and multimodal; Create incentives (cost evaluation, tolling, gamification); Implement multimodal ticket schemes; Consider multimodal performance in traffic control systems; Design new data standards for interoperability across the EU (identify best practices for data management; define minimal operational standards for data requirements).

## 4 Data Sharing at the Network Edge

The disturbance-mode-network model defines combinations of disturbances and affected transportation modes/networks, but not all users or vehicles of the affected mode-network combination must be warned. Only relevant edge devices should be informed with specific details. Given the small size of the basic warning data package, this can be spread quite broadly with more details given upon request, if available. Disturbance warnings sent to edge devices should include the following information, –Type of disturbance, –Location on the network affected modes, and class of the network segment for each mode (e.g., critical, major, inferior, minor), –Expected impact severity (one or more measures as applicable): Capacity reduction; Lanes affected; Severity index; Displaced traffic volume, –Estimated time of duration, and any other case-specific information.

To efficiently distribute warnings for disturbances, it is crucial to consider various parameters like the affected area, specific modes, networks, and user classes. The goal is to notify only relevant users and devices without overwhelming them. This involves a combination of general heuristic rules for area-based warnings, C-ITS traces for approaching vehicles, data from edge devices regarding their planned routes (including non-scheduled traffic), adaptation strategies for dealing with the disturbance, and machine learning algorithms for predicting trajectories. There are two main aspects to consider: (i) information about the disturbance, which is part of the warning itself (type, location, severity, duration), and (2) information about the recipient of the warning. For recipients, it

is essential to account for their expected or planned trajectory, any expected TF changes along that trajectory, and whether they are part of the adaptation strategy.

Edge devices in this environment encompass a wide range of components, from sensors and processors within vehicles, through users' mobile phones, to infrastructure elements like traffic signal controllers and communication nodes. Edge computing can greatly enhance the efficiency of distributing warnings for disturbances based on the following considerations: **Efficient Data Processing:** Edge computing processes data closer to the source, enabling quick assessment of disturbances and reducing response times. For example, a CAV detects a fallen tree on the road and immediately sends an alert to nearby vehicles. **Localized Decision-Making:** Edge devices can make localized decisions based on the available information. They can analyze their planned routes, expected TF changes, and other relevant factors to determine whether a particular disturbance warning is relevant to them and address it accordingly. **Adaptation Strategies:** Edge devices can autonomously implement the pre-defined adaptation strategies and cooperate with other devices to optimize overall performance. **Reduced Communication Network Congestion:** By processing and filtering data at the edge, the system can significantly reduce congestion of the communication network. This is crucial during disturbances when there may be an increased volume of data traffic due to widespread alerts.

## 5 Conclusions

This paper has explored the critical role of M-ITS in enhancing MaaS efficiency, especially during disturbances. Establishing relationships between transportation modes, networks, and disturbances, has highlighted the importance of data sharing on the network edge. The selective distribution of disturbance warnings to relevant users and devices is crucial for effective disturbance mitigation. This framework offers valuable insights for building resilient and adaptive urban transportation systems that prioritize sustainability and user needs.

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# nuMIDAS: The New Mobility Data and Solutions Toolkit

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**Abstract.** The mobility ecosystem is rapidly evolving, with the rise of new stakeholders and services, accompanied by new ways for the generation, collection, and storing of data. In the nuMIDAS (New Mobility Data and Solutions Toolkit) project, we provided insights into what methodological tools, databases, and models are required, and how existing ones need to be adapted with new data. We started from insights obtained through (market) research and stake-holders, as well as quantitative modelling. A wider applicability of the project's results across the whole EU was guaranteed as all the research was validated within a selection of case studies in pilot cities, with varying characteristics, thereby giving more credibility to these results. Finally, through an iterative approach, nuMIDAS created a tangible and readily available toolkit that can be deployed elsewhere, including a set of transferability guidelines, thus thereby contributing to the further adoption and exploitation of the project's results.

**Keywords:** Intelligent traffic and mobility management · Data management

## 1 Introduction

The mobility ecosystem is rapidly evolving, whereby we see the rise of new stakeholders and services. Examples of these are the presence of connected and automated vehicles, a large group of organisations that rally to establish various forms of shared mobility, with the pinnacle being all of these incorporated into a large MaaS ecosystem. As these new forms of mobility offerings start to appear within cities, so do new ways in which data are being generated, collected, and stored. Analysing this (Big) data with suitable (artificial intelligence) techniques becomes more paramount, as it leads to insights in the performance of certain mobility solutions, and is able to highlight (mobility) needs of citizens in a broader context, in addition to a rise in new risks and various socio-economic impacts. Successfully integrating all these disruptive technologies and solutions with the

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designs of policy makers remains a challenge at current. Let alone being able to analyse, monitor, and assess mobility solutions and their potential socio-economic impacts.

nuMIDAS, the New Mobility Data and Solutions Toolkit, bridged this (knowledge) gap, by providing insights into what methodological tools, databases, and models are required, and how existing ones need to be adapted or augmented with new data. To this end, it started from insights obtained through (market) research and stakeholders, as well as quantitative modelling.

A wider applicability of the project's results across the whole EU was guaranteed as all the research was validated within a selection of case studies in pilot cities, with varying characteristics, thereby giving more credibility to these results. Finally, through an iterative approach, nuMIDAS created a tangible and readily available toolkit that can be deployed elsewhere, including a set of transferability guidelines, thus thereby contributing to the further adoption and exploitation of the project's results.

nuMIDAS, the New Mobility Data and Solutions Toolkit, ran during 2021 and 2022 under the Horizon 2020 programme and was developed by a European Consortium, composed of 9 partners from 6 countries: Belgium, Czech Republic, Greece, Italy, The Netherlands, and Spain.

The project built on a distributed selection of case studies in four pilot cities to provide a geographic coverage of the EU: Barcelona (Spain), Milan (Italy), Leuven (Belgium), and Thessaloniki (Greece). All public deliverables can be readily downloaded from our website (https://numidas.eu/). The novelty of our project lies in the fact that we now have a platform that is more generally and broadly applicable, whereby new use cases can be more quickly added, thereby leveraging the existing functionalities of the platform.

In the following paragraphs we will elaborate more extensively on the various aspects of our completed research. First, we describe how we selected the different use cases tackled in our project. Then we show our software architecture by explaining the construction of our back-end and front-end engines. Next, we elaborate on a selection of the use cases, how they were modelled, implemented, and applied. Finally, we provide some conclusions and recommendations.




**Fig. 1.** Geographical overview (figure created by Factual using QGIS).

## 2 Selection of Use Cases

In order to achieve the project's outcomes, we took the following steps:

- Perform an assessment of the current trends
- Define advanced methods and tools
- Execute case studies in pilot cities

- Create a consolidated toolkit for stakeholders

Some of these steps ran in parallel, with feedback mechanisms involved in order to capture and process the latest developments and insights during the creation of the nuMIDAS toolkit.

### 2.1 Process for Scoping the Use Cases

To successfully support transportation planners, researchers, and policy makers, emphasis was put on the harmonisation of the development of the toolkit. With this objective, a series of parameters was defined: extensibility, interoperability, minimisation of development and operational costs, reliability, and usefulness and user-friendliness of the toolkit. nuMIDAS provided high-level descriptions of the use cases, along with descriptions of problems which need to be addressed in the specific city(ies) and the technical approach to be adopted. In addition, we also provided UML mock-ups giving the visual representation of each use case approach, and capturing the entire process of a tool in combination with the interrelations with the involved actors. In order to make the scope of each use case more understandable and tangible, they set the boundaries of the tool, the steps to be followed each time, and the requirements needed to move forward (see also Fig. 1). Various use cases were implemented in the toolkit, some fully, others partially, thus providing researchers, planners, and policy makers with visualisations of the results derived from the methods and tools used in the case studies (Fig. 2).

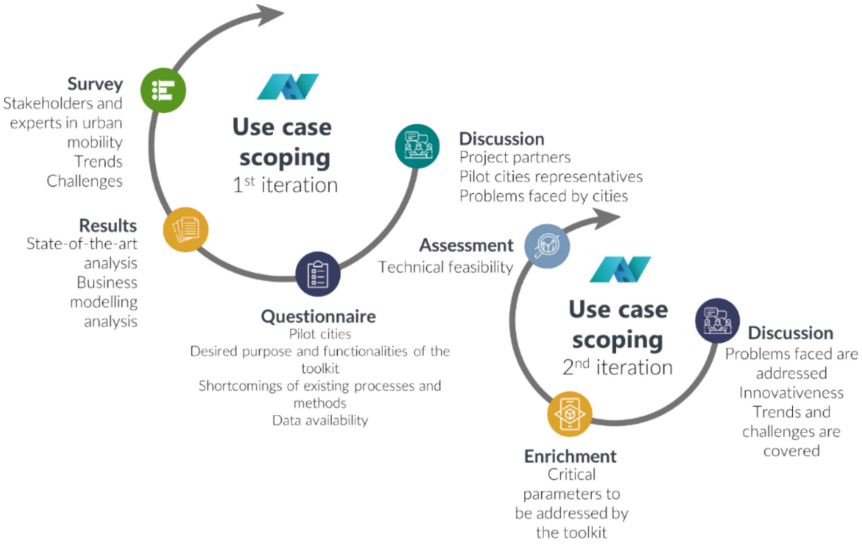



**Fig. 2.** Overview of the processes followed for scoping the use cases in nuMIDAS. Figure created using Microsoft PowerPoint; icons created by Factual of the developed methodology.

### 2.2 Final Selection of Use Cases

Thanks to the requirements that emerged from the discussion and the interaction with the project pilot cities and relevant stakeholders, we identified the following 6 use cases (UC) to address the problems and provide the technical support to solve them by creating specific methods and tools: **Use case 1: Pre-planning of shared mobility services (Milan and Leuven)**: This use case designed a tool for optimising the fleet size of shared mobility services, like bikes and e-scooters, by considering various factors to minimise both the generalised trip costs and the system's operating costs. **Use case 2: Operative areas analysis (Milan)**: This use case sought to allocate shared mobility service fleets across metropolitan sub-areas to minimise service providers' economic losses and maintain equitable, high-quality service for citizens. **Use case 3: Air quality and vehicle emissions analysis based on multi-source data (Barcelona and Leuven)**: This use case involved integrating diverse data sources, such as traffic, emissions, and weather, to evaluate traffic's impact on air quality and support the forecasting and policy-making process for air quality improvement. **Use case 4: Planning for parking (Leuven)**: This use case analysed the impact of decreasing on-street parking in urban centers on traffic flow, assisting in crafting and applying policies that address longer parking search times and the shift of parking demand to adjacent areas. **Use case 5: Inflows and outflows in a metropolitan area (Barcelona)**: This use case focused on using data from ANPR-systems and census information to estimate vehicle movements between metropolitan districts, aiding in the enhancement and enforcement of environmental policies like low-emission zones. **Use case 6: Assessment of traffic management scenarios (Thessaloniki and Leuven)**: This use case evaluated traffic management scenarios through simulation and data analytics, integrating data from connected vehicles and traditional counting systems to support decision-making.

We implemented all of these use case, some more as a proof-of-concept, others more as prototype that could (and was) already be put to use by the cities. As such, our nuMIDAS toolkit now supports answering the following questions from policy makers:

- Milan: How many shared (micro)mobility services need to be provided, and where?
- Barcelona: How large are the vehicle emissions (CO2, NOx, and PM)? How much vehicles drive from A to B?
- Leuven: What is the impact of removing on-street parking spaces?
- Thessaloniki: What is the impact of traffic management measures (traffic lights and speed limits)?

## 3 Deploying a Suitable Software Architecture

In order to make sense, and to have a common and agreed upon language of terminology, the nuMIDAS project adopted a service-oriented architecture. Advanced methods and tools are required to analyse, assess, and monitor new mobility solutions and policies including new data management techniques. The toolkit (in the form of a dashboard) incorporated these methods and tools providing researchers, planners, and policy makers a visualisation of the results through a GUI. For each of the use cases, we devised new algorithms that took the current state of the art into account and add new elements to it. The algorithms were initially coded in Python and first tested under stand-alone lab

conditions. Then they were ported to a back-end engine (forming part of the toolkit) that runs an instance of Amazon Web Services (AWS) with appropriate GIS-databases and input/output file handling capabilities. To perform smooth operations, the entire endeavour operates using private and public APIs, with the front-end system containing access control regulations and the visual part of the different use cases (e.g., graphs for geographical interpretations, monitoring of key performance indicators, etc.), as well as scenario management where suitable.

## 4 Implementation of the Specific Use Cases

### 4.1 Example Implementation of a Use Case: Shared Mobility Planning

As an example, in the city of Milan, the policy maker required a tool for the preplanning of shared mobility services. The nuMIDAS team designed and developed a tool that processes available data to produce the output required by Milan city mobility planners. The aim was to produce a tool replicable and scalable in different cities/regions in Europe. In the case of station-based car-sharing, as an example, the dashboard suggests the proper location of new car-sharing stations and a well-balanced car fleet. This outcome is produced by back-end algorithms that elaborate data provided by the municipality. New car-sharing services, or extensions of the existing ones, can then be planned based on the outcomes of the nuMIDAS tool. The dashboard allows tuning parameters of the algorithms to compare different scenarios, depending on the weight given to conflicting objectives. Examples of the latter are the increase of shared mobility options to citizens in low-demand areas, and the economic sustainability of car-sharing operators. A policy maker can use the dashboard to link data sources and input parameters, and to visualise the results of the computation in a user-friendly environment. This specific example was tested in the case of Milan, but can be extended to be used by any European city willing to make use of a tool that supports car-sharing planning. For Milan, we modelled and simulated various scenarios through the dashboard, using a suitable set of input parameters: scenario 1: high demand/low fleet; scenario 2: low demand/high fleet; scenario 3: weight factor significantly in favour of the society; scenario 4: weight significantly in favour of the service provider. For example, scenario 1's outcome showed the optimal fleet to be 84 free-floating bicycles. In addition, demand was about 97% covered, outlining a very good coverage of the service for the user segment. The average walking time was within an acceptable value for which the user may choose to use the bicycle for his or her commute. Scenario 3 on the other hand, considered a net imbalance for society. In fact, looking at the results, the optimal fleet value of 93 was deemed very close to the optimal fleet value for the end user (which was 94), indicating how the algorithm took into account that the preponderant objective for this simulation is to satisfy demand at the expense of the operator's profit. As a result, compared to scenario 1, demand coverage was greater while profits were slightly lower (the same reasoning applies to profits as for scenario 1).

### 4.2 Example Implementation of a Use Case: Planning for Parking

The main objective was to assess the potential impact of on-street parking restriction policies in the city of Leuven. The city is especially concerned with possible spill-over effects of hyperlocal policy changes, such as substantively reducing the available parking spaces in one street or neighbourhood. Operationally, the algorithm, relies on the discretisation of a road network using a grid comprised of cells of appropriate size and the use of parameters, such as the demand for parking and parking capacity (number of parking places) corresponding to each cell. By that means, the tool will enable the simulation of enforcing a parking restriction policy in one or more grid cells and the assessment of its impacts on the remaining cells. Through the simulation of enforcing a parking restriction policy in one or more roads of the network, both the policy maker as well as the transport planner are able to evaluate the effects, on the basis of the KPIs provided by the tool. Specifically, the evaluation of an on-street parking restriction policy includes the calculation of parking pressure, the calculation of searching time, and the examination of the extent of the effect. For the city of Leuven, we used the tool to evaluate a number of scenario's, varying in complexity. Here, several parking places were suspended, leading to a redistribution of the parking demand. Some areas indicated a drop in demand (as expected), with some redistribution to the neighbouring areas, mostly to the southern region. This redistribution had an effect on the parking searching times (Fig. 3).

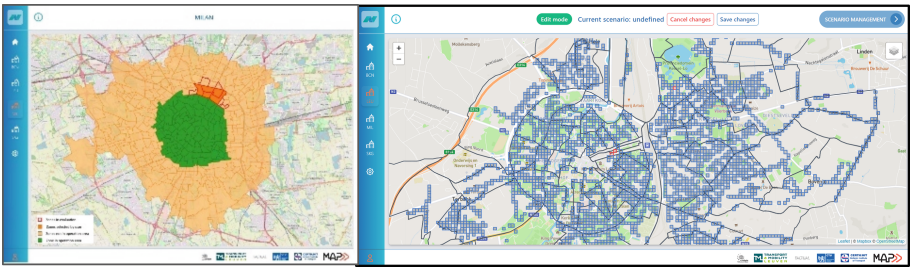


**Fig. 3.** Example of the shared mobility planning (left) and planning for parking (right) use cases in the nuMIDAS toolkit's. Figures created within the nuMIDAS toolkit.

## 5 Conclusions and Further Recommendations

### 5.1 General Conclusions

Our nuMIDAS project provided insights into what methodological tools, databases, and models are required, and how existing ones need to be adapted or augmented with new data. To this end, we started from insights obtained through (market) research and stakeholders, as well as quantitative modelling. A wider applicability of the project's results across the whole EU was guaranteed as all the research was validated within a selection of case studies in pilot cities, with varying characteristics. Finally, through an

iterative approach, nuMIDAS created a tangible and readily available toolkit that can now be deployed elsewhere, including a set of transferability guidelines, thus thereby contributing to the further adoption and exploitation of the project's results.

nuMIDAS's project results represented a reference for any other future scientific work in Europe and provided to the whole scientific community more advanced bases for the theoretical elaboration on mobility. This outcome of nuMIDAS can be quite beneficial for city administrations and local policy makers, as they not always have a clear view of the real role and potential of data in cities. This work can help them in making more informed and evidence-based decisions, and in getting the mobility system "ready" through land use planning and zoning, transport system design, information services and processes for bringing together the different interested actors (city departments, public transport and sharing-mobility operators, developers, etc.).

### 5.2 Upscaling and Transferability to Other Cities

In order to maximise the exploitation of project results, and in particular a widespread use of our new mobility toolkit, we drew up transferability guidelines. These describe how new cities can implement new instances of the tools within the nuMIDAS architecture framework, and use them for new mobility solutions analysis, assessing, and monitoring. From an operational point of view, due to the city-specific and location specific parameters and constraints (air quality, origin-destination matrix, etc.), the guidelines transferred not the models themselves, but rather provided a useful methodology to adapt the model to each city.

### 5.3 Further Exploitation via Suitable Business Models

The state-of-the-art analysis provided early on in our project the basis for the work on business models for particular services. As the mobility field is rapidly changing due to, among others, digitalisation, as well as the uprise of small and large electric vehicles, business models and stakeholder roles change. Furthermore, more and more services combine many disciplines, which often means that services require multiple types of stakeholders to become effective. For this reason, a stakeholder analysis was performed in the context of nuMIDAS, in combination with a business model analysis. The analysis was performed using a Service Dominant Business Model Radar (SDBM/R). The SDBM/R gives insight into which stakeholders can be found within the business model, as well as the way these stakeholders add value to this service. In addition to the SDBM/R, the analysis contains descriptions of the change in business models and stakeholder roles within the business models over time. All SDBM/Rs were created per service, based on the achievement of shared goals and value co-creation by a group of actors (businesses, firms, and costumers) which interact to achieve that shared goal. This activity required to identify the values-in-use as the focal points of the services, and further the value propositions (part of the central values contributed by the particular actors), coproduction activities (i.e. those that actors perform to achieve the co-creation of the values), and costs and benefits for particular actors. The radars were complemented with the description of the corresponding business model scenarios, descriptions of actors and their roles and activities, and the discussions of the transitions of business models influenced by

new methods and tools. The summary resulted in a short list of the most common stakeholders within the SDBM/Rs. These are: municipalities, travellers, (mobility) service providers, intermediaries, and MaaS providers. The first three stakeholders within this list are most important and most common. These three stakeholders respectively provide policies, demand, and supply for transportation. The last two of these stakeholder types, intermediaries and MaaS providers, are not yet so common in the actual urban mobility field. These are categorised as future partners and are expected to become more prevalent. As transport systems become more and more integrated, while mobility service providers are competing, intermediaries stay independent and are able to handle data of competing partners with care to provide services which would otherwise not have been possible due to said competition. When the apps of MaaS providers finally really take-off, many services are expected to change, as mobility will be even more accessible from within our pockets. As such, our nuMIDAS toolkit is excellently positioned in light of further commercial exploitation.

**Acknowledgements.** This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007153. nu-MIDAS, the New Mobility Data and Solutions Toolkit, ran during 2021 and 2022 under the Horizon 2020 programme and was developed by a European Consortium, composed of 9 partners from 6 countries: Belgium, Czech Republic, Greece, Italy, The Netherlands, and Spain. The project built on a distributed selection of case studies in four pilot cities to provide a geographic coverage of the EU: Barcelona (Spain), Milan (Italy), Leuven (Belgium), and Thessaloniki (Greece). All public deliverables can be readily downloaded from our website (https://www.numidas.eu/).

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# Integrated Evaluation of and Vision on Truck Parking in Flanders, Belgium

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**Abstract.** The Flemish government launched two related projects in Belgium between 2020 and 2023. First, they rolled out an Intelligent Truck Parking Service (ITPS) along a part of the E17 motorway. Then we supported them to develop a vision on truck parking. The ITPS consisted of an app for truck drivers, combined with information on variable message signs. We evaluated the ITPS so as to provide answers to the following research questions: (i) which technology best measures parking occupancy? (ii) what is the impact of providing parking occupancy information to the truck driver? (iii) how do users deal with the information (user experience)? In order to evaluate the ITPS, we performed a technical analysis, an im-pact analysis, a user acceptance analysis, and performed interviews with stakeholders regarding the eco-system. In addition, the analysis of GPS measurements provided insights into used parking locations and occupancies for developing the vision.

**Keywords:** Intelligent traffic and mobility management · User behaviour and acceptance

## 1 Background and Research Questions

The Flemish government launched two related projects in Belgium between 2020 and 2023. First, they rolled out an Intelligent Truck Parking Service (ITPS) testing ground along the E17 motorway corridor between the community of Kalken and the French border (see also Fig. 1). Then we supported them to develop a vision on truck parking. After some quality improvements, the ITPS was commissioned with the launch of an app, a dynamic DATEX II flow, a web interface, and the visualisation on VMS boards. The goal of the evaluation of the ITPS was to provide answers to the following three research questions:

- RQ1: What is the best technology to measure parking occupancy?
- RQ2: What is the impact of providing information to the truck driver on the occupancy of the parking?
- RQ3: How do users deal with the information (user experience)?

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During our evaluation, we performed a technical analysis, an impact analysis, a user acceptance analysis, and performed interviews with stakeholders regarding the ecosystem. Finally, we analysed GPS measurements to obtain insights into used parking locations and occupancies for developing a vision on truck parking. We will provide details on each of these aspects in the following sections.




**Fig. 1.** Geographical overview of the truck parkings along the E17 motorway within the pilot project. (created using QGIS and Microsoft PowerPoint)

## 2 Analyses

### 2.1 Technical Evaluation

A number of detection methods (not the same everywhere) have been made available at the various rest areas and service zones, including (i) loop detectors, (ii) barriers and ticket system, (iii) parking sensors, (iv) DSRC readers, (v) traffic sensors, and (vi) truck OBU data. In order to assess the accuracy of the measurement systems, manual counts were performed (which were also initially used to (re)calibrate the systems). During the baseline measurement, one measurement was performed per car park every day, at a specific time, for two weeks between September 15, 2020 and September 28, 2020. This means that a total of 14 measurements were performed per car park over the measurement period. Four measurement moments are possible per day: morning (between 6 am and 12 pm), afternoon (between 12 pm and 6 pm), evening (between 6 pm and midnight) and night (between midnight and 6 am). For each manual count, we determined the absolute and the percentage error, and the mean absolute percent error (MAPE) in relation to the different measurement methods (in the morning when there are fewer trucks, the absolute error is decisive, at night the percentage error is decisive, and in the afternoon both are important). For each type of count, we also looked at the statistical distribution of the errors, and whether outliers occur.

## 2.2 Impact Analysis

To measure the impact of the different incentives on the occupancy rate, we organised three successive phases:

- Phase 1: this is the baseline measurement (there is no app and the VMS boards are not active)
- Phase 2: an app is available to the truck drivers (Truckmeister, on Android and iOS)
- Phase 3: the app is available and the VMS boards are active.

For each of these phases, we performed an analysis of the parking occupancies, the impact of the VMS, and the results from the OBU data (Fig. 2).

| | | W38 | W39 | W40 | W41 | W42 | W43 | W44 | W45 | W46 | W47 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fase | Info | 14/sep | 21/sep | 28/sep | 5/okt | 12/okt | 19/okt | 26/okt | 2/nov | 9/nov | 16/nov |
| Fase 1 | Nulmeting | | | | | | | | | | |
| Fase 2 | App | | | | | | | | | | |
| Fase 3 | App+VMS | | | | | | | | | | |
| | | | | (1/10) | | | (22/10) | | | | |

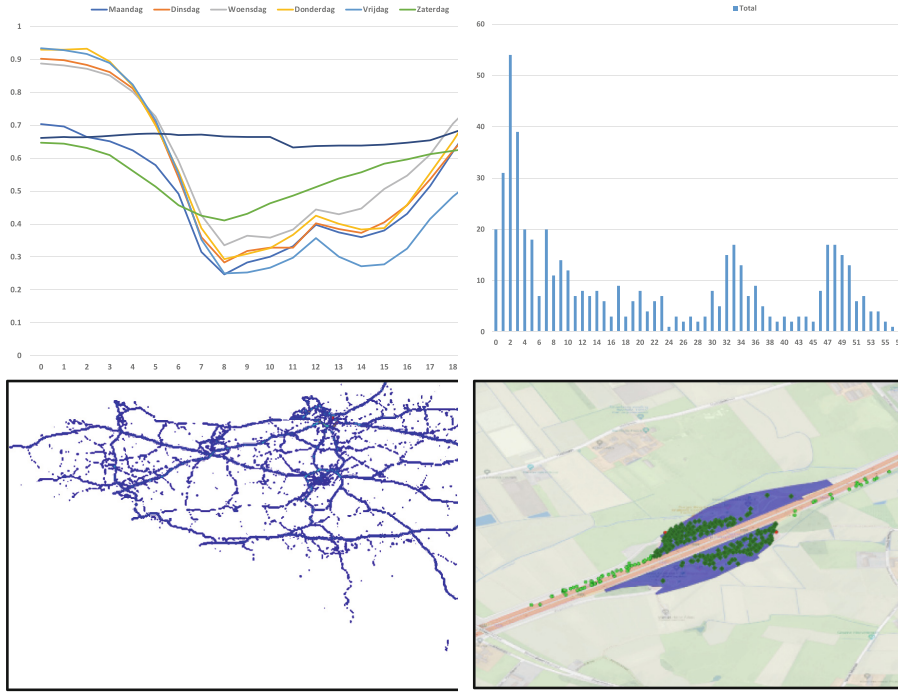



**Fig. 2.** Example data sources used for the analysis of the research questions: parking occupancies per day of the week (upper-left), distribution of parking durations in minutes (upper-right), truck OBU data from trucks (bottom-left), truck OBU data matched on motorway parking terrains (bottom-right). Figures created using Microsoft Excel, Java, and QGIS.

### 2.3 Analysis of User Acceptance

#### 2.3.1 Surveying Truck Drivers

We rolled out a survey after the end of phase 3, containing an extensive questionnaire. The survey could not be conducted in the car parks themselves due to the COVID-19 pandemic and the associated measures. As such, we created it digitally. Because the truck drivers had to be reached on the route, the concession holders of the car parks were approached for this, advertisements were posted in specific Facebook groups of truck drivers (both those of the government and others), via LinkedIn posts, and finally it was also distributed among the truck drivers of a specific local distribution company. In addition, QR codes were also made available, which referred to the survey. The survey was available in Dutch, French, English, and German. The survey was closely monitored week after week, with appropriate actions taken to receive statistically significant feedback and a high response rate. In total we had 256 complete (42%) and 349 (58%) incomplete answers for a total of 605 together.

#### 2.3.2 Surveying Truck Drivers

As a final step in our evaluation, we held interviews with nine relevant stakeholders from the ecosystem: transport sector organisations, private concession holders, public stakeholders, service providers, and stakeholders from policy. Through the interview we wanted to gauge the use, the possibilities, and the findings about services that provide information about the occupancy rate. Each interview included the following three main parts that were surveyed from all stakeholders:

- In the first part, we asked about more general aspects of service zones and the extent to which the interviewee or the organisation has knowledge about the services to communicate occupancy rates to truck drivers or others.
- In the second part, we mainly asked how the organisation feels about this service.
- In a final part, we discussed the specific aspects of this service: to what extent is it effective? What impact can it have on the organisation? How do you see the costs and benefits? Etc.

## 3 Conclusions

### 3.1 Research Question 1: Which Technology Best Measures Parking Occupancy?

After analysing parking occupancy measurements, the answer to this question appears to be nuanced, whereby the traffic sensors appear to score less well, barriers score quite well, as do parking sensors (if there is no overcrowding). This answer is based on a detailed technical evaluation of measuring methods for the dynamic occupancy rates of truck parkings.

Analyses of the OBU data showed that most trucks that were already in the car park leave before 7 am (these have mainly Poland, Belgium, Lithuania, the Netherlands, and Romania as countries of registration). Conversely, most trucks stop (for the rest of the day) more at Nazareth and Marke than the other car parks. The bulk of trucks routinely

arrive at a car park throughout the day, with a slight dip around 8 am. When it comes to regular car park arrivals, Kalken, Nazareth, and Marke have the highest volumes. In these, the parking peak is earlier in the morning/early afternoon. Finally, we also analysed the lorries' dwell times in the car parks. There is a large spread here with local maxima. Nevertheless, the majority of trucks appear to be in the car park for only a very short time (less than 10 min), followed by two groups around 35 and 50 min. These two local peaks occur around 10h00 -11h00.

### 3.2 Research Question 2: What is the Impact of Providing Parking Occupancy Information to the Truck Driver?

To measure the impact of the different incentives on the occupancy rate, we organised three successive phases: a baseline measurement, an app made available to the truck drivers, and both an app and active VMS boards. Compared to the baseline measurement in phase 1, making the app available in phase 2 had a negligible to nonexistent effect on the parking behaviour of truck drivers (due to the very low penetration rate).

It was not possible to uncover a direct relationship between the messages on the VMS signs and parking occupancies. Nevertheless, the VMS signs were the only variable across the three phases, excluding other factors such as seasonal effects, for example, and we could not observe any other measures taken or behavioural changes. Consequently, the activation of the VMS signs in phase 3 probably did have a positive effect, with the indication of the current occupancy rate presumably leading to a better distribution in the car parks. Note that the VMS signs mainly provided information for the car parks at Nazareth, Kruishoutem, and Marke. Only the VMS sign near Kortrijk also gave information for Rekkem.

### 3.3 Research Question 3: How Do Users Deal with the Information (User Experience)?

We rolled out our own survey after phase 3, which contained an extensive questionnaire. Almost all respondents (239 of 256, 93%) drove on the A10 / E17 towards France, which gave relevant results. There were 164 respondents (69%) who used the information from the VMS. Almost all (89%) found the information offered useful to very useful. Most of the respondents (76%) thought that the information on the VMS was usually correct, and if this was not the case, it turned out that there was no space left while the signs indicated the opposite (just like with the app). In the future, a large proportion of truck drivers (80%) would find an app useful to very useful, and a smaller proportion (20%) rather useless.

## 4 Recommendations

The issue of truck parking in Flanders has been studied and plays out in three areas:

1. Truck parking in motorway car parks, especially in service areas during night and weekend rest. This problem occurs on all axes of freight transport on motorways in Flanders. The problem is most pronounced in the Ghent-Brussels-Antwerp triangle and extends along the E17 towards the French border;

2. Truck parking along regional roads and near residential areas. This often involves truck parking by employees who take the truck home and park it locally. It is more of a local problem where parked trucks take up public space and sometimes cause danger;
3. Truck parking for loading and unloading where trucks occupy public domain or wait on the street until it is their turn or their time slot to load or unload. The problem here is that trucks sometimes block public roads.

A total of over 5,300 long-term parking events per day are measured in Flanders. Parking on the secondary road network is often linked to the function of the location. Areas attracting freight traffic (industrial zones, airports, and ports) have more trucks parked along the road. Of the total number of trucks parked, about one-fifth are parked in unofficial car parks.

Our study had a very broad approach, in which a number of aspects were highlighted in great detail. To answer the three research questions, various analyses were performed, experiments were set up, and groups of users were questioned. There are consequently a number of comments with regard to the implementation of the study and the interpretation of the results.

- Before such a study like this can be started, the technical systems to be considered must already be operating under good conditions. This was not always the case, which meant that certain analyses had to be repeated several times.
- Various problems occurred during the study, including detection methods that were set over time with different parameters, problems with technical installations, missing measurements, manual counts that were partly incorrect, etc.
- Further research could be useful, given that a significant number of manual counts are available. This would then make it possible to determine whether data is best fused or not, or recalibrated regularly, and to what extent raw data is suitable for achieving a good fusion. A larger amount of data and a greater mutual comparability of the various locations are strong pluses. Another caveat to the impact analyses is that more data would in any case lead to more stable results.

A comment on the impact analyses is that more data would lead to more stable results anyway. Initially, a longer baseline measurement is recommended (at least four weeks). On top of that, the app penetration rate needs to be significantly higher if we want to measure any impact from that. Finally, it is also true that the spatial scope of the study is limited on two levels: on the one hand, we do not know what happens beyond the border with France (after Rekkem), and on the other hand, parking could also occur on breakdown lanes, and possibly even on (car parks on) the underlying road network.

It is not clear whether VMS or the app can guarantee a better service: VMS appears to be necessary if one gets closer to the car parks. An app allows for more options and can, if necessary, be more complete. The reluctance to an app is more about the use of a mobile phone and road safety. If this service is integrated into the truck itself, the reluctance is less. Providing the service is mainly placed in the hands of the government by some stakeholders, one expects that the government will outline the guidelines and assume responsibility for both the detection facilities and the provision of data.

The problem of overcrowded car parks and the need for a better distribution of use is almost unanimously endorsed. Service provision, as in the pilot project, will certainly make its contribution but should be seen as part of a more global approach: better legislative framework, enforcement, more parking facilities including (private) ones not along motorways, etc. A parking policy/vision therefore urges both regional and European. The main stakeholders seen are the government, parking operators (concessions/private/public), service providers and truck manufacturers. The provision of the service is mainly put in the government's shoes. People expect the government to set the outline and take on both the detection provisions and the provision of data.

There is certainly the will of organisations to contribute to tackle the problem. How far one wishes to go as an organisation to facilitate this service is closely related to the business potential of the service and what role one should assume as a stakeholder (facilitator, data provider, etc.). Minimum information that should be provided is indicating which car park is full or free and the travel time to the relevant (free) car park. Preference is given to using figures/icons and as little text as possible.

**Acknowledgements.** The projects referenced in this paper have received funding from the European Union's Connected European Facilities (CEF) programme under grant agreement No 2014-BE-TM-0694-S, the Flemish government, Administration of Roads and Traffic, contract No TDV.064.EVCITS_009, and the Flemish Department of Mobility and Public Works.

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# The TANGENT Governance Model for Mobility Data Sharing

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**Abstract.** Guaranteed access to mobility for all is one of the conditions for the participation of all individuals in an inclusive society. On the one hand, there is a significant increase in the availability of multimodal mobility services for people. On the other hand, the increase in the movement of people using different mobility services makes traffic management an even more difficult challenge to overcome. Traffic management must move from the traditional management of traffic volumes to managing the different types of available vehicles. For this purpose, the EU-funded TANGENT project is developing new complementary services for optimising multimodal traffic operations. Data from heterogeneous data sources must be appropriately shared between the stakeholders involved in the project to enable the development and testing of these innovative services. This paper presents the methodology adopted by the TANGENT project for formalising the TANGENT Data Sharing Governance model and adequately managing and facilitating data-sharing tasks.

**Keywords:** Mobility Data · Data Governance · Data Sharing

## 1 Introduction

The European Strategy for Data [1] defines data-sharing as the process of making the same data source accessible to numerous users or applications. The strategy includes the creation of a common European mobility data space (EMDS) 2] that should facilitate the access, pooling and sharing of data from existing and future transport and mobility data sources. The goal is to overcome technical and legal barriers and to ensure trusted and secure data-sharing by combining data governance frameworks and technical infrastructures. With this objective, the Data Governance Act [3] has been stipulated to increase all the benefits from data for European citizens and businesses by fostering secure data handling and more transparent data governance.

The TANGENT project[1] is developing new complementary tools for optimising traffic operations, elaborating data related to multimodal transport services and considering automated/non-automated vehicles, passengers, and freight transport.

A structured and effective data governance model is crucial for managing and facilitating data-sharing between the different stakeholders involved in the project. This paper

[1] https://tangent-h2020.eu/.

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presents the methodology adopted by the TANGENT project for formalising the TANGENT Data Sharing Governance model based on an extensive analysis of the literature and the adoption of best practices.

## 2 Methodology

Defining a governance model is crucial to regulate the data-sharing between data providers and the organisations involved in the TANGENT project. The methodology adopted by the project to define the data-sharing governance model includes the following propaedeutic activities: (i) extraction of a Data Governance Reference Schema from relevant papers in data governance literature representing the main aspects to consider to handle data governance properly; (ii) usage of the Data Governance Reference Schema to guide the analysis, comparison, and discussion of literature related to data governance in the transport domain and to identify best practices to be adopted in the TANGENT project; (iii) discussion of the best practices and collection of additional information about data governance aspects in dedicated workshops with relevant stakeholders of the TANGENT case study cities (i.e., Athens, Lisbon, Greater Manchester, and Rennes).

### 2.1 Data Governance Reference Schema

The analysis of relevant papers in data governance literature (e.g., [4–6]) has guided the definition of the *Data Governance Reference Schema* shown in Fig. 1.

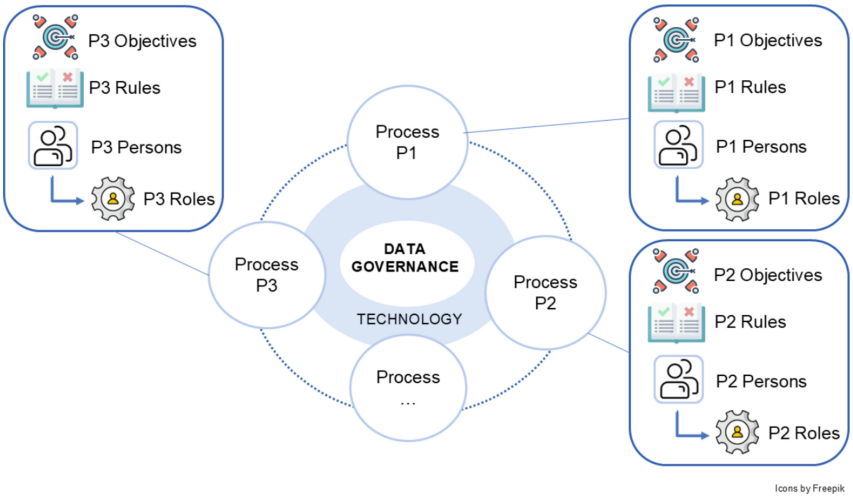



**Fig. 1.** The Data Governance Reference Schema

Data governance (DG) involves different *processes* (e.g., data collection, sharing, usage) characterised by several *objectives* (e.g., data quality, data accessibility, compliance with European directives). The *rules* that enable each process to achieve the

objectives are defined through the DG model. An example is represented by the rules that must be applied and observed to allow for data accessibility in the data-sharing process, such as the acquisition of metadata, the definition of a descriptor, its validation, and so on.

The stakeholders involved in executing the different processes represent all the significant *actors* to be considered in the definition of the DG model. Each actor may assume one or more *roles* (e.g., data publisher, data controller, data owner). A committee or an authority body may be defined to cover the role of the central DG authority. Other roles often considered by a DG model are the data steering committee, the DG officer, the data owner, the data steward (i.e., who oversees aspects related in general to data management, e.g., format, accessibility, description and quality), and the technology steward (i.e., who is responsible for regulating the use of the different technological solutions and tools needed to perform a specific process).

### 2.2 Mobility Data Governance: Best Practices

The Data Governance Reference Schema has guided the analysis, comparison, and discussion of DG models defined by European research projects (e.g., Transforming Transport[2], HARMONY[3], MOMENTUM[4], NOESIS[5], LEMO[6]) in the transport domain. The analysis of the proposed DG models has highlighted the following best practices:

- definition of rules and establishment of a Technical Management Board for facilitating the processes of data collection, publication, and sharing;
- definition of a metadata catalogue for supporting the data-sharing;
- definition of rules to enforce compliance with European regulations on data (e.g., [7]) and to ensure interoperability and reuse of data and metadata;
- definition of rules to properly govern data manipulation (e.g., data harmonisation and fusion);
- definition of rules to properly govern data reuse.

### 2.3 Workshops with Stakeholders

The objective of data-sharing in the TANGENT project is to enable the testing of the TANGENT solutions for optimising traffic operations in each case study. Data-sharing must be performed following a structured and effective Data Governance model.

The project has organised multi-actor cooperation workshops with the stakeholders involved in the TANGENT case studies. Each workshop had a dedicated section on data governance to collect additional information about directives, regulations, and DG aspects to be considered for managing data related to the TANGENT case studies.

The following data governance processes were presented and discussed in the first part of each DG section: (i) dataset identification and description, (ii) data access, (iii)

[2] https://transformingtransport.eu/.
[3] https://harmony-h2020.eu/.
[4] https://h2020-momentum.eu/.
[5] http://noesis-project.eu/.
[6] https://lemo-h2020.eu/.

data harmonisation and fusion, and (iv) data usage. Then, in the second part, the participants were invited to actively join a working session aimed at collecting (i) feedback on rules proposed by TANGENT to regulate data-sharing within the project partners, (ii) information on active regulations and directives at the city or national level that TANGENT must be aware of, and (iii) information about stakeholders potentially involved in the process.

The analysis of the collected information has shown that all the participants agreed on the importance of:

- adopting a metadata profile for describing datasets;
- signing an NDA between TANGENT partners and each external data provider to enable and regulate access to and the use of private datasets;
- assuring a high level of data quality of the dataset;
- ensuring compliance with existing licences for handling datasets' access, manipulation and use.

## 3 TANGENT Data Sharing Governance Model

Based on the results of the propedeutic activities described in Sect. 2, the TANGENT project considered the following elements as crucial aspects for the definition of the TANGENT Data Sharing Governance Model:

- data governance is characterised by different *objectives* (e.g., enhance findability and reuse of data);
- data governance should consider *different data source types*;
- data governance should consider *tools and technologies* adopted for data-sharing;
- data governance refers to different *processes* (e.g., data publication, data access);
- different *actors with different roles* are involved in the governance of each process;
- different *rules* (both external and defined by the project) should be applied to establish effective data governance.

The TANGENT Data Sharing Governance Model focuses on five different processes identified according to the project objectives:

- *Data publication*: the process of describing a data source in a shared catalogue according to a metadata profile;
- *Data quality*: the process of assessing the quality of a data source and its metadata published in the shared catalogue;
- *Data access*: the process of accessing data contained in or exposed from a data source;
- *Data storage*: the process of storing (a portion of) data provided from a data source;
- *Data usage*: the process of using and/or manipulating data from one or more data sources.

This section focuses on the data publication process and describes the main data governance rules regulating it in the TANGENT Data Sharing Governance Model (listed below). These rules require the usage of the *TANGENT Data Catalogue* (i.e., a data catalogue implementing a single solution for the findability and accessibility of all the data sources shared within the TANGENT project) and the *TANGENT Metadata Profile*

(i.e., a specification defining metadata fields for the description of the data sources in the TANGENT Data Catalogue). Moreover, the rules must be applied by stakeholders covering two different roles: the *TANGENT data publisher* (i.e., the person responsible for publishing and describing a data source within the TANGENT Data Catalogue) and the *TANGENT Data Catalogue Management Board* (i.e., a group of persons responsible for the management and control of a (set of) data source(s) within the TANGENT Data Catalogue).

- Rule "*Sharing of external data sources for the case study*": The external data sources (both open and proprietary) required for each case study should be published in the TANGENT Data Catalogue. The TANGENT case study leader assumes the role of TANGENT data publisher for all the external data sources related to a specific case study.
- Rule "*Metadata description of data sources*": The TANGENT data publisher should describe a data source in the TANGENT Data Catalogue according to the TANGENT Metadata Profile. The licence selected for metadata in the TANGENT Data Catalogue is Creative Commons CC-BY. Metadata requiring a stricter licence should not be added to the TANGENT Data Catalogue.
- Rule "*Approval of data source publication*": The TANGENT Data Catalogue Management Board validates the publication of data sources shared and described by the TANGENT data publisher. In particular, the TANGENT Data Catalogue Management Board should ensure the publication of data sources following signed NDAs and data licences.

## 4 Conclusions

Based on an extensive analysis of the literature related to data governance, this paper has provided a Data Governance Reference Schema describing the proper structures and processes to handle data governance properly. The reference schema has been used to guide a more tailored analysis of literature related to data governance in the transport domain. The comparison led to identifying best practices for the TANGENT project.

These propaedeutic activities and the inputs collected from stakeholders during the multi-actor cooperation workshops have been used to define the TANGENT Data Sharing Governance model. The model identifies crucial processes (data publication, data quality, data access, data storage, data usage) to be addressed by TANGENT stakeholders with different roles and following a detailed list of rules.

The TANGENT Data Sharing Governance model represents a best practice that can be easily adapted for the governance of a mobility data space, guiding data sharing between data owners and consumers properly.

Effective data governance, such as the one defined by TANGENT, can facilitate the sharing and reuse of data and enable the creation of new tools for optimising traffic management operations. Through simple rules and agreements on data-sharing, it is, in fact, possible to improve real-time traffic management and mobility planning, reducing road congestion and pollution and increasing our security.

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# An Integration Framework to Support Data Sharing and Process Tracking in Intelligent Asset Management Systems

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**Abstract.** The advancement of Intelligent Asset Management Systems (IAMS) in the railway sector can be fostered by integrating data and trustworthy artificial/human intelligence. However, the implementation of solutions for maintenance prescription and optimized intervention plans requires the integration of multiple digital artifacts and the involvement of different stakeholders. This paper discusses an IAMS Support Integration Framework, facilitating the integration of diverse digital artifacts for the implementation of intelligent maintenance scenarios in a multi-stakeholder environment. To support the integration, the framework offers functionalities for enhancing data sharing and guaranteeing process tracking within an IAMS. The paper outlines the framework's requirements and architecture, demonstrates its implementation in practical scenarios from the DAYDREAMS project and presents the preliminary evaluation performed with relevant stakeholders.

**Keywords:** Intelligent Asset Management System · Data Sharing · Reproducibility · Data Catalogue · Process Tracking

## 1 Introduction

DAYDREAMS, which completed its activities in May 2023, is a project within Shift2Rail's 3rd Innovation Programme (IP3). The project's overall objective was to advance the integration and use of data and artificial/human trustworthy intelligence for Intelligent Asset Management Systems (IAMS) in the railway domain. The adoption of an integrated Intelligent Asset Management System is highly relevant in the digitalisation process of railway companies, and different solutions can be considered according to specific needs [2]. The DAYDREAMS project focused on a set of maintenance scenarios proposed by three railway maintenance stakeholders to implement intelligent asset management solutions such as (i) prescription based on asset status forecasting (prescriptive analytics, PA), (ii) optimisation of maintenance intervention plans considering different metrics and constraints (multi-objective optimisation, MOO), (iii) contextdriven interfaces to enhance human decision-making (human-machine interface, HMI).

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This paper reports on the design and demonstration of an IAMS Support Integration Framework to enable the integration of different digital artifacts for an intelligent maintenance scenario in a multi-stakeholder environment. In this direction, the complementary objectives of the framework are: (i) to enhance data sharing to support better the reuse of solutions developed by different stakeholders, e.g., a prediction model for a specific type of asset may be reused, and (ii) to introduce a trusted way of tracking and auditing the adoption of digital solutions within maintenance process, e.g., to identify users and software components that failed to predict a breakdown. A prototype, implementing the IAMS Support Integration Framework for the three DAYDREAMS scenarios, is discussed and evaluated to demonstrate the proposed solution.

## 2 Challenges and Related Works

The SHIFT2RAIL[1] Innovation Program 3 promoted the development of solutions for intelligent maintenance in the context of railway asset management [9]. In this framework, DAYDREAMS tries to make a step forward (leveraging the knowledge and results of IN2RAIL, IN2DREAMS, IN2SMART and IN2SMART2 projects[2]), proposing a holistic approach where the information on the current and future status of the assets (e.g., actual faults to repair and probability of news faults) together with the estimated information on the maintenance (e.g., costs and duration), are exploited to deliver options to decisionmakers on how to schedule, improve, and reduce the impact of the maintenance with the purpose to improve the infrastructure maintenance management.

The implementation of such a solution requires the collection of data from different data sources and the implementation of specific software components for data analytics (PA, MOO) and visualisation (HMI). Moreover, an effective deployment in an integrated system is needed for users to adopt it within maintenance operations. A significant challenge is associated with multiple stakeholders involved in maintenance processes, e.g., asset manufacturers, maintenance supervisors, and maintenance teams. Moreover, the definition of digital solutions supporting asset management introduces a set of additional stakeholders to be considered, e.g., sensor manufacturers, vendors of data collection solutions, and data scientists developing models for prediction and prescription. Each stakeholder may contribute or use different digital artifacts and should be made accountable for its involvement in the overall maintenance process. Finally, other actors often have similar needs for implementing intelligent maintenance solutions but adopt different or non-interoperable software solutions, thus slowing down the digitalisation process.

To streamline and enhance the integration, two fundamental sets of guidelines were considered in the design of the proposed framework. On the one hand, the FAIR principles (Findability, Accessibility, Interoperability, Reusability) defined in the context of research data management [10], can be adapted to consider different digital artifacts, from software components [6] to machine learning models [4]. The principles emphasize: (i) the importance of structured metadata for facilitating the findability of digital

[1] https://rail-research.europa.eu/research-development/.
[2] https://projects.shift2rail.org/s2r_ip.aspx?ip=3.

artifacts, (i) the publication of digital artifacts online for accessibility, (iii) the adoption of best practices and standards to facilitate the interoperability of the solutions, and (iv) the need for precise documentation and legal terms of access and usage to support reusability. On the other hand, the Machine Learning Operations (MLOps) guidelines [7] were considered to promote automation in the development and deployment cycle of software components for prediction, prescription and optimisation.

Adopting a shared catalogue of digital artifacts [5] allows actors belonging to different roles to publish and manage descriptions of web services, datasets, and software components promoting their findability and reusability. In the DAYDREAMS project, we focused on how to effectively implement a shared catalogue for intelligent asset maintenance by identifying the relevant digital artifacts and associated requirements. Moreover, while many works in the literature focus on platforms for the development of machine learning models [1], we focused on how to enable the deployment and integrated execution of such models and related software components to support the end users. Finally, considering previous results from the IN2DREAMS project on the usage of blockchain technologies for auditability purposes in the railway domain [8], we define a seamless solution to keep track of operations associated with an intelligent maintenance scenario.

## 3 IAMS Integration Support Framework

To design a solution supporting the implementation of Intelligent Asset Management Systems, we focused first on the elicitation of the technical requirements associated with it. Integration means first of all the identification or development of the relevant digital artifacts (e.g., datasets, machine learning models, software components) and the availability of a runtime environment for the deployment. Then, it means allowing proper communication between components, which have been developed independently, and guaranteeing their integrated execution according to well-defined processes, i.e., sequence of operations. Finally, the execution of processes must be monitored to ensure that all the stakeholders involved in developing and using the components acted appropriately.

The architecture designed for the IAMS Integration Support Framework, shown in Fig. 1, is based on three macro-functionalities defined to support the elicited requirements: (i) a shared catalogue to enhance the findability and reusability of digital artifacts (IAMS Shared Catalogue); (ii) a runtime area for the integrated deployment and execution of artifacts associated with intelligent maintenance scenarios (IAMS Runtime Area); and (iii) a blockchain-based system to handle the monitoring and tracking of artifacts, processes and operations performed by users (IAMS Process Tracking).

Stakeholders can store and describe in the shared catalogue their digital artifacts, as well as Intelligent Maintenance Packages (IAM Package) defined to group artifacts for integrated execution. The catalogue supports the configuration of metadata profiles for the consistent description of artifacts, and lifecycle processes defining their governance (e.g., process to request/grant access to an artifact). Additionally, it implements programmatic access to the artifacts, allowing stakeholders to develop advanced functionalities (e.g., creation or update of artifacts at runtime). We identified four basic digital artifact

types: Dataset, Software Components, Machine Learning Model, and Maintenance Plan. We defined a metadata schema for each of them relying on the generic ADMS-AP specification [3] and on more specific controlled vocabularies targeting each artifact type. The runtime environment enables stakeholders to deploy software components needed for the integrated execution of IAM Packages in a secure and integrated environment. Software components should be containerised[3] and expose well-documented interfaces (e.g., HTTP API documented through OpenAPI[4]) to facilitate their deployment and integration with other components. Finally, the tracking functionality allows stakeholders to monitor the lifecycle of digital artifacts, tracking it together with the runtime operations performed by users. Each lifecycle and runtime interaction is transparently registered as an operation, and a blockchain-based infrastructure is leveraged to provide additional trust among the involved stakeholders. This information can also be saved within the shared catalogue as an Intelligent Maintenance Session (IAM Session) artifact and exported for auditing and reproducibility purposes, ensuring transparency and accountability in managing digital artifacts.

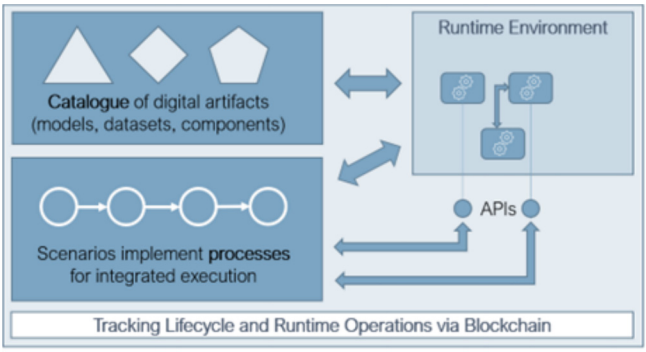



**Fig. 1.** Overview of the IAMS Integration Support Framework

## 4 IAMS Integration Support Prototype

The IAMS prototype, developed by DAYDREAMS and shown in Fig. 2, demonstrates the implementation of the IAMS Integration Support Framework and its application considering three intelligent maintenance scenarios proposed by railway stakeholders. The digital artifacts are described in the IAMS Shared Catalogue by different users, and an IAM Package is defined for each scenario grouping together the relevant artifacts. Each IAM Package comprises real datasets provided by railway stakeholders to address a proposed maintenance scenario, innovative software components and machine-learning models for PA e MOO developed by the project, and a dedicated HMI designed by UI experts. The users can access the catalogue through a dedicated web interface and

[3] https://opencontainers.org/.
[4] https://www.openapis.org/.

access all the metadata of the digital artifacts. All the lifecycle operations associated with digital artifacts are tracked and can be visualised through the catalogue. The containerised software components are automatically deployed in the IAMS Runtime Area in isolated sub-networks for each IAM Package. The IAMS Prototype functionalities are implemented transparently by a set of dedicated components, i.e., without requiring a modification of the integrated PA and MOO components. The IAMS Gateway handles the authentication and redirects the requests made by users interacting with the HMI. Additional functionalities enabling the tracking of runtime operations and the implementation of advanced integration with the shared catalogue are implemented by dedicated Package Handler components. In the IAMS prototype, we demonstrated the automatic update of the metadata of a machine learning model every time a training operation is performed, as well as the usage of the shared catalogue to store and retrieve maintenance plans generated and modified by different stakeholders. The IAMS Process Tracking component receives all the tracked operations and registers them through the blockchain-based infrastructure to ensure trust among various stakeholders interacting with the system. The user can retrieve the list of operations performed in each IAM Session and trace back all steps taken during the runtime interaction with the digital artifacts in an IAM Package. All the operations returned to the user are validated through the blockchain, and an alert is produced if the validation is unsuccessful.

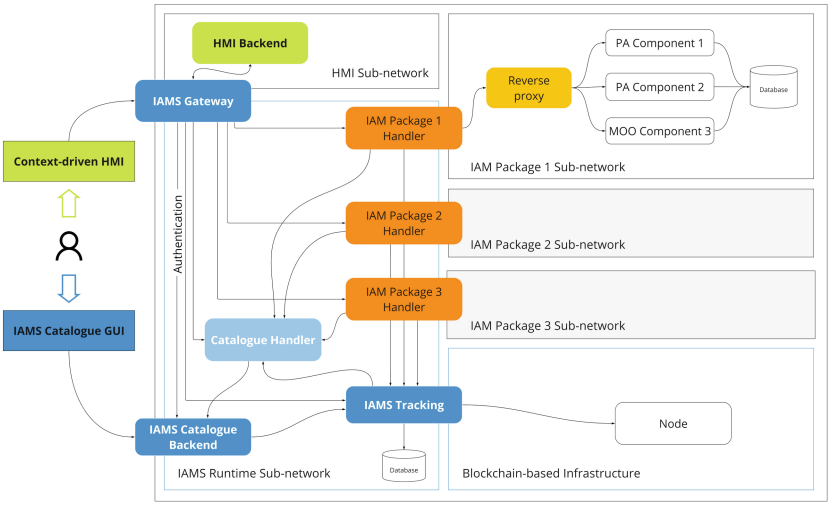



**Fig. 2.** Overview of components integrated within the DAYDREAMS IAMS prototype to demonstrate the IAMS Integration Support Framework.

The implemented prototype successfully supported the demonstration of the final project results within the three practical use cases for railway maintenance considered. It demonstrated the sharing of digital artifacts through structured descriptors and a common catalogue, the integrated deployment of the software components for end-users to visually inspect and interact with maintenance predictions and prescriptions, and the adoption of a blockchain-based solution to track and audit operations in a trusted way.

Moreover, we performed an initial assessment of the prototype by showcasing its capabilities to six stakeholders from three distinct railway-related companies specialized in infrastructure management and intelligent maintenance solutions. This assessment aimed to gather their insights through interviews regarding the technical feasibility and business potential of implementing this solution within their organizations. The participating stakeholders recognized the benefits of integrating similar functionalities into their operations to enhance the reusability of digital artifacts and foster trust among involved parties. All stakeholders indicated their interest in potentially adopting a similar solution in the near future, with an average rating of 3.5 out of 4. Notably, one stakeholder highlighted the importance of applying these principles to external entities (e.g., external service/product providers) and various units and geographical divisions within large corporations. Regarding potential enhancements, the stakeholders stressed the need to ensure the tool's user-friendliness for individuals with diverse technical backgrounds and to meet stringent security requirements for handling proprietary and confidential digital artifacts.

## 5 Conclusions

The paper presented an IAMS Integration Support Framework to foster the sharing and reuse of digital artifacts for different intelligent maintenance scenarios, and to enable process tracking mechanisms guaranteeing trust in a multistakeholder environment. The discussion of the IAMS Prototype, developed within the DAYDREAMS project, demonstrated the application of the proposed framework to a set of practical intelligent maintenance scenarios involving different digital artifacts and processes. The implemented prototype and its evaluation by stakeholders highlight how the proposed framework can effectively support the integration of digital artifacts for a generic intelligent maintenance scenario and the potential interest for adoption by companies.

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# Implementation of a Novel Concept to Unlock Data Value in Multimodal Systems

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**Abstract.** This paper aims to present the basic elements of the Smart Contract Framework (SCF) and the value of data sharing in a multimodal system. SCF is a business process that defines data exchange rules among Transport Service Providers (TSPs) that share the common goal of getting the passenger to his/her destination through a multimodal trip chain. It provides a centralized hub for the generation and management of contracts (i.e., data sharing agreements and smart contracts) via a web platform that allows TSPs to create, negotiate and continuously monitoring and making use of signed contracts. Most importantly, the storage of TSPs' data and all the data sharing processes are executed outside this platform. Moreover, the SCF will provide a data driven environment where exchanged data can be further used for other purposes (e.g., analytics and business relationships' analysis). Additionally, data sharing has the potential to create benefits for TSPs in the form of greater transparency, reduced costs, increased revenue, strengthened business relationships, etc.

**Keywords:** Multimodality · Transport Service Providers (TSPs) · Seamless door-to-door (D2D) transport · Data Sharing Agreement (DSA) · Travel Companions (TC) · Single Ticketing

## 1 Introduction and Literature Review

The stakeholders of air transport are integrated into the air transport system. They permanently exchange their data to provide safe, secure, and expeditious transport. However, connection with the other modes of transport has not reached the same level, since there are no regulations and a common channel of communication between stakeholders of different modes of transport. The European Air Traffic Management (ATM) Master plan [1] envisions the integration of air transport into the transport system with all other modes of transport.

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Multimodality as a concept implies full coordination and integration of different modes of transport including a single ticket for the whole journey, coordinated timetables, the possibility of remote check-in, etc., [2]. To provide multimodal service and to include air transport in multimodal chains, stakeholders from different modes of transport must collaborate. To ensure successful collaboration, some preconditions need to be satisfied, i.e., stakeholders involved in the multimodal chains need to have data in digital form and a standard format. Moreover, the stakeholders must recognize the benefits of multimodal service and must be willing to cooperate and share their data.

To fulfill a selected goal (e.g., single ticketing, synchronization of timetables etc.), data which need to be shared has to be precisely defined. More data is not mandatory but less can be an issue. Therefore, depending on the selected objective, data sets that need to be shared are defined [3]. The participants involved in providing the multimodal service should trust each other and should show a willingness to start the collaboration and further sign a data sharing agreement (DSA) and/or smart contract (SC) as well. SCs are proposed by [4] representing computerized transaction protocol that executes the contractual terms of an agreement. Although there is no uniform definition regarding the SC, it can be defined from two main perspectives, from the lawyers and from the IT perspective.

Regarding SCs, computer scientists refer to the code, while lawyers are more focused on the legal relationship of obligations [5]. Therefore, we can say that a smart contract is an e-contract composed of a legal part and a software part (i.e., external smarter contract model). Contractual clauses embedded in smart contracts enable automatic enforcement in the case that a defined condition is met [6]. They pointed out the advantages of SC over conventional contracts emphasizing that they reduced risks, cut down administration and service costs, and improved the efficiency of business processes. Data sharing agreement (DSA) is an e-contract that defines the data that should be shared between the two Transport Service Providers (TSPs) who signed the contract. More precisely, a TSP who is a provider should make data available to another TSP who has the role of data consumer. These contracts also set out the specific terms and conditions for the lawful use of such data. In our research there are predefined objectives of data sharing agreements that can be selected by TSPs who want to sign the DSA. Therefore, the objective of a DSA can be single ticketing, synchronization of timetables, optimization of resources, increased ridesharing, etc. This objective determines the required datasets. On the other hand, the SC is an operational contract that details the objective of the DSA and defines specific Triggers (conditions) and Actions (contractual obligation).

Collaborative transport requires that all participants share relevant data, but individual TSPs may hesitate to share (parts of) their information due to reasons of security and competition. However, the precise value of realistic and complete information sharing can be very high. This value can be seen in about 20–30% reduced travel costs, pollution, and congestion when different TSPs cooperate by combining transport services [7]. If TSPs cooperate in larger coalitions research shows that individual TSP can improve profit up to 800% [8]. In [9] can be found a comprehensive review on the modelling of information sharing in collaborative transport and the estimated value of sharing different levels of TSP data.

The objective of this paper is to propose a new business model aligned with EU policies, namely Smart Contract Framework (SCF) which sets common goals for data sharing between TSPs and points out the value of data sharing in the multimodal transport system. After a brief introduction and the literature review, the new concept is described. It is followed by the need and value of sharing the data in the multimodal transport chain. The paper finishes with some concluding remarks.

## 2 Smart Contract Framework

SCF, proposed in this paper and in the SYN + AIR[1] project, is a process designed to manage (i.e., negotiate, create, modify, terminate and monitor) DSAs and SCs between the two TSPs. To facilitate this process and to materialize the SYN + AIR's findings, a web platform will be developed by the SIGN-AIR[2] project. SC will detail different modalities of the operational collaboration between TSPs, depending on the selected multimodal transport objective(s). To provide a safe and secure data sharing process, the TSPs willing to collaborate should sign the DSA, which will regulate all actions. A DSA defines the "who" and "what" should be shared. Such an agreement could be complemented with a SC [10] which defines the rules concerning "how" and "when".

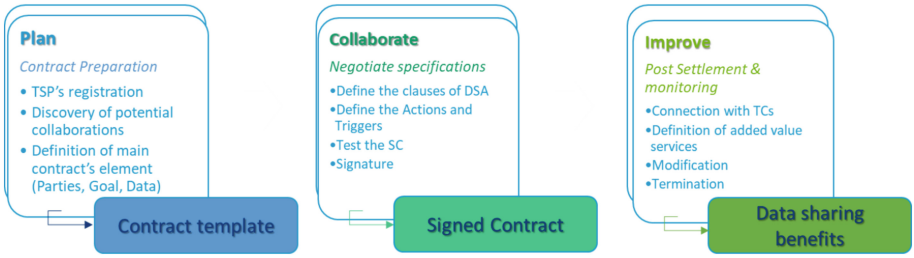



**Fig. 1.** Smart Contract Framework phases.

The platform's overall objective is to simplify and standardize the process of data sharing between two TSPs. It facilitates their mutual obligations in the field of multimodal transport. What is the motivation for TSPs to use SCF and sign SC? The usage of SCF will bring certain benefits to the TSPs that can motivate them to join the platform. For example, TSPs will get familiar with a standardized process for data sharing, and they will optimize negotiation time from a legal perspective using technological aids. Moreover, signing a DSA will clarify the minimum data sets required and the objective that should be shared. Finally, by signing a SC, the operational obligations of TSPs will be unambiguously defined, as well as the time when they need to be executed. Most importantly, by using the TSPs platform could identify potential collaborations and to unlock the value of their datasets (Fig. 1).

[1] Synergies between transport modes and air transportation, SYN + AIR, funded by SESAR Joint Undertaking, GA No 894116.

[2] Implemented Synergies, data sharing contracts and goals between transport modes and air transportation, funded by SESAR Joint Undertaking, GA No 101114845.

**Contract preparation.** It allows the TSPs to create their identity and find potential collaborations, and the platform to prepare for them the relevant contracts' templates. *Registration.* At the beginning of the process the Terms & Conditions (rules of platform provision and framework for DSAs & SCs) should be signed by a person who is authorized and entitled to act on behalf of the legal entity. This person will become platform user and provide access to certain colleagues to sign the User Agreement. The latter is used to identify the authorized end users of the TSP, namely the signing representative, administrative (negotiator), and technical (data/transport expert). *Discovery –Definition.* By the registration at the platform a TSP has three different pathways using a graph database running at the backend (Fig. 2). A TSP based on the reason that it is registered (e.g., needs, ambitions etc.) can: 1) Select a specific goal of DSA that applies to multimodality (e.g., Single ticketing, Synchronization of timetables, Optimization of resources, Increase ridesharing, etc.) The platform proposes a list of potential collaborators and the required data to be provided and consumed by the TSP to be able to fulfill the selected goal. 2) Select to provide the data that TSP wants to offer (create its catalogue). Then based on that data, the platform can indicate a list of goals and specific collaborators (TSPs). 3) Choose a specific TSP, then the platform provides the type of collaboration (goal) that they can fulfill and the data that are required to be shared between them.

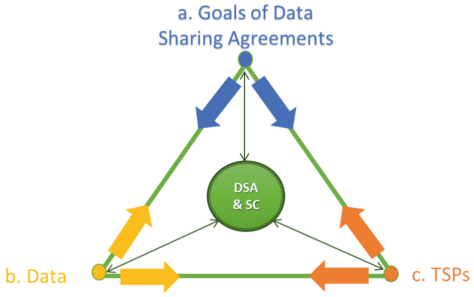



**Fig. 2.** Triangle of collaboration vision.

Therefore, based on the lists/options of potential collaboration the TSPs can make a decision on how to proceed. The outcome is the same in all the pathways, the TSP will have defined the basic elements of the DSA creation which are the Goal of the Agreement, the data that are required to be provided and consumed and also the counterparty of the agreement. Based on these elements the platform provides the adequate DSA and SC template.

**Contract Creation.** It allows TSPs to proceed in negotiations with one or more of the identified collaborators and create DSAs and SCs. Furthermore, to test and sign their contracts. *Negotiation.* The two TSPs will use the provided template of a DSA. To be more precise on the one hand, a DSA: 1) Sets the rules between Data Provider TSP and Data Consumer TSP; 2) Terms and conditions for the allowed use of data; 3) Set out a Multimodal Transport Goal for the data sharing; 4) This goal determines the required datasets and the Triggers and Actions of the Smart Contract and the issues of Revenue

Sharing and Responsibility Sharing; 5) Legal principles already included in Terms & Conditions (incorporated); 6) Specific obligations of DSA will prevail (negotiation and drafting); 7) Mandatory law, such as GDPR, must be taken into consideration.

On the other hand, a SC is an operational contract that details the Goal of the DSA that defines specific Triggers (a certain condition, event, choice) and Actions (obligation that must be fulfilled in case a Trigger is realized). It also contains terms of Revenue Sharing (how the revenue or benefit of Actions are shared between TSPs) and Responsibility Sharing (how liability is shared (e.g., who will pay delay/cancellation compensation to a traveler in case of certain Triggers).

*Settlement* enables the use of the aforementioned created e-contracts for the data sharing agreements and the "external smarter contract model" (composed of a legal part and a software part) for the SC.

**Post Settlement and Monitoring.** It sets all the necessary mechanisms to support an effective data sharing process after the signature of the DSA. *Monitoring* enables smooth data sharing processes based on the contracts signed by the implementation of the TSP's Dashboard and 3rd parties' services such as Travel Companion(s) (TCs). A TC application is an integral part of the platform ecosystem, and it interfaces with the traveler and enables monitoring the contracts signed and passengers' consent (if it necessary). Additionally, in this phase the TSPs are able to select added value services that are offered by the platform such as analytics, optimization algorithms etc. *Modification and Termination.* The TSPs are able to perform modifications and terminate their contracts in accordance with the relevant clauses.

## 3 Data Sharing and Data Value

We live in a world full of data. However, most transport data remain in the storage of their owner with little or no chance to be reused by other TSPs who may extract more information from them. In each transport system there are a large number of actors but with limited accessibility to data that exist on that market. One of the possible solutions is raising awareness that data has more value when shared. The examples of good practice related to data sharing in the transport sector are Airport Collaborative Decision Making (A-CDM), Global Distribution Systems (GDS) and Mobility-as-a-Service (MaaS). These proven business models have a common approach in their strategy: place data sharing at the center and use data in the best way. It enabled stakeholders to use and analyze the shared data, which produced a new insight into a wider system and resulted in certain actions that have outcomes affected wider society (e.g., enriching the type of service or through the development of additional services, i.e., hub control center, information apps, journey planners, TCs, etc.).

Regarding multimodal service, there are number of opportunities for TSPs that arose from offering the new public transport infrastructure [2], and the one enabled by data sharing are following: increasing interconnection/connectivity, cost efficiency, performing complex analysis of data to guide decision-making processes (in terms of capacity, disruption management, infrastructure usage, etc.), creating personalized services, etc.

Besides the benefits that data sharing can unlock for the TSPs, it can also support developing transport systems towards more sustainable mobility systems in less developing countries (better infrastructure usage, driving innovations, etc.).

## 4 Conclusion

In this paper the theoretical foundations of a platform for generating, managing and monitoring DSA and SC between TSPs. The starting point are TSPs, who understand the value of data sharing and the multitude of ways to collaborate, but mostly willing to make progress towards seamless multimodal travel. Starting with this assumption, we developed a detailed framework that sets up all the processes required by two willing-to-collaborate TSPs, to write and sign both, DSA and SC. The SCF is a bottom-up concept aiming to facilitate TSPs to unlock their data value.

If well implemented, data sharing has the potential to create benefits for TSPs in the form of greater transparency, reduced costs (either on planning or operational level), valuable customer information provision, increased revenue, strengthened business relationships, etc. It can also unlock benefits for the environment and to society as a whole, such as improved quality of life and increased safety.

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# Knowledgeable Comprehensive and Fully Integrated Smart Solution for Resilient, Sustainable, and Optimized Transport Operations

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**Abstract.** The overreaching goal of this paper is to present how KEYSTONE - a project funded under the Horizon Europe program – aims to develop a knowledgeable, comprehensive, and fully integrated smart solution for resilient, sustainable, and optimized transport operations. Treasuring previous projects that have worked on standardization and learning from the challenges and strength of current European platforms, KEYSTONE has the goal to support the development of a sustainable, efficient, and safe transport system, allowing enforcement authorities to access data for the purpose of checking compliance with rules applied in the transport of goods and passengers. The aim is to tailor standardized digital solutions that can be used from several realities to standardize the transport system. In this paper, the authors present the on-going activities and the methodology that will be followed in order to develop new solutions and demonstrate their validity through an app and through its test with two highly diverse pilots.

**Keywords:** Logistics · Digital Transport · Digital Transition

## 1 Introduction

According to EU objectives for a resilient, sustainable, and more efficient transport system, the improvement of smart enforcement concept constitutes a fundamental aspect. The objective is to apply harmonized communication and procedural standards, which create a more comprehensive and harmonized environment for transport enforcement. Such solutions should be viable, effective, and feasible under economical and technical aspects, allowing future integration with newly developed systems and devices in order to exchange relevant information [1]. In 2022, the European Commission launched the new European Standardisation strategy, outlining the importance of increasing the EU's

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competitiveness to enable a resilient, green, and digital economy [2]. This includes the necessity to improve and standardize technological applications, such as plug & play systems, connectivity technologies, and communication standards across Member States.

The following paragraphs are aimed to show the key contributions that will provide the EU-funded KEYSTONE project to achieve these objectives between June 2023 and May 2026. More specifically, they will explain in detail the scopes and the methodologies adopted in the KEYSTONE project, as well as other related EU projects aimed at achieving a more comprehensive, sustainable, and efficient transport system across Europe.

## 2 KEYSTONE Project Description

KEYSTONE is an acronym and stands for "knowledgeable comprehensive and fully integrated smart solution for resilient, sustainable and optimized transport operations". It is an EU-funded project under the Horizon Europe programme (Grant Agreement number 101103740), which started in June 2023 and ends in May 2026 that aims to develop an ecosystem for the integration and exchange of data and information of an interoperable, intermodal, and seamless transport and logistics system.

The KEYSTONE ecosystem will be established in eight phases which are characterized by a sequential approach. The first three phases are dedicated to the identification of the users' needs, to the requirements of the KEYSTONE ecosystem and to the development of a project vision. The identified solutions create a federation of platforms and standardised data and information exchange, which is then developed and tested within two pilot settings. Finally, a set of guidelines and recommendations are created to replicate and extend at European level the proposed ecosystem. Within these phases and through the development of the project, KEYSTONE aims to have a strong impact on the environment, on the society, on the economy, on the industry sector and on the science and knowledge field. In particular, KEYSTONE has the ambition to improve the ability to use transport data to find impactful actions to decrease the CO2 and NOX emissions, monitor the progress of the biosphere and to intervene on specific problems within the context of future R&D projects or initiatives. This will increase the ability to acquire knowledge and find concrete solutions which improve the quality of the goods and services offered, thus improving the quality of life within society.

## 3 Methods

KEYSTONE is an ambitious project that aims at revolutionising the European transport system, it stands at the forefront of innovation and efficiency. With its overarching goal of fostering sustainability, efficiency, and safety in the transportation of goods and passengers, KEYSTONE is poised to build upon the ground-breaking work of the Digital Transport and Logistics Forum's (DTLF) Subgroup 2 [3]. This subgroup, focused on "Corridor Freight Information Systems", has paved the way for a common framework for information sharing in multimodal transport and logistics chains. KEYSTONE's mission is to take this foundation and implement the principles of "plug & play" [4], enabling seamless data exchange among diverse stakeholders.

Additionally, KEYSTONE draws inspiration from previous EU-funded projects that acted as support projects to DTLF, FEDeRATED and FENIX, harnessing their knowledge, technologies, and semantic models to create a standardised API reference model. This collaborative effort will not only enhance connectivity but also advance automation, ultimately transforming the European transport landscape towards a more sustainable, efficient, and interconnected future, while also ensuring compliance with the rules and legislation that apply in the logistics sector.

### 3.1 FEDeRATED Project

FEDeRATED is part of the broader DTLF initiative chaired by the European Commission, Directorate for movement of persons and freight (EC DG Move). Its primary aim is to develop a federated network of platforms ensuring interoperability among existing logistics platforms and solutions. This network allows logistics enterprises and authorities to connect to a single solution, facilitating digital business collaboration [5]. The project's four core principles are: i) plug and play, ii) federation, iii) independent technology services, and iv) safety and security, all aligning with the European Interoperability Framework (EIF) [6]. KEYSTONE is keenly interested in FEDeRATED's semantic model and aims to use the knowledge and model developed. While FENIX focuses on platform connectivity, FEDeRATED enables business interoperability with a chosen solution, aiming for an open and neutral data-sharing infrastructure. This infrastructure can aid KEYSTONE in developing standardized solutions for seamless data exchange and collaboration across logistics platforms [7]. FEDeRATED's semantic model, defining shared data as "linked data" with consistent semantics and syntax, is invaluable for KEYSTONE's standardization efforts.

FEDeRATED aligns with the eFTI Regulation [8] and eCMR Convention [9], aiding KEYSTONE in ensuring regulatory compliance. Insights from FEDeRATED on data sovereignty, where data remains under its source's control, can enhance KEYSTONE's standardized solutions. Understanding stakeholder roles within the logistics ecosystem from FEDeRATED will help KEYSTONE tailor solutions to specific needs. Additionally, FEDeRATED's deployment approach with "Basic Data Infrastructure" (BDI) nodes serves as a practical reference for implementing standardized solutions in real logistics scenarios.

### 3.2 FENIX Project

FENIX is pioneering a European federated architecture for data sharing in the logistics community, aiming to establish seamless interoperability among various logistics platforms for Business-to-Administration (B2A) and Business-to-Business (B2B) data exchange [10]. Inspired by the European Commission's Digital Transport and Logistics Forum (DTLF), FENIX promotes efficient data sharing, enabling stakeholders to connect, collaborate, and comply with legislation while ensuring trust and security.

KEYSTONE finds FENIX highly relevant due to its guidance on standards in logistics and data sharing, which can inform KEYSTONE's standardization efforts and ensure alignment with industry norms. FENIX's commitment to European Commission policies

offers insights for KEYSTONE to support compliance with European regulations effectively. Additionally, FENIX's achievements in interoperability among logistics platforms provide valuable knowledge for KEYSTONE's goal of creating a seamless digital transport ecosystem [11, 12]. KEYSTONE can leverage FENIX's federated architecture as a reference to develop an evolved transport system infrastructure, reducing implementation challenges and risks. FENIX's focus on semantic interoperability and experiences from pilot sites offer valuable lessons for structuring and standardizing data, crucial for developing standard APIs. KEYSTONE will build upon FENIX's governance model to create a framework suitable for its digital transport ecosystem, including roles, procedures, and certification processes.

### 3.3 Digital Transport and Logistics Forum (DTLF)

The Digital Transport and Logistics Forum (DTLF), established by the European Commission, brings together stakeholders from the transport and logistics sectors to promote digitization. This analysis covers DTLF's history, mandate, structure, and impact on European transport. DTLF addresses the need for digitization in the transport industry, aiming to create a common vision and roadmap for digitalization. It includes stakeholders from public and private sectors to coordinate efforts and support EU-level measures.

The DTLF operates through two subgroups: one focuses on electronic transport documents, and the other on optimizing goods flow through freight information systems. A significant milestone was the EFTI Regulation, which established standardization in the sector. The DTLF later expanded its working groups to address regulatory aspects, reflecting the sector's evolving needs. Subgroup 2, focusing on data sharing, is crucial for "plug and play" activities, aiming to integrate DTLF principles into market dynamics.

Despite challenges in practical implementation, the DTLF's work remains vital. It shifted from unique digital platforms to an "ecosystem of platforms," involving a wide range of participants to address transport and logistics issues comprehensively. While ambitious, the DTLF continues to push for a fully digitized and cooperative European transport sector.

### 3.4 Overview of the Main European Platforms

The KEYSTONE digital solution will consider the main existing European platforms today (RESPER, ERRU, IMI, TACHONET) used by authorities for the exchange of information in the logistics and road transport sector, in order to develop an innovative application that allow to directly access all relevant data to verify compliancy to social regulations, market rules as well as safety legislation. In terms of safety legislation, RESPER [13], (Réseau permis de conduire) is the EU network of driving licenses. It guarantees effective freedom of movement for license holders issued in the Member States, enhancing road safety, reducing the possibility of document fraud, and avoiding the issuance of multiple licenses in compliance with the EU Directive 2018/645.

The compliance with social road transport rules such as Regulation 165/2014 and 68/2016 on driving times and resting period, is verified by authorities through TACHONET [14], the telematics network for the exchange of information concerning the issuing of a tachograph cart, i.e., tool which records driving time, period of work,

other periods of availability, breaks of work and daily rest periods, as well as vehicle speed and distance of the journey.

On the side of market rules, ERRU [15] (European Registers of Road Transport Undertakings) allows Member States to exchange information on road transport companies in line with the requirements of the Regulation 1071/2009 on the access to the profession of road transport undertakings. ERRU provides a means to interconnect the national registries through the exchange of structured (XML) messages to a central hub, so that the competent authorities can mutually exchange information contained in their respective databases.

Moreover, the system IMI [16] (Internal Market Information) allows authorities of each Member State to acquire information about companies that post workers to EU countries and about posted workers, necessary for the definition of inspections in the matter of transnational posting under the competence of the requesting authority, in accordance with directives 2005/36, 2006/123 and 2014/67.

## 4 Results and Discussion

KEYSTONE will face several key challenges. Establishing seamless access to real-time information for authorities and private stakeholders is crucial for ensuring compliance with transport rules and optimizing logistics. This requires breaking down data silos and promoting interoperability. Additionally, implementing "compliance by design" and "compliance by default" principles is essential to protect users' privacy while enabling efficient data sharing. Standardizing digital information and data exchange among logistics stakeholders is necessary to fully leverage digital technologies and improve freight transport services. Enhancing road safety through standard safety standards and innovative technologies, as well as improving social conditions for transport workers and reducing bureaucratic burdens, will support economic growth in logistics. Lastly, adopting an integrated approach to sustainability, covering economic, social, and environmental aspects, is vital to ensure that solutions align with sustainability goals.

At the end of its three-year project, KEYSTONE aims to create a sustainable, efficient, and safe transport solution through a web app designed to enhance data exchange between enforcement authorities and logistics operators. From defining the state-of-the-art, developing and testing the KEYSTONE solution, to evaluating and replicating it, stakeholders play a strategic role.

The web app will demonstrate the API standard and reference model proposed by the consortium. It will be an open-source service for small transport operators, accessible via eID without additional registration, and implement a plug-and-play concept. The app will provide complete documentation for border controls and highlight data inconsistencies for verification. Using business intelligence, it will extract data from users and fill any information gaps. The two pilot projects will refine the software and model to ensure maximum utility and acceptance.

**Declarations.** KEYSTONE (Knowledgable comprEhensive and fullY integrated SmarT sOlutioNs for rEsilient, sustainable, and optimised transport operations) has received funding from the Horizon Europe research and innovation programme under grant agreement No 101103740.

Views and opinions expressed are those of the authors only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

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# Sociocultural Scenarios for Transport Data Sharing

## The Case of Multimodal Traffic Management in ORCHESTRA Project

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**Abstract.** What would the advent of Multimodal Traffic Management (MTM) be like in Europe by 2050? This paper provides some answers by suggesting three contrasted sociocultural scenarios that refer to different key societal values.

Traffic management has been siloed so far with few or no communication between stakeholders (i.e. network and traffic managers, transport service providers, fleet operators, users, etc.). Yet better coordination based on Data sharing among traffic stakeholders could facilitate the future of more efficient transport from an economic and environmental point of view in line with the European policies. It would also make it easier to manage recurrent or exceptional disruptions.

Beyond the technological issues raised up by the sharing of traffic data, this paper's main challenge is to consider the future societal contexts and values on which European society could be based in the next decades.

Based on a literature review, on practitioners' and experts' workshops and interviews, the paper provides three explorative scenarios addressing two questions:

– How could/should data sharing and its governance be implemented?
– What societal aspects and concerns should be considered when sharing data?

These explorative scenarios are thus designed to stimulate debate.

**Keywords:** Traffic data governance · traffic management · explorative sociocultural scenarios

## 1 Introduction

Seamless, carbon-free and smart transport is the main objective that Europe has fixed by 2050 [3]. But the way to achieve this goal is not self-evident, given the potential lock-in features of the systems of all kinds. As an answer, the ORCHESTRA project suggests

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that Intelligent Transport Systems can help to reach this target by improving traffic management within each mode of transport and through their combinations. Typically, it could support door-to-door services as proposed by Mobility-as-a-Service or Physical Internet. In this context, the availability and the accessibility of traffic and transport data is a major challenge that particularly raises two questions:

– How could/should data sharing and its governance be implemented?
– What societal aspects and concerns should be considered when sharing data?

After outlining the founding concepts of ORCHESTRA, the paper describes the scenario-building process and presents three scenarios in a short story-telling form.

## 2 Multimodal Traffic Management (MTM) Concepts

MTM is the original concept addressed by ORCHESTRA, as a meta-coordination of traffic management through different transport modes and areas. **MTM relies on a multi-stakeholder and multilevel governance** that define an ecosystem (MTME) made of transport, traffic and society stakeholders (Fig. 1). Among them, a **Traffic Orchestrator (TO)** performs optimal measures for traffic management within its Governance Area in normal situations as well as in case of disruptions. TO uses arbitration models to balance conflicts involving a trade-off between many performance criteria: transport efficiency, environment and social aspects, according to the Strategic Planning Manager's decisions. **Thus, data availability and accessibility are essential for the TOs' performance** which needs real-time data related to current and upcoming traffic, network conditions, transport operations plans, network users (vehicles, vessels, travellers, goods, etc.) with credentials confirming their user profiles. **The Data Intermediary (DI)**, as defined in the Data governance act [5], plays a key role in the MTME even though it is not compulsory: whether international, national or local, it guarantees the respect of data confidentiality, commercial secrecy and data processing ethics.

## 3 Sociocultural Scenarios' Building Process

The work carried out relies on **the core assumption that the power relations between traffic stakeholders (private actors and public authorities) shape the data availability, accessibility and use.** The transport system is characterised by a lot of stakeholders -Motorists, Network Managers, Transport Service Providers, individuals' location data owners, etc., potentially **gatekeepers** to data. Indeed, in spite of the national and international incentives and regulatory measures, public and private structures are not always willing to share the data they hold because of ownership, security, integrity, traceability or privacy issues. So, beyond the technological issues raised up by the sharing of traffic data, **data governance appears to be a main issue as well.**

From the sociological perspective that founds the scenarios, data governance can be defined as *"the power relations between all the actors affected by, or having an effect on, the way data is accessed, controlled, shared and used, the various sociotechnical arrangements set in place to generate value from data, and how such value is redistributed between actors"* [5].

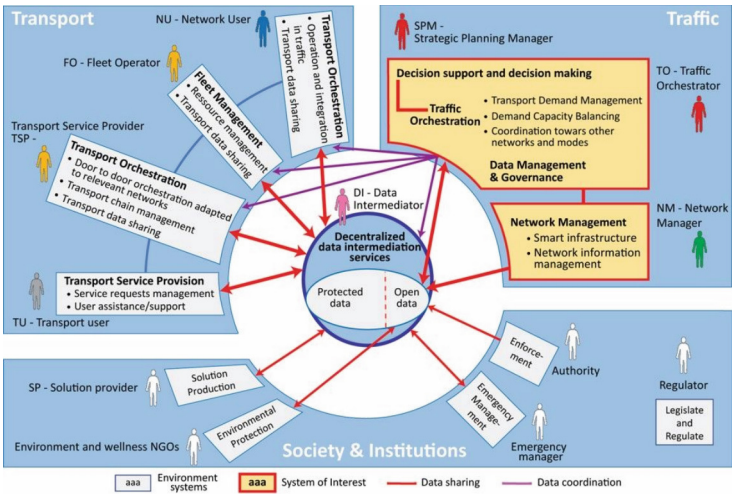



**Fig. 1.** The MTME stakeholders and the key role of Data intermediary [11]

Yet, the development of **explorative scenarios** is a relevant way of depicting the contexts in which the MTME could occur by 2050, as they "*respond to the question What can happen?"* [2]. Thus, the design of the scenarios relies on different combinations of assumptions referring to different economic, political and societal contexts. These assumptions have been defined through a literature review, four workshops and several interviews, all involving various transport and data practitioners and experts. Figure 2 describes more precisely the scenarios' building process followed step by step.

## 4 Three Contrasted Scenarios for the Future of MTME

The three designed explorative scenarios assume that by 2050 each mode of transport will have reached a sufficient level of digitalisation to enable an effective MTM, even if they currently do not start from the same level of development. In 2050, people, goods, vehicles and infrastructures have been completely immersed in digital data.

Given these prerequisites, the scenario 1 corresponds to a future where data sharing between stakeholders and its processing by the TOs is performed reliably and transparently at an optimum level in compliance with the RGPD, throughout Europe. The scenario 2 emphasises the strategic place that the Tech Giants could take in the MTME. The scenario 3 suggests an MTM implementation context in which the planet boundaries and the social equity issues justify all the TO's decisions.

**Scenario 1: MTM has Become Seamless and Optimised**

In 2050 the European Union (EU) policies have been successful and MTM concepts have become true all over Europe. Economic growth, freedom and individual mobility have remained the society's core values. EU has built up its autonomy in terms of data storage and processing infrastructures. Data sharing has been fully compliant with the GDPR. DIs have operated as a decentralised network and have ensured the collection of

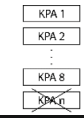
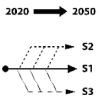
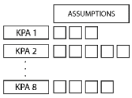
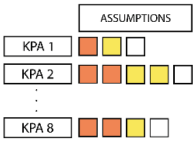
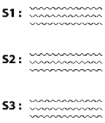
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| **Selecting key-factors** |  | 8 ORCHESTRA-specific Key Performance Areas[1] were considered as influencing main drivers regarding the MTME implementation. They were defined through ORCHESTRA experts' analysis. |
| **Collecting data** |  | Collection and data analysis related to each of the key KPAs from policies reports, regulations, research articles, practitioners' Workshops and experts' interviews. |
| **Raw scenarios description** |  | Three contrasted raw scenarios were built using the data analysis results. They were then submitted to experts and practitioners to validate them and to refine them on the least documented key-factors, through workshops. |
| **Formulating assumptions for the 3 scenarios** |  | For each of the 8 KPAs, a set of assumptions were first designed. These assumptions were then discussed through the experts of ORCHESTRA. |
| **Assumptions clustering** |  | Then these assumptions were clustered in three groups:<br>• Those that were common to the 3 scenarios and implemented in the same way.<br>• Those that were common to the 3 scenarios but implemented in the different ways.<br>• Those related to only one or two scenario(s) and implemented in different ways. |
| **Story telling of each scenario** |  | The scenario 1 was written first.<br>Then, scenarios 2 and 3 were written as forks from the scenario 1. These scenarios were finally read and commented by experts of ORCHESTRA's consortium. |

**Fig. 2.** Method used to build the three exploratory sociocultural scenarios [10]

data required by TOs. Compulsory certification of these DIs has trusting relationships between public and private traffic stakeholders. The proportion of protected data has been much higher than open access ones. Protected data has ensured greater territorial equity and has encouraged the provision of high-quality and resilient door-to-door transport services all over Europe.

**Scenario 2: The Tech Giants have Become the Main Traffic Data Providers**

In 2050 the basic trend of data technological progress observed since the early 2000s has been confirmed and amplified: The Tech Giants have owned the great majority of digital data storage and exchange infrastructures. Yet, they have been the main collectors and processors of traffic data, and DIs have guaranteed a small fraction of the data exchanged. The prevailing ideology of Big Tech companies has spread throughout Europe: a great ambition in digital technology associated with a libertarian vision of society which tends to emancipate itself from the state framework [1]. In this future, the market regulates itself and public authorities should intervene as little as possible.

Thus, the Tech Giants have become key providers of transport and traffic data as well as new services that can predict, influence and sometimes control mobility. These

services have mainly been based on a continuous personal data collection from personal devices. Thus, **MTM became part of the *"surveillance capitalism"*** *defined as a new form of capitalism that translates human experience into behavioural data in order to produce predictions that are then sold on the markets of future behaviour"* [11].

In this context, most traffic and mobility data have remained private, only partially accessible to the public. Thus, the MTM stakeholders have had to negotiate with the Tech Giants for providing MTM with solutions, and the access to most traffic data has been subjected to a fee. So, only the richest cities have been able to develop MTM, thus reinforcing territorial inequalities. Furthermore, as data have been mainly stored outside the EU, they have not been bound by the GDPR requirements.

**Scenario 3: Welcome to a Sustainable MTME**

In 2050, public policies have been implemented within the framework of the political economy of **frugality** with reference to **planetary limits** [8] and **social limits** [6]. Thus, people's well-being and shared prosperity have been ensured. [9]. As a result, wealth has no longer been based on the unlimited growth paradigm.

Then MTM has always been implemented in the light of **Life-Cycle Analysis** (LCA). DIs have collected and harmonised all the data supporting LCA and social assessments in terms of people's well-being. Particularly, TOs has operated MTM decisions that have fitted with environmental and social issues considering the costs of resources, materials, energy, space consumption, and negative externalities (Green House Gas and pollutant emissions). This is why MTM have been implemented only in places where the environmental and social assessment were positive. Furthermore, **traffic and mobility data have been managed through the concept of Commons** [6]: democratic values have made it possible to set up a particular governance of the DIs: the participation of stakeholders in their governance, including people from civil society, reinforces the confidence given to it as regards the security and reliability of the data and the use made of it. Yet, every citizen and company receive an annual mobility credit defined as part of a concerted process. Once the mobility credit is used up, users have to pay for all the external costs of their trips or shipments.

## 5 Conclusions

Of course, the future by 2050 cannot be predicted but alternative futures can. Building and studying different contrasting scenarios helps to act for or against some of them. Each of the three sociocultural scenarios depicts different MTM data governance contexts which encompass political, economic, ethical, legal and technical issues.

Scenario 1 reflects the ideal scenario from ORCHESTRA's perspective: all the data required for an efficient MTM is actually securely exchanged via trusted third parties in compliance with the GDPR. This presupposes the full success of EU's policies to promote Europe's digital independence, especially with regard to the Tech Giants.

Scenario 2 describes a future in which the Tech Giants have strengthened their supremacy, possessing the data infrastructures and knowledge, limiting the action of public authorities and weakening democracy. The laws of the market prevail with the risk of threatening freedom.

Scenario 3 depicts a European society that is fully aware of the planet's limits and concerned about social well-being. These values prevail over TO's decisions that are always taken in a democratic way as data and mobility are common goods, and as everyone has been given an annual CO2-credit for mobility.

The authors assume that scenario 3 could be the only one able to help to achieve the ambitious objectives of the European Green Deal in accordance with the 2015 Paris agreements. But, the way in which these scenarios might be assessed depends on the sociocultural contexts themselves that give different weight respectively to social, environmental and economic issues. The evaluation work is continuing as part of the ORCHESTRA project, mainly in the economic and environmental fields.

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# Creating Efficient and Safe Traffic in a Data Ecosystem

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**Abstract.** Over the coming years, renewing traffic will, above all, be about making much better use of all kinds of traffic-related data. Data must flow smoothly and be compatible & interoperable between vehicles, different modes of transport, service providers and end users in order for us to create the strongest possible foundation for a sustainable transport system and new transport services and solutions.

In a data ecosystem, data is exchanged between platforms using interfaces (APIs). In the traffic data ecosystem, we focus on traffic-related data, such as public transport schedules, traffic disruptions or weather conditions, with which service providers and application developers work together to create better customer experience and services.

Those operating in the data ecosystem have a need for rules, as operators have a need to obtain data from each other. The fair data economy rulebook enables operators to better retain control over the data they share and decide on the related access rights and other business rules. The Rulebook is a tool for sharing increasing quantities of data either free of charge or for a fee, as agreed jointly. In practical terms, this will improve confidence in data integrity, quality, security, identity, operator roles and terms and conditions of use.

**Keywords:** Data · ecosystem · data economy · APIs

## 1 Need for Traffic Data Ecosystems

In the Traffic Data Ecosystem, the community creates solutions for mobility by combining platforms and service providers. Building the transport system of the future requires cooperation from the entire sector.

Over the coming years, renewing traffic will, above all, be about making much better use of all kinds of traffic-related data [2]. Data must flow smoothly and be compatible & interoperable between vehicles, different modes of transport, service providers and end users in order for us to create the strongest possible foundation for a sustainable transport system and new transport services and solutions.

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## 2 Finnish Traffic Data Ecosystem Has Gathered Loads of Interest

We are very pleased that the Traffic Data Ecosystem, launched in 2021 in Finland, already includes more than 200 organizations. We promote, for instance, new travel chain services in our community, improve the efficiency of transport hubs, reduce waiting times and support the increase in future drone traffic volumes. At the same time, we achieve economic benefits for different parties across the board, but, most importantly, we improve efficiency and safety. This accounts for an immeasurably significant value that can only be produced in cooperation. No party alone can produce the same value as a network in which people and organizations share knowledge. The organizations produce services that are better and more efficient or create completely new business models in a community where the services can be continuously refined through work carried out in the community, growing amount of data and developing platforms.

In a data ecosystem, data is exchanged between platforms using interfaces (APIs). In the traffic data ecosystem, we focus on traffic-related data, such as public transport locations, traffic disruptions or weather conditions, with which service providers and application developers work together to create better customer experience and services.

Those operating in the data ecosystem have a need for rules, as operators have a need to obtain data from each other. The fair data economy rulebook enables organizations to better retain control over the data they share. The Rulebook is a tool for sharing increasing quantities of data either free of charge or for a fee, as agreed jointly. In practical terms, this will improve confidence in data integrity, quality, security, operator identity, operator roles and terms and conditions of use.

The traffic data ecosystem provides up-to-date traffic data concerning the Finnish road, railway and waterway traffic for application development. Our services support the mobility of citizens, the needs and logistics of the business community, the operations of the security authorities and the competitiveness and welfare of Finland. We collect, manage and open up data and create opportunities for new business emerging in the market.

## 3 Approach for Achieving the Goals

There are a number of mechanisms for achieving the goals:

- We invite all parties to participate equally in the joint and open development of a traffic data ecosystem.
- We work towards common objectives and common action, by sharing knowledge, and by engaging in co-development to increase the value of the traffic and logistics market.
- We make more data available – either with or without charge – in a mutually agreed format.
- We use jointly developed rules and clear working practices.
- We make it easier for different operators to work together with the aid of things such as common data models, jointly defined technical interfaces, and international standards.

- We build cooperation networks that can market, sell and supply interoperable solutions.
- We respect current legislation under all circumstances, and particularly with regard to privacy protection, trade secrets, competition law, data protection and data security.
- We leverage Fintraffic's unifying role between all modes of transport in the creation of the data ecosystem, particularly in the creation of market references and key market-based services that are difficult to launch, and primarily as an enabler rather than a creator of services for end users.
- We actively communicate agreed measures, progress, and achievements; and facilitate interaction between organizations at all stages of the process.

## 4 Benefits and Impacts of the Traffic Data Ecosystem

A traffic data ecosystem offers numerous benefits that can significantly improve transportation systems and enhance mobility for individuals and communities.

A well-established traffic data ecosystem enables real-time monitoring of traffic conditions, congestion, and incidents. This information helps traffic management authorities make informed decisions about signal timing, route diversions, and incident management, leading to more efficient traffic flow and reduced congestion. It allows for proactive measures to mitigate bottlenecks, optimize traffic signal timings, and implement adaptive traffic control systems.

By leveraging real-time traffic data, transportation authorities can identify potential safety hazards and take proactive measures to prevent accidents. The ecosystem enables the implementation of intelligent systems for incident detection, such as identifying accidents or traffic violations using video analytics or vehicle data. This promotes quicker emergency response, reduces response times, and enhances overall road safety.

Traffic data provides insights into transportation patterns, volume, and demand. This information aids urban planners and infrastructure developers in making informed decisions about road network expansions, new infrastructure projects, and maintenance schedules. It ensures that infrastructure developments align with changing traffic demands, resulting in optimized road networks and reduced construction-related disruptions.

A robust traffic data ecosystem forms the foundation for intelligent transportation systems. ITS leverages data analytics, connected vehicles, and advanced communication technologies to enable smart functionalities such as dynamic routing, real-time traveller information, adaptive signal control, and integrated multimodal transportation. These systems enhance efficiency, reduce travel times, and provide seamless mobility experiences.

The traffic data ecosystem plays a vital role in enabling smart mobility solutions such as ridesharing, carpooling, and micro-mobility services. Real-time data on traffic conditions and demand patterns allows for optimized routing, efficient trip planning, and better utilization of transportation resources. This leads to reduced congestion, lower emissions, and improved accessibility for individuals and communities.

By leveraging comprehensive traffic data, policymakers, urban planners, and transportation authorities can make data-driven decisions. They can analyze historical data, identify trends, and evaluate the impact of various interventions and policies. This enables

evidence-based decision-making, ensuring that transportation strategies align with the evolving needs of the community and promote sustainable mobility.

Optimized traffic management and reduced congestion lead to lower fuel consumption and emissions. By improving traffic flow and promoting alternative modes of transportation, a traffic data ecosystem contributes to reduced air pollution and environmental impact.

Overall, a well-developed traffic data ecosystem enhances transportation efficiency, promotes safety, supports sustainable mobility, and empowers decision-makers with valuable insights to create smarter and more resilient transportation systems.

The traffic data ecosystem will generate diverse benefits for society, it will provide resource-wise transport system data that will enable us to reap the full benefits of data processing and also act as a building block for a sustainable and competitive society. The ecosystem will also spawn new innovations, companies, and jobs.

- For the environment, it will mean cleaner traffic thanks to greater utilization of public and shared transport, which will be enabled by providing alternatives to private cars and individual deliveries.
- For households, it will mean better-informed travelling and data-based services that provide genuine alternatives for safe, sustainable, more affordable and smooth travel and logistics, in both rural and urban areas.
- For organisations that use services, it will provide attractive and competitive service packages with lower emissions and lower costs.
- For companies that provide services, easily accessible traffic data will accelerate the creation of new business, create new markets (including internationally), and facilitate cooperation and the formation of joint offerings in business networks.
- For logistics operators, it will provide cost-effective and integrated logistics chains enabled by data sharing.
- For the public sector, it will mean the opportunity to build higher quality and more efficient mobility and transport services that are more compatible with companies.
- For R&D operators, widely available open traffic data will provide an internationally significant advantage in setting up research activities that accelerate service development and in implementing development environments that involves several actors.
- For the international community, it will enable data-utilization operating models and service packages tried and tested in Finland to be tailored to local needs or scaled up for a wider market.

Based on analysis executed as part of the study “Impact potential of the Traffic Data Ecosystem”, Fintraffic’s share of the Finnish transport data economy is estimated to be approximately 40 MEUR (direct & indirect) [3] (Fig. 1).

Fintraffic aims to have an impact and to create new business through cooperation between the public and private sectors. Fintraffic also wants to create new business opportunities for the private sector and to help cities and municipalities access and utilize data effectively and cost-effectively.

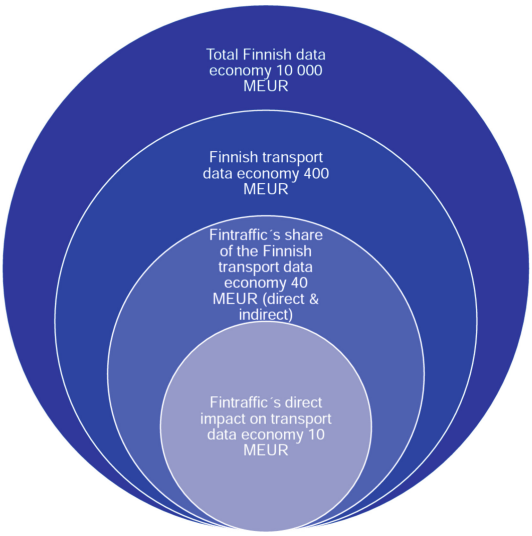



**Fig. 1.** Fintraffic's share of the total Finnish data economy.

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# Digitalisation for Optimal Traffic Management: Future-Proofing TfGM's Intelligent Transport System Platform

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**Abstract.** This project aims to develop an enhanced Intelligent Transport System (ITS) platform at Transport for Greater Manchester (TfGM) to optimise traffic management and improve efficiency. The focus is on leveraging the collaborative capabilities of the Urban Traffic Management Control (UTMC) system for strategic management of the road network through digital data and smart mobility assets, enabling effective traffic management and fostering collaboration among stakeholders.

The delivery of the ITS platform will enable the ability to make informed decisions, efficient traffic management, and a holistic approach to transportation. By leveraging the collaborative capabilities of the UTMC system and digitising legacy systems, the project paves the way for a resilient and future-ready transport ecosystem.

**Keywords:** Intelligent transport systems · Urban Traffic and Management · traffic management

## 1 Introduction

This project aims to enhance the Intelligent Transport System (ITS) platform at Transport for Greater Manchester (TfGM) for better traffic management, fostering collaboration among stakeholders. It also addresses broader goals of boosting the regional economy, promoting social mobility, and improving the environment.

Urban transportation networks are complex, demanding efficient management for safety and sustainability. TfGM's partnership with Atkins in this project follows standard practices in urban Network Management (NM) systems, addressing common challenges in the UK and Europe. Additionally, it embraces future technologies and standards. This project builds on the 1990s foundation, focusing on the Urban Traffic Management Control (UTMC) system, which TfGM adopted early.

A comprehensive transformation of TfGM's traffic management capabilities was explored throughout the project. The approach integrates real-time traffic data and

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deploys smart mobility assets leveraging the collaborative features of the UTMC system and embracing digitalisation. This aims to enable informed decision-making, optimise traffic flow, enhance safety, and prepare for a resilient and future-ready transport ecosystem.

## 2 Literature Review

It is widely acknowledged across governments, cities, and agencies that Intelligent Transport Systems play a significant role in the strategic management of goods, people and services in cities and regions around the globe (DfT, 2017). Anderson and Sutcliffe (2000) outline the importance of such systems, exploring ITS' role in improving road safety, efficiency and the environment, noting the crucial part of integration and technology, along with the need for national and regional ITS strategies. This is further explored by Miles (2014), exploring the structure and evolution of worldwide ITS applications, from its early origins to the emergence of ITS into the mainstream of transport network management, looking at how ITS standards also play a key role.

The importance of standards in the development of ITS systems is demonstrated by the inception of the UTMC framework in UK, formally being adopted in 1997, with the UK Department for Transport identifying the "additional benefits that can be obtained from integrating applications including better services, reduced costs, and increased flexibility" (CIHT, 1999), specifically the definition of "open systems" that enable "network managers to expand and develop their systems to implement the new policies". This digital collaboration lies at the core of ITS systems and is further emphasised through the development of CEN/TC 278 Intelligent Transport Systems, established in 1992 and adopted by 33 member states, where CEN (2018) describes the importance of the integration of assets and systems in a multi-modal and mixed vendor environment.

This mixed vendor environment, and a lack of open specifications and standards has been widely acknowledged across the industry from both a public and private sector perspective, spawning a number of projects and initiatives, such as the Promotion of Open Specifications and Standards in Europe (POSSE) project in 2012–14. This looked to demonstrate the benefits of open standards such as UTMC and how this can "encourage and maintain more sustainable patterns of travel and reduce environmental impacts through prioritising the highway for public transport, walking and cycling, better management of the networks to reduce congestion, and through providing multimodal travel information to enable travellers to make informed choices" (EC, 2014).

Williams (2008) extensively reviews ITS standards across global markets, echoing others in identifying the need for integration between assets, systems, and data, however, the case is also made for greater collaboration between industry organisations, public sector, and the wider technology community. With a view to future ITS systems and applications, Williams also discusses the continuous development of the ITS market sector, notably driven by advances in telecommunication technologies that enable real-time decision-making, congestion reduction and the enhancement of safety and efficiencies.

Through this continuously developing transport landscape, it is imperative that transport authorities adapt to rapidly developing systems and technologies and can harness

these to connecting communities safely and reliably, deliver economic prosperity, and enable a strong sense of social value through a thriving environment. This is reflected in the development of 'Digital Roads 2025' by National Highways, a strategic vision which sets out to "improve the way the Strategic Road Network is designed, built, operated and used, enabling safer journeys, faster delivery and an enhanced customer experience for all." (National Highways, 2021), through embracing data, technology and connectivity.

As the transport authority for a growing population of over 2.8 million residents, TfGM is responsible for ensuring safe, reliable, and integrated transport network. To achieve this, the organisation has embraced changes in technologies and cultivated a pro-active approach to network management. This is demonstrated through TfGM's history of being an 'early adopter' of ITS, through the rollout of SCOOT adaptive control in the 1990s and the early implementation of UTMC in the Control Centre. Recognising the continuous need to adapt and harness new technologies for a world-leading city region, TfGM's partnership with Atkins to support the delivery of an ITS platform represents a move towards the aspiration for a safe, reliable and fully integrated transport network, known as "The Bee Network". This will provide an integrated transport system which will join buses, trams, cycling, walking and rail, supporting seamless end-to-end journeys.

## 3 Implementation and Results

The progression towards enhancing the TfGM's ITS platform entailed a systematic and collaborative methodology, guiding the project from inception to implementation.

The project initiated with a feasibility phase, during which an assessment was carried out on the existing infrastructure, identifying areas for improvement. TfGM's ITS Team played a central role in shaping the project's direction, aligning it with TfGM's objectives, and securing the necessary resources.

The procurement phase will be pivotal, involving the selection of technology and solutions to underpin the enhanced ITS platform. Consultations with key stakeholders, including transport operators and internal TfGM teams ensured their insights and requirements were integrated into the project's design.

The implementation process will encompass deploying advanced technologies and integrating real-time traffic data sources. This involved upgrading and expanding the existing infrastructure to accommodate the new system's demands.

A vital aspect of the project will be the integration of data from diverse sources, such as CCTV, Floating Vehicle Data, and Bus Priority Data. This real-time data fusion will form the backbone of the enhanced ITS platform. The project will also maximise the value of existing smart mobility assets, such as connected traffic signals and adaptive signage, aimed at improving traffic flow and responsiveness.

Leveraging the existing Urban Traffic Management Control (UTMC) system and enhancing its capabilities for seamless data exchange and collaborative decision-making holds a significant role.

The implementation of the enhanced ITS platform is expected to yield substantial results and improvements in traffic management and efficiency. Benefits such as real-time

decision-making will improve due to the integration of multiple data sources enabling TfGM to respond efficiently to traffic incidents and congestion.

Traffic flow optimisation will be achieved through the deployment of ITS assets, combined with data-driven insights that may result in smoother traffic flow, reduced congestion, and shorter commute times for commuters.

Digitalisation will play a pivotal role in transforming legacy systems into dynamic, data-driven solutions. The UTMC system's collaborative capabilities will be instrumental in facilitating data exchange and decision-making among stakeholders, underscoring its importance in modern urban traffic management.

The data-driven approach will demonstrate efficiency in asset utilisation. By optimising the use of existing resources and reducing maintenance costs, TfGM will not only enhanc its fiscal sustainability but will also contribute to the longevity of transportation infrastructure.

## 4 Alignment with Strategic Ambitions

TfGM, supporting the growth of the Greater Manchester city-region with it's ambitious 'Transport Strategy 2040', is taking bold steps to meet its vision of supporting sustainable economic growth, protecting the environment, improving quality of life for all and developing an innovative city-region. The strategy outlines a comprehensive vision in enabling a transport system that supports a strong economy by enabling goods to reach customers, and businesses to access skills and talent. This also has a major bearing on people's health and well-being by supporting social interaction, encouraging more active travel and reducing pollution.

Across Greater Manchester and the wider transport networks, the way people travel and how roads are used is changing. Transport users expect more information on their journeys and need that information in increasingly digitised ways, indicating more needs to be done across transport networks. This creates significant challenges; transport demand is increasing and changing, existing transport modes and traffic management solutions are under pressure, and new business models and transport modes are emerging. Transport network operations are becoming more connected, more digital, and more complex. In order to meet these challenges, we need to harness the opportunities of data, connectivity and growth in digital technologies in an integrated and harmonised way.

Recognising that transport is crucial in unlocking these benefits, TfGM has also acknowledged the pivotal role of technology and innovation in bringing the plan to fruition. This is demonstrated through the roadmap identified through this workstream, in the planned delivery of an ITS Platform that will fully integrate existing and new traffic management systems and data streams, to provide a holistic view of the transport network. Making better use of data and providing customer information will allow customers to make more informed choices about how and when they travel, choosing more sustainable modes- walking and cycling and public transport.

Aligning with TfGM's flagship Bee Network, a vision for a world-class transport system, with all modes integrated to enable seamless journeys, the ITS platform will bring together a technology package, that promotes innovation, data sharing and a move

toward a digitised highway environment, whilst also supporting existing ongoing investment into cycling & walking infrastructure programmes, along with bus, tram and rail improvements.

TfGM have long understood that ITS solutions can deliver better facilities for all modes, improved customer information and data to assist planning and forecasting. Additionally, data for real time operations utilised in the Control Centre and operational teams, supports the response to events and incidents on the network, reducing congestion and the negative impacts this has on the transport network and environment.

With digital collaboration central to the approach in the delivery of the ITS platform, it is imperative that TfGM fosters partnerships between various stakeholders, including government agencies, local authorities, public transport operators, and private mobility service providers to facilitate this. The ITS platform will act as a central hub, where data from various sources, such as traffic sensors, public transport systems, and real-time passenger information, can be collected, analysed, and shared in real-time. This data-sharing ecosystem enables better coordination, leading to more efficient and pro-active network management.

Paramount to this, are 'core' established services, such as a UTMC system, which through existing defined standards, allow for real-time monitoring of traffic conditions, enabling TfGM to make data-driven interventions swiftly across the network. As outlined, this will be enhanced through harnessing advances in data services and technologies, such as artificial intelligence, connected vehicles and the emergence of new, granular datasets, such as in-vehicle monitoring and information services. The ITS platform aligns seamlessly with the strategic ambitions of Greater Manchester's 2040 transport strategy and will serve as the operational backbone that enables TfGM to achieve its key objectives.

## 5 Anticipated Findings

The implementation of the enhanced Intelligent Transport System (ITS) platform at Transport for Greater Manchester (TfGM) will yield extensive benefits that extend far beyond improving traffic management, efficiency, and sustainability, supporting the strategic vision of improving economic growth and enabling a healthier society.

While the project is expected to achieve a multitude of benefits, it is imperative to acknowledge and address the limitations and challenges that may arise during implementation. The integration of data from diverse sources is expected to present technical challenges. However, through close stakeholder engagement, advances in systems integration that enable digital collaboration will enhance robust data management systems and interoperability standards. Moving forwards, continued investment in technology and data integration will be essential to sustain the system's effectiveness, adopting a continuous improvement approach.

Central to the project will be the collaborative approach embraced by TfGM and its partners. This cooperative spirit among transport operators, local authorities, and stakeholders will demonstrate the potential for comprehensive and effective traffic management solutions. The shared expertise, resources, and data exchange will maximise the value of the project outcomes.

Digitalisation will also play a pivotal role in modernising legacy systems. The Urban Traffic Management Control (UTMC) system, with its collaborative capabilities, will facilitate seamless data exchange and decision-making among stakeholders, emphasising the system's crucial role in the future of urban traffic management. There are plans to complete further UTMC to UTMC connections with neighbouring authorities to enhance collaborative network management efforts.

As discussed, the ambitions for the delivery of an ITS platform align with TfGM's strategic ambitions, particularly the 2040 transport strategy and the rapidly developing Bee Network. By embracing data-driven decision-making, enhancing safety, reducing congestion, and optimising resources, this initiative significantly contributes to creating a smarter and more interconnected transport network. It also supports TfGM's dedication to enhancing the overall quality of life for Greater Manchester's residents and commuters. The system will also provide a basis for continuous enhancements, with a future-proofed platform that will adapt to new emerging technologies.

The project sets the stage for exciting possibilities. Future developments may include the expansion of smart mobility assets, further integration of emerging technologies, and an ongoing commitment to sustainability.

TfGM's journey towards a smarter and more connected transport network is well underway, and the future holds the promise of continuous innovation and enhancements in urban traffic management.

## 6 Conclusion

The project's efforts to enhance TfGM's Intelligent Transport System (ITS) mark a significant milestone in urban traffic management. Driven by data-driven decision-making and collaborative digitalisation, this project has outlined a shift in approach to deliver an optimised traffic management and fostered cooperation among stakeholders.

Integrating real-time data sources and deploying smart mobility assets is expected to improve decision-making, traffic flow, and safety. This benefits not only Greater Manchester but will also sets a standard for urban traffic management across the UK and Europe. The enhanced ITS platform positions TfGM at the forefront of urban transportation management. It's ready to meet future challenges and opportunities with efficiency and resilience.

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# Interoperability Push in Combined Transport: EDICT Increases Digital Collaboration and Establishes a Collaborative Quality Management System

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**Abstract.** Combined Transport (CT) is one of the most sustainable and safest mode of freight transport in Europe using the advantages of road for the first and last mile and rail for the long-haul journey. The CT chain consists of a comparatively large set of actors and organisation specific rules. Operational issues like a low level of punctuality and related company-specific delay management block efficient quality management and concerted improvement across multiple stakeholders. Under the CEF programme, the European Climate, Infrastructure and Environment Executive Agency (CINEA) co-funded the EDICT project to find pragmatic solutions to ease the connectivity of several existing platforms and to develop standardised master and transaction data to provide a set of interoperable platforms that facilitate the data sharing and interaction between key CT stakeholders. The core innovation is a collaborative Quality Management System (cQMS) that is conceptualised and implemented based on harmonised and improved existing company specific standards for timestamps, delay and cancellation reason codes, and master data. The project partners intend to share a common process design and use a set of interoperable software-as-a-service solutions to improve process and cost efficiency. During the two-year EDICT project lifetime, eight CT stakeholders, under the coordination of the industry association UIRR and consulting partner Consilis, jointly conceptualise, implement, and run a 5-month cQMS demonstrator pilot based on actual operational data.

The project aims to facilitate the digital integration of Road-Rail Terminal Operators, CT Operators, Railway Undertakings and Infrastructure Managers to provide accurate information and ultimately to improve the overall punctuality, reporting and data analysis capabilities, and service quality to door-to-door customers (LSPs and shippers). Thereby, the project contributes to achieve the EU's policy objectives to increase the share of rail, to push forward the greening of freight transport and contribute to the European mobility data space. The targeted project results lay the foundation for an industry ecosystem solution providing standardised electronic data interchange and sector-wide processes to improve the service quality of regular Combined Transport trains.

Technically, several digital platforms are either introduced, modernised or integrated to achieve the best cost-performance ratio and become attractive for a

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larger group of customers. Piloting 5 regular trains on 3 different TEN-T corridors will serve to learn in practice about benefits and improvement potentials. The evaluation will be used to refine the business model and the adoption strategy to facilitate a future roll-out to become an industry standard. Consequently, not only the CTOs but also the shippers and LSPs will profit from better information transparency on the status of their goods, causes of delays and long-term improvements based on the analysis and elimination of the root causes of disruptions. Thereby, the project and its future roll-out will significantly contribute to a higher attractiveness of Combined Transport and to achieve the declared objectives of the Green Deal, Fit-for-55 and REPowerEU policy initiatives.

**Keywords:** Digital platform · interoperability · combined transport · quality management system · data sharing · quality improvement

## 1 Quality Management Improvement Needs in Combined Transport

Combined Transport (CT) needs to improve the service quality and costs compared to pure road and maritime shipments. Despite several previous sector and legal initiatives (e.g. UIRR project in 2006[1]) punctuality of trains as one of the main KPIs on quality performance for Combined Transport customers is currently deteriorating. The main causes are driven by (1) major infrastructure disruptions (e.g. Gotthard Base Tunnel incident in 2023), (2) the Russian-Ukrainian war, (3) post-pandemic recovery lags and slow economic recovery in Europe and China, and (4) shortage of locomotive drivers. Major customer groups such as the chemical industry request a long list of improvements in order to enable a more profound shift to rail [1] with punctuality, information and service quality amongst the highest priorities.

A systemic challenge is that CT is a complex transport system that requires many actors to interact seamlessly while building on initially national-oriented little interoperable railway systems still in transition. The EDICT (Electronic Data Interoperability for Combined Transport) project (www.edict-project.eu) aims to address some of these deficits through an improved information exchange, standardisation and improved collaboration processes through facilitating the identification and resolution of quality failures. Previous projects such as ELETA,[2] Q-ELETA feasibility study,[3] Digital Train 1.0 and 2.0 (all co-funded under the CEF programme) confirmed that improved processes and IT solutions are needed paired with the different stakeholders' intention to collaborate more intensively. The targeted outcome is a set of enhancements on standardisation areas, processes and interoperable IT applications that increase the competitiveness of

[1] Part of European Commission co-funded project of Sixth Framework Programme (2002–06) Project TREND (TREN-05-FP6TR-S07.43661–513504).

[2] ELETA (2016-EU-TA-0185-S) – Digital Train 1.0 (MOVE/C4/2020–62) - Digital Train 2.0 (MOVE/C4/2020–103).

[3] Q-ELETA feasibility study was a sub-project under Digital Train 2.0 CEF co-financed. It analysed the quality management system of European Combined Transport operations coordinated by UIRR (2021).

CT, and thereby contribute to the carbon reduction of the transport sector that is still difficult to achieve in the near future [1].

Based on the preliminary activities performed in the Digital Train 2.0, EDICT consists of a set of improvement sub-projects grouped into three work packages. Work package 1 focuses on the amended integration of Combined Transport and TAF TSI compliant data exchange improvement on timestamps between Terminal Operators (TOs), CTOs and the railway stakeholders IMs and RUs within Europe. Work package 2 establishes a collaborative Quality Management System (cQMS) to improve the timely identification of delays, their causes and harmonise the processes of identification and delay reconciliation across stakeholder groups. Work package 3 focuses on providing additional services and standardisation of the relevant master data and communication to customers of CT.

Operational issues like the lack of punctuality, lack of supply chain visibility [2] and related company-specific delay management hinder the efficient quality management and concerted improvement across multiple stakeholders. Customer requests for example from the chemical transport industry (ECTA) identify improvement needs related to (1) supply chain visibility, (2) improved interoperability between modes and stakeholders, (3) data sharing and quality (accuracy, timeliness), and (4) missing standardised KPIs and reporting on punctuality and quality [3].

Section 2 focuses on the IT-supported quality improvement and quality assurance identified in the literature on logistics and its implications for the EDICT project. Section 3 presents the preliminary results and Sect. 4 focuses on the targeted final outcomes. The conclusions highlight the hurdles that still exist and further progress areas required to make CT more efficient and attractive to support the greening of European transport, increase the sustainability of businesses towards a zero-emission future and still offer flexible intermodal mobility options.

## 2 Quality Improvements in Complex Logistics Services – Status Quo and Development Needs

### 2.1 Specific Quality Challenges for Logistics Industry

Quality management standards exist in many industries. The ISO 900x standards family [4] is the basis and is supplemented by many industry-specific standards mainly focusing on the product manufacturing parts such as aviation (ISO 9100), automotive (ISO/TS 16949) or pharma (GMP, GDP). Most of these international standards focus on the manufacturing or distribution of products (e.g. GDP). For the logistics service industry specific standards are developed (e.g. ISO 23354) and for the rail industry the newly updated standard ISO/DIS22163[4] is officially available since July 2023. As for other service industries, the key challenge is that the expected quality needs to be agreed upon between the service partners in the tolerance zone between desired and adequate quality service levels [5]. One challenge of logistics services is that only part of the total service has physically measurable characteristics where the production-oriented quality measures of manufacturing industries are applicable. The concept of perceived

[4] The standard is now officially available since July 2023. The literature review was based on the draft for review [32].

quality [6] as defined by the customer group versus the objective service quality is highly relevant for transport logistics services. The end customer defines the quality standards, and the complex business ecosystem of service providers needs to exchange information and documents, optimise processes and commercial data exchange to meet the customer expectations. These requirements must cascade down from the logistics forwarders to the CTOs, TOs, RUs, and IMs with optionally inspection and shunting yard service providers in between. The classical quality in services (e.g. SERVQUAL service quality measurement model) are for business-to-business services considered as too much focused on functional and process aspects and too little on the technical and outcome perspectives [7].

Quality in logistics services [8] and e-service success [9] are key drivers for logistics success. This correlation has been demonstrated in many papers [7] and a causation is plausible. The significant impacts of facilitating the use of IT systems to positively influence the logistics process service quality and the customer satisfaction via the logistics service outcome quality is shown in Fig. 1.

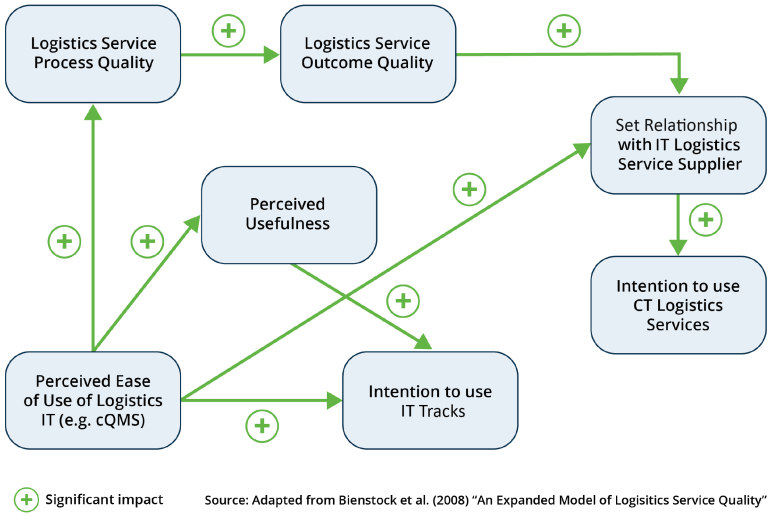



**Fig. 1.** Logistics Service Quality improvements and IT systems use

Logistics Service Quality (LSQ) in recent years is gaining importance. LSQ is equally essential for Logistics Service Providers (LSPs) and customers [10]. In the context of CT, the logistics quality has an additional eminent sector importance through its contribution to the modal shift and greening of freight. In the competition between transport modes not only price but increasingly quality in terms of reliability, correctness and punctuality is a driving factor. In 2023, the Combined Transport sector suffered from lower service quality – especially in the punctuality dimension due to infrastructure outages and fierce price competition that led to a reduced service frequency on some routes.

For an industry-wide solution, a standard set of service quality KPIs and reports were to be agreed between the EDICT project members. With increasing IT-intensity

and availability of data that is shared (see European Common Mobility Data Space (COM(2020)789, 2020)) the application of efficient and effective IT solutions to improve services is a relevant factor identified already several decades ago [11] and still requiring improvement.

In this paper we will only address the efforts towards improving the punctuality measurement as key focus of the EDICT project. It defines a set of measures, interorganisational processes and IT changes to increase the service quality of Combined Transport. The IT technical purpose of the EDICT project is to improve the interorganisational processes, data exchange and IT-integration between stakeholders and other CT IT platforms.

A lack of common data quality [12] and quality understanding in the logistics industry in Europe was identified [8] which prompted to focus on a common definition of "Transport logistics quality (..) as the degree to which the performance of the freight transport operations, across modes in the supply chains, meets stated service criteria and should incorporate the elements of reasonable price, transit time, punctuality, reliability and sustainability" [13].

### 2.2 Quality Improvement Needs in Combined Transport

Several overview papers on the state and importance of logistics quality were published recently [14]. Bienstock et al. [7] analysed the impact of IT tools and services to increase the quality of logistics services. We slightly adapted their key findings to the context of CT from a customer viewpoint (LSPs or shippers). An industry comparison on centralized aviation quality management has been performed in the Feasibility Study to Rail Collaborative Decision Making (Rail CDM) and several timestamps and principles were transferred to the EDICT solution design where applicable in review workshops with the seven operative business partners of EDICT. The outputs of predecessor projects ELETA, and Digital Train 1.0 and 2.0 were integrated, too. Especially TOs face the lack of easy to use and cost-efficient data exchange and quality management processes. Within the CTOs company-specific approaches were analysed and compared. The desire to improve the standardisation of data exchange and unified quality measurements with a focus on punctuality was guiding the target solution within the EDICT project.

## 3 Results and Discussion

One key challenge was to identify the degree of collaboration achievable between competitors. The provision of the project guidance towards collaboration and sustain the commitment to deliver a common solution with partial funding is instrumental to change mindsets towards solving challenges collaboratively to improve logistics quality and performance. Complementary, the orientation towards common objectives needs to be tracked and broken down in the project lifetime plus the success monitored to avoid operative day-to-day tasks to weaken momentum.

### 3.1 Solution Design Challenges

The solution design challenge the EDICT project partners faced was to overcome several hurdles together and to agree upon a common process, data exchange and IT solution architecture:

1. Company-specific punctuality measurement and reason code harmonization challenges
2. Avoid the 'blame & shame' game between two supply chain players via a conflict reducing reconciliation facilitation process
3. Avoid company focused or only bilateral relationship regulations for common challenges to materialise (see [8])
4. Overcome the distributed benefits challenge [9] where partners are not equally benefiting from a change without readjusting the boundary conditions

Together with the project partners the insight was reached that total efficiency, cost savings and global quality improvement goals are only achievable through enhanced collaboration based on a common IT application (cQMS).

### 3.2 Business Ecosystem Design for Interoperability

Interoperability of organisations, processes, and data [15] within the regulatory environment builds on extending the conceptual interoperability to organisational units including the business ecosystem interoperability level required for CT [16] (see Fig. 2). The need arises from the decentralised interorganisational and multi-stakeholder nature of the CT business [17, 18]. Additionally, modularity and complementarity are design principles for both Business Ecosystems (BE) such as for CT [19] and the cQMS complemented by standardisation and interoperability. The full set of interoperability levels needs to be addressed for successful BE-wide transformations such as the CT sector with mutual adjustment needs on all levels to increase competitiveness with other transport modes.

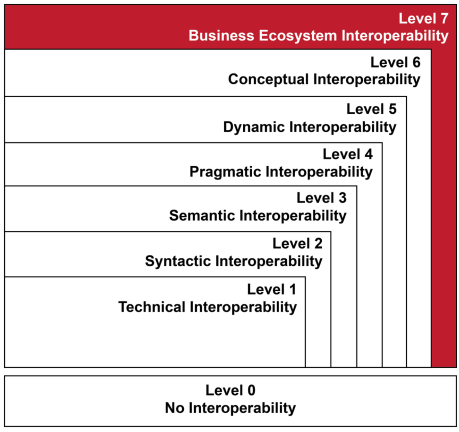



**Fig. 2.** Interoperability levels to be covered for collaborative processes and IT architectures

The partial transformation of CT with at minimum 6 different stakeholder types can be best understood with an underlying BE view (see [18, 20]). The CT innovation area requires co-opetition between competitors and co-creation to agree on common future processes, interoperable standards and IT services. The role of the orchestrator fostering open innovation [21] is temporarily performed by Consilis and UIRR in the project context. Business ecosystems transformation including all stakeholders is complex and time consuming [22, 23]. The total scope can be visualised in the Business Ecosystem Transformation framework applied to other large-scale transformations [15, 24].

The need to collaborate is not only given by the multi-stakeholder structure but also to achieve process efficiency, customer-orientation and IT efficiency driven. Identifying different reason codes per bilateral customer-supplier relationship is time consuming and inefficient. Avoiding different coding systems per customer-supplier relationship is a key driver to strive for a standard. The project developed together with seven combined transport actors harmonised timestamps and a two-level delay reason and train cancellation coding system. The purpose of these emerging standards is to ease the harmonised classification of a disruption and the corresponding reporting system. The cQMS provides the standardised information basis to identify delays compared to the scheduled train run as well as documenting and analysing the causes.

The following data exchange gaps required to be closed as pre-requisites to meet the punctuality assessment and improvement tasks:

- Identifiable stakeholders (e.g. CTO to be introduced into the TAF TSI legal framework) (see TAF TSI handbook)
- List of common delay reason and cancellations codes related to CT operations (to be introduced as well in the TAF TSI Regulation)
- Definition and improvement of a standard message format to exchange the relevant information between all actors and IT platforms
- Provide a process for the clarification of the main causes of delays to facilitate the dispute resolution (reconciliation process)

### 3.3 Solution Elements

The design and specification phase of the 10 subcomponents of the project has been completed. Their conceptual interplay is visualised in Fig. 3. The internal interdependencies are more complex on a detailed level which increases the need to motivate and align the project partners to dedicate sufficient resources and priorities for a two-year transformation project.

The standardisation of the data exchange and CT-compatible list of timestamps has been achieved (WP1) and the specification of the cQMS and the tender process is completed (WP2). The cQMS is in its configuration process and the testing of the collaborative solution with live data starts in December 2023. The chosen solution was the best fit from 4 short-listed providers. The winning company offers an existing Software-as-a-Service (SaaS) solution for CT. Due to the complex BE, the choice was made for a hybrid agile design method to be able to deliver in time and reduce the time to provide a working pilot. A two-phase roll-out was chosen to reduce complexity, implementation risk and give all cQMS demonstrator partners and involved IT platforms sufficient time to prepare their interfaces, standards, and mapping activities.

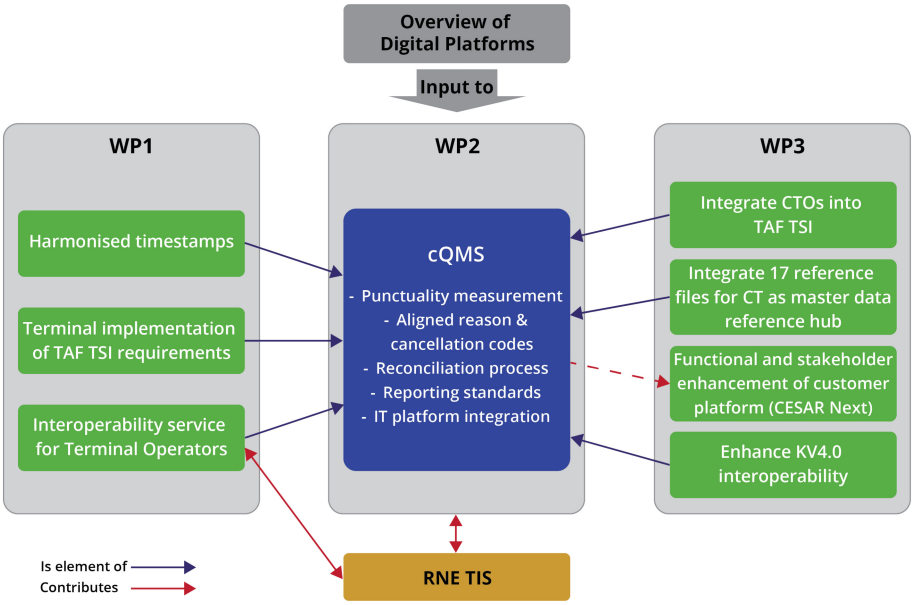



**Fig. 3.** EDICT solution elements overview

The cQMS is based on harmonised and improved existing company specific standards for timestamps, delay and cancellation reason codes, their reconciliation as well as digital, harmonised reporting, and master data exchange via several IT platforms.

Central alignment instruments were the 'AS IS' and'TO BE' process modelling with each partner to identify if a common approach is feasible within the project constraints. Due to a high degree of similarity the partners agreed to a common future process flow and interface standards.

The second key alignment activity was the BE-wide IT architecture design (see Fig. 4). The selection of messages, the IT platforms to be used and the conversion activities between the IT platforms were salient prerequisites towards implementation planning. Both the process design and the IT architecture were required to explore the appropriate degree of change the project members were able to collectively commit to.

Thirdly, the specification and alignment of the first set of delay reason codes and cancellation codes within the project partners as well as an extended group of terminals was required to establish the foundation for the harmonised reporting system.

Fourthly, the selection of master data and transaction data elements throughout the project partners and the migration paths towards the common set was required to simplify the final solution and reduce the costs and efforts to implement and maintain the solution.

Lastly, the interoperability of platforms is a central element to increase the efficiency of the data exchange capabilities between the relevant players. Figure 4 highlights the 5 relevant IT platforms that need to interchange messages to record the timetables, timestamps, reason and cancellation codes with the respective stakeholders. The integrated solutions are (1) KV4.0 as central data hub, (2) cQMS as centralized information collection, delay processing and reporting platform, (3) RNE TIS for information exchange

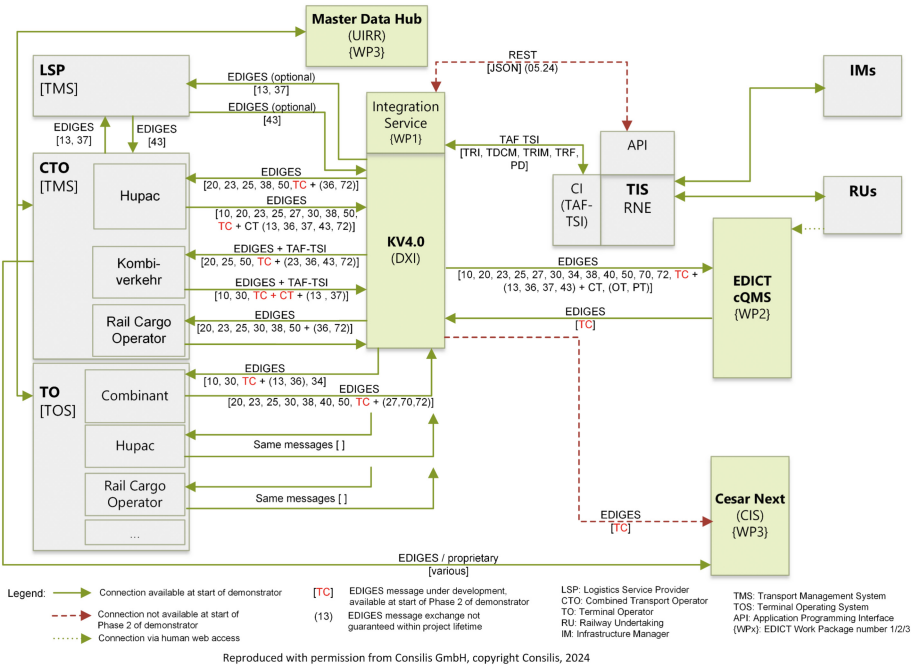



**Fig. 4.** Current EDICT project architecture

with the IMs and RUs, and the (4) UIRR master data service platform to synchronise ILU codes, location codes etc. according to TAF TSI standards, and (5) the CESAR Next CT customer communication platform. The long-term target should be to establish interoperable digital services that facilitate the shift-to-rail for all business ecosystem stakeholders similar to efforts initiated in the rail-based passenger transport environment [25].

### 3.4 Expected Final EDICT Results

The tender process resulted in the selection of Simply Deliver as SaaS platform provider and the interoperability of several existing IT platforms. The project enables the exchange of standardised information via EDIGES (rail-road transport) and TAF TSI (rail transport) standards.

In the cause of the project several replanning processes were required due to time and resource constraints that were not foreseeable at the conception phase. Despite these extra hurdles the partners are motivated to deliver meaningful results to improve the data exchange, quality measurement, and improvement potentials.

### 3.5 Limitations and Future Development and Research Needs

The following improvement areas are identifiable before the final results are produced on the assumption that no unknown and unsurmountable hurdles may occur during the remaining project phase:

1. Adoption of status, reason code and message standards, processes and IT services by more sector stakeholder types (e.g. RUs, LSPs and consignors)
2. Direct involvement of other partners to enhance the business ecosystem through enabling the roll-out to more CT stakeholders within Europe and Central Asia (long-term view)
3. Faster reaction to disruptions by functional enhancements towards exception and prevention management
4. Interface modernisation and migration to renewed platforms to reduce interfacing costs (e.g. REST APIs)
5. Quality improvement measures to identify and manage collaborative quality improvement projects and identify measures within the common cQMS
6. Explore the extension of scope (e.g. document exchange and electronic freight transport information (eFTI) compliance (EU 2020/1056)

The above-mentioned future development directions will be assessed after the final outcome of the live demo and the evaluation of the data quality, user acceptance and cQMS project assessment.

## 4 Conclusions

Early results are the aligned set of timestamps, delay reason and cancellation codes for the identification of disruptions in the supply chain and to assure a TAF TSI compliant information exchange between CT stakeholders. Furthermore, an extension of the communication with CT customers via the updated CESAR Next platform has been achieved. These efforts should contribute to fostering CT attractiveness to shift to rail by contributing to increased stability, punctuality and reliability for customers through facilitated information exchange, quality management process enabling, and eased interoperability.

Future research is required to accelerate the adoption and further refinement of the established and newly created standards (e.g. CT reason and cancellation codes). The harmonization and extension of the nucleus to include both LSPs and shippers is part of the way forward and the integration of higher automation in the classification as well as enhanced exception and prevention processes are natural development phases. This targeted achievement and future larger scale impact relies on the incentives, positive results, and the willingness to collaborate with the existing and potential future partners of the cQMS.

Key learnings are that further improvement and alignment of processes between different stakeholder groups takes time and a BE coordination which was performed by UIRR with the support of Consilis is instrumental. First successful steps have been made. More effort to increase the interoperability of processes and information systems is required to improve the competitive position of CT in areas where the access is available and the service offering is possible. The EDICT project and especially cQMS show a path to improve the service quality with punctuality as one of the key deficits of CT if compared to pure road or sea freight and road shipments. The contribution to a larger shift to rail and CT can be significant if the outcome of the project is successful and widely adapted in the future. The first implemented steps on a longer BE transformation roadmap

that not only require processes and IT improvements but also further asset availability and standardisation improvements towards a greener transport future in compliance with the Green Deal and REPowerEU targets.

## 5 Methods Applied

Participatory action research [26] is well suited for complex and sometimes messy situations often uncovered in complex logistics and supply chain settings [27]. It is a fitting qualitative research method to innovate, reality test and learn from new or adapted artefacts. It is positively applied to logistics context to innovate processes in a small business ecosystem [28]. Consilis conducted as-is and to-be process and IT architecture improvement interventions as well as master data and transaction data workshops with all four companies to identify the change needs and common process requirements. Research methods applied used multiple sources of evidence collection [29] such as online plus physical workshops, document studies, and meetings that were transcribed to identify key themes. The constructs were presented and discussed with representatives of different functions of the four company participants and additional UIRR association members. The identified hurdles were resource constraints and other projects that were prerequisites to the agreed-upon changes corroborated by unplannable external events with significant business impact outside the sphere of influence of the core CT stakeholders.

A mix of qualitative research methods [30, 31] are used to innovate current practice with solution elements present in other comparable industries (e.g. aviation) or established in a few companies only. The objective of the demonstrator is to identify the suitability of the chosen processes, standards and IT architecture. With the real-life insights and single loop plus double loop learning the adoption strategy for the future roll-out to a wider scope will be crafted, if successful.

## List of abbreviations

| | |
|---|---|
| BE | Business Ecosystem |
| CINEA | European Climate, Infrastructure and Environment Executive Agency |
| cQMS | Collaborative Quality Management System |
| CT | Combined Transport |
| CTO | Combined Transport Operator |
| ECTA | European Chemical Transport Association |
| EDICT | Enhanced Data Interoperability for Combined Transport |
| EDIGES | Electronic Data Interchange (for) Intermodal Global European Standard |
| IM | Infrastructure Manager |
| KPI | Key Performance Indicator |
| KV4.0 | Kombinierter Verkehr 4.0 |
| LSP | Logistics Service Provider (including forwarders) |
| RU | Railway Undertaking |
| TO | Terminal Operator |
| TAF TSI | Telematics Applications for Freight Technical Specification for Interoperability |
| TIS | Train Information System |

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# Integrated Data Monitoring in Support of Sustainable Mobility Planners in Tourism Destinations

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**Abstract.** Tourism destinations are often confronted with the challenge of balancing the capacity of their transport systems, between peak and off-peak periods. In order to properly design, implement and measure solutions' impacts, data on mobility demand are required. This paper presents an integrated mobility data monitoring scheme, tested for the first time in Rethymno and Platanias, two small insular cities in Crete. The monitoring scheme included mobility and environmental indicators measurements, field research and data analysis methods. Results helped to capture the variation in traffic flows and driving behaviours by vehicle type and daytime, between winter and summer, and better understand the city's seasonal mobility characteristics. Cities of similar typology (Mediterranean climate, seasonal flows, linear coastal development, limited transport network capacity) can benefit from such simplified schemes. Since the cost is low, cities can acquire real-time data to feed smart tools, like GIS models. Data interpretation allows policymakers, governmental authorities and tourism stakeholders to design traffic calming measures in high-risk locations, to enhance traffic safety for citizens and visitors and improve conditions for active mobility, as well as to introduce policy measures and behaviour change activities for drivers. Cross-analysis with tourism and user behaviour data supports overall mobility and resilience planning.

**Keywords:** Mobility Data · Tourism Destinations · Traffic Safety

## 1 Introduction

More often than not, popular touristic destinations in islands face significant pressure from inbound tourism flows, with the capacity of their systems (natural and man-made) reaching and even surpassing their limits. Especially seasonal destinations are confronted with challenges in the design of their vital infrastructure, such as energy systems, transportation network, ports etc. In addition, the use of space, fuel supply, road safety, environmental pollution are critical issues which island communities have to cope with [1]. At the same time, such destinations are expected to meet high-quality standards set by the tourism industry and respond to the urgency of the climate crisis by adopting environmentally friendly policies and sustainable practices in all sectors.

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As regards the transportation system in specific, island destinations need to focus on designing a system of adequate capacity to accommodate for the increased number of users during the seasonal touristic period, taking caution to preserve their natural and cultural characteristics. Concurrently, road safety and accessibility are matters of utmost importance. For proper sustainable mobility planning, data availability is key; however, this is not always the case for most islands, which usually consist of small cities with limited resources.

A simplified yet robust data monitoring scheme has been designed and tested in two small cities on the Greek island of Crete, Rethymno and Platanias, of 65,000 and 20,000 residents, respectively. Both are popular destinations, accommodating a large number of visitors, which exceeds up to 10 times their population during the six-month touristic period (lasting from April to October), while their road networks and mobility infrastructure are utilized by over a million passing visitors [2]. Despite significant mobility challenges, the cities did not previously have access to mobility data at the local level. The aim was to collect real, on-the-field data about traffic flows, use of the mobility network and users' behaviour, in order for these to be used by sustainable mobility planners for the design of measures. The scheme was designed and implemented by the Sustainable Energy and Mobility Unit of the Technical University of Crete in the context of CIVITAS DESTINATIONS [3] and SUMP-PLUS [4] projects, funded by the European Union's Horizon 2020 Research and Innovation Programme.

## 2 Methodology

The monitoring scheme comprises of two parts:

(a) a portable measurement system to monitor mobility and environmental indicators, and
(b) research and analysis methods, to monitor modal shares, user behaviour, satisfaction levels etc., of different network users (residents, tourists, public transport users).

### 2.1 Mobility and Environmental Indicators Measurement System

The measurement system included:

– Traffic measurement devices. Battery-operated radar sensors, compliant with GDPR, were installed on the road side, able to count passing vehicles in both directions 24/7, as well as to measure their speed and length. The latter was used to classify vehicles into five types: two-wheeler, small/standard car, big car, logistics vehicle (van), small bus, large vehicle/bus. The devices allow for remote data access, through modem on-board GPRS wireless communication, and provide real-time data.
– Environmental measurements equipment. Environmental monitoring stations and portable instruments, able to measure various environmental indicators such as: air pollutants, including CO, NO, $NO_2$, $SO_2$, Particulate Matter (PM2.5, PM10), Volatile Organic Compounds (VOCs), noise levels and meteorological parameters.

The monitoring systems were installed in selected locations in the urban centre, the city entrances and other critical spots, after discussion with the cities' policy actors. For

instance, in Platanias, three points on the main road going through the touristic centre were selected, which would reveal the incoming and outgoing traffic flow from the city centre and the share of traffic flow channelled to neighbouring urban areas. As regards the period of installation, they were installed in two seasons, winter and summer (the latter coinciding with the touristic season), for two consecutive years, 2021 and 2022. The traffic parameters measured are explained in detail in Table 1.

**Table 1.** Traffic parameters measured at each monitoring station.

| Measurements | Description | Unit |
|---|---|---|
| Speed | The speed of vehicles moving on both lanes | km/h |
| Direction | The number of vehicles moving in both directions (1: oncoming and 2: outgoing) | 1 or 2 |
| Length | The length of passing vehicles | m |
| Time | Date and time for each record | To the second |

### 2.2 Research and Analysis Methods

This part included the development of tailored questionnaires for three groups of mobility users, specifically residents, tourists and public transport passengers, aiming to collect data about their mobility habits and behaviour, their perception of the network and services, their opinions about future measures, and demographics. In the case of tourists and public transport passengers, the interviews were done on the field, i.e. at hotels of various categories and other places of touristic interest and at bus stops, spread in the wider study area. Interviews of residents were done via telephone survey, using stratified random sampling. Subsequently, data were analysed statistically to reach aggregated results.

## 3 Results

Monitoring results revealed the fluctuation of traffic flows between winter and summer, per type of vehicle and time of the day, as well as the vehicles' speed distribution.

Key findings of traffic measurements suggest that summer traffic flows can be up to 16 times higher than winter ones, depending on location and time of day, and are more extended towards the evening hours, especially in the touristic centre. The fluctuations of the curves in Fig. 1 show a strong dependence of traffic flow on the hour of the day. Winter and summer have different trendlines; in a typical day, the total 24-h traffic flow is approximately double during summer and remains high for more hours throughout the day.

At the same time, logistics vehicles dramatically increase in the summer within the urban area, as shown in Fig. 2; more specifically, in the city centre (ELTA station) they were increased by 358%, whereas outside the centre (Town Hall station) the rise was

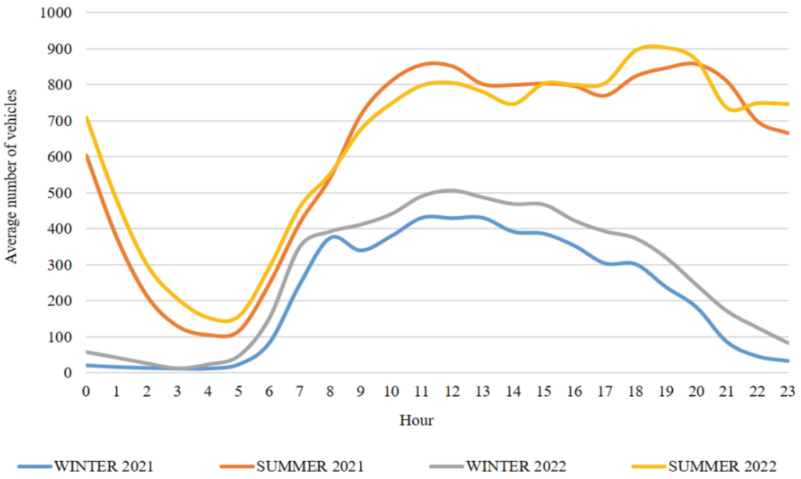



**Fig. 1.** Average number of vehicles on a typical day, peak and off-peak, 2021 - 2022, Platanias

just 50%. The same stands for buses, where their increase was ranging from 2 to 12-fold (city centre), due to the increased public transport routes and tourist coaches.

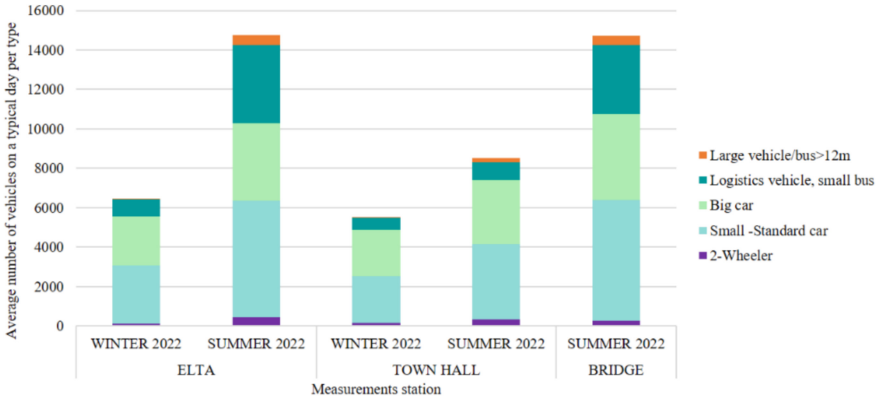



**Fig. 2.** Average number of vehicles per type, winter and summer 2022, Platanias

Violations of the speed limit are frequent. Figure 3 shows the number of vehicles that exceed the speed limit of 50 km/h at one of the monitoring stations throughout a typical winter and summer 2022 day, with most of them belonging to the 50–60 km/h category. The diagrams for the two seasons have different profiles, with far more speeding vehicles in summer. Additionally, a significant number of severe violations in the 80 + km/h category is observed in the early morning hours during summer.

Results of environmental monitoring and cross-analysis with tourist data, show a correlation of environmental pollutants, such as CO, with tourism flows (Fig. 4). Nevertheless, overall both cities featured good air quality in both winter and summer.

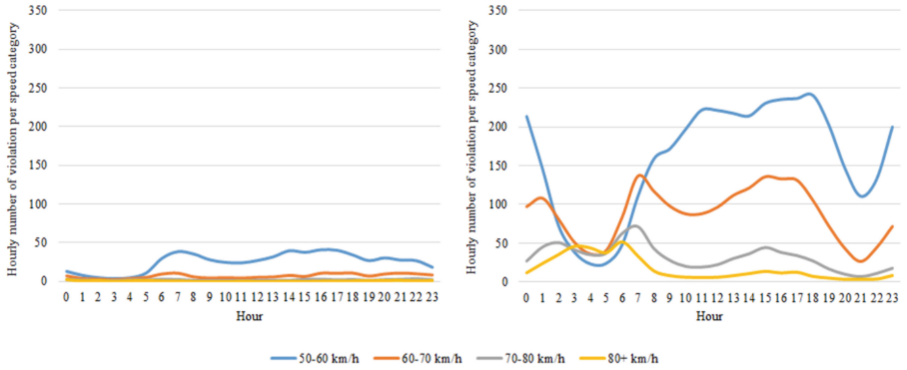



**Fig. 3.** Speed limit violations on a typical winter (left) and summer (right) day, 2022, Platanias

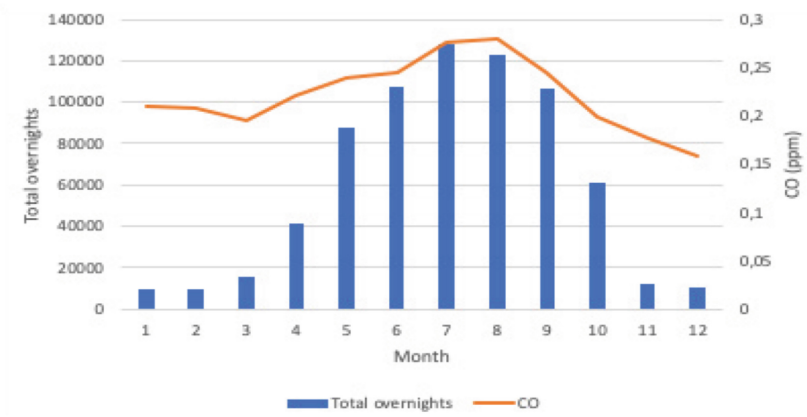



**Fig. 4.** Correlation of total tourism overnights and CO concentration at Rethymno old city

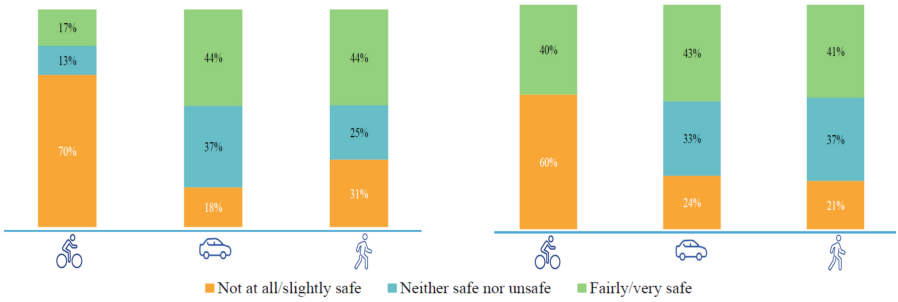



**Fig. 5.** Feeling of safety of residents (left) and tourists (right), when using different transportation means, Platanias

The analysis of users' questionnaires yielded valuable information about mobility in the wider area, such as the modal split for both residents and tourists, the mobility profiles, the parameters affecting users' mobility, evaluation of the network and services, priorities for interventions, amongst others. Parameters, such as the feeling of safety of the network users (Fig. 5) and especially cyclists who feel particularly vulnerable according to the survey (70% of residents and 60% of tourists-cyclists feel unsafe), can be co-evaluated with the aforementioned results about speed violations, to reach conclusions about dangerous parts of the road.

## 4 Conclusion and Future Research

Analysis of the measurements data reveals the seasonality and intensity of the traffic flows as well as the drivers' behaviour, which is vital information for designing sustainable mobility measures. The combined interpretation of users' behaviour data from questionnaires provides a better understanding of the use of the mobility network, and takes the users' views into account for the design. Real local data help provide context to the engagement processes with stakeholders and put the problem into perspective, thus supporting decision-making. Especially, when speaking about tourism destinations, such data help to showcase infrastructure weaknesses and lack of services and support the co-design of mobility measures, with tourism stakeholders and long term contributes to boosting the city's image as a green destination. Moreover, it allows the setting of indicators and targets on sustainable mobility, which can be monitored in regular timeframes, so as to evaluate measures, and adapt, if needed.

The monitoring methodology is simple enough for small cities to use; the equipment is low-cost, non-intrusive and versatile, requiring minimal technical knowledge for installation and use, and provides actual real data on the field. Additionally, it offers data-sharing possibilities with mobility operators, researchers, and authorities.

Results were used to complete the mobility baseline for the cities, with important data such as the modal split, which was not previously available, to locate accident-prone areas and to design traffic calming and active mobility measures for improving traffic safety of residents and tourists in the area.

Future analysis may involve data integration in spatial models to evaluate future mobility scenarios and interventions.

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# Connected, Cooperative and Automated Mobility

# Automated Shuttle Experiments in Helmond

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**Abstract.** The City of Helmond aims to offer new mobility services to users by operating on public roads a fleet of remotely supervised automated public transport vehicles from/ to mobility hubs/stations to Helmond's neighbourhoods and (economic) hotspots. The first step has been to set up two pilots with automated shuttles in 2021 and 2022 (in FABULOS and LivingLAPT EU projects). These two pilots showed that some improvements of the automated shuttle service are necessary to offer a quality of service (speed, comfort, perception of (social) safety) at least equivalent to the current conventional public transport.

To go beyond these projects and to achieve Helmond's ambition, Helmond participates in specific projects (like Move2CCAM – on citizen/organization attitudes and on the impact of CCAM) and adopted a "Roadmap for automated public transport services in Helmond" in 2023. A stepwise approach has been chosen to develop and test automated public transport services in order to be able to implement and upscale them in the city. Starting with automated public transport service operations in an easy environment and then later in more complex environments. In 2024, we will start with the first step; an automated public transport service without the need of a (remote) safety driver in "Bedrijventerrein Zuid Oost Brabant" (BZOB) – an industrial area with an easy Operational Design Domain (ODD).

**Keywords:** Automated Shuttle experiments · Automated Public Transport Services · CCAM

## 1 Background Information

### 1.1 Helmond's Challenges

Currently, the City of Helmond is a medium-sized city with around 95 000 inhabitants. Despite the fact that Helmond's four train stations provide good public transport connections to the outside world, efficient last mile connections from/to these train stations (covering a big part of the city (see Fig. 1)) are currently lacking. In addition, for 2040, there will be an expected increase of population resulting in an expected increase housing and working demand of about 25% (10k houses). This increase in population will also generate growing need for mobility without having space to build extra roads.

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**Fig. 1.** Area covered within the one mile range from the four train stations in Helmond (map: © Google Maps)

### 1.2 Helmond's Ambition

The City has identified the use of automated public transport services as an enabler for current and future last/first mile challenges (in addition to a very active policy promoting cycling), in particular for user groups with special needs. These automated public transport services have to be well integrated with the other (public) transport modes like the train.

The City of Helmond aims to offer automated public transport services between mobility hubs/stations and Helmond's neighbourhoods and (economic) hotspots, like the hospital and industrial areas/business districts (e.g. BZOB, the Automotive Campus). These automated public transport services should provide a high frequency (5–10 min) service within a short distance from people's homes and main mobility attractors (e.g. 200m), should take users within 10 min to their next stop (e.g. mobility hub or one of Helmond's train stations) and a ticket should not be more expensive than current public transport tickets.

### 1.3 Helmond's Roadmap for Automated Public Transport Services

In 2023, the City adopted a "Roadmap for automated public transport services in Helmond" [1]. A stepwise approach has been chosen to develop and test automated public transport services in order to be able to implement them in the city. Starting with automated public transport service operations in an easy environment (an environment without (or with as few as possible) unpredictable situations), and then later in more complex

environments. In 2024, we will start with the first step by implementing an automated public transport service without the need of a (remote) safety driver in "Bedrijventerrein Zuid Oost Brabant" (BZOB) – an industrial area with an easy ODD.

## 2 Experience from Previous Projects

### 2.1 FABULOS Project

In the FABULOS project [2], during seven weeks (2021), an automated passenger shuttle was running on a route between Brandevoort train station and the Automotive Campus. This was the first trial carried out in Helmond on such a complex route, while at the same time being integrated with regular public transport. This field test also showed the possibilities of mixing fixed schedules and on-demand service operation of automated vehicles and the remote supervision of the fleet. Moreover, an integration with Google Maps, the Hermes app and the national route planner (9292) was made.

Even though the vehicles operated primarily in their automated mode during the FABULOS pilot, a safety operator and a "host" (accompanying users and providing them with explanations) were always onboard the shuttle. Unfortunately, due to the social distancing rules imposed during the Covid pandemic the number of passengers transported was limited.

### 2.2 LivingLAPT Project

In another project, LivingLAPT [3], the focus was on testing the performance of the automated shuttle, the workload of a tele-operator and passenger experience. In September 2022 the automated shuttle tests took place in a closed environment on a 200 m route [4].

**Performance of the Automated Shuttle**
Before every test, the operators performed practice rounds in both manual and automated modes within the shuttle. After having been familiarized with the controls, positions were taken for the tests; one operator would remain inside the shuttle as steward whereas another went to the control room. The main experiments were divided into 2 subtests - teleoperation and automated mode. Each subtest consisted of trials including the collection of data. The main study parameter was passenger comfort. This was assessed from the perspective of the steward inside the shuttle when additional passengers were not available during trials.

A total of 10 experiments were carried: 1) Stopping for a traffic light, which changed changing green-yellow-red when the shuttle was 25 m away from the traffic light; 2) Stopping for a dummy, which got pulled on the trajectory of the shuttle when it was 8 m away; 3) Long duration (10 laps) of tele-operation; 4) Low light (during sunset) operation; 5) Static obstacle avoidance; 6) Overtaking by a cyclist; 7) High speed (21 km/h) operation; 8) Road narrowing (from 4.65 m to 2.65 m); 9) Teleoperation take-over; 10) Dynamic obstacle avoidance – a pedestrian walking towards the shuttle on the edge of the trajectory.

Comparisons between the performance of the teleoperator and automated modes were made where passenger comfort was the main study parameter. Considering all test runs in this study, the average comfort level of passengers during teleoperation was 7.65/10 (n = 55). Average passenger comfort during all trials in automated mode was 6.62/10 (n = 38). This suggests that human performance from the control room results in higher comfort levels in most contexts.

**Tele-operator Workload**

Another focus of this study was the workload of the teleoperator in the control room. Both subjective and objective measurements were taken. The teleoperator was equipped with an EEG and eye-tracking glasses to monitor their physiological and behavioural reaction to remotely operating the shuttle. Additionally, after every trial they filled out a standardized questionnaire to self-report on six different aspects of their perceived workload.

In total 20 trials were performed, which differed in the type of operation (e.g., tele-operator remotely driving the shuttle, teleoperator monitoring an on-board driver, or teleoperator monitoring automated operation) and the type of task (e.g., stopping in front of an intelligent traffic light, dummy pull test, obstacle avoidance, driving in low-light conditions etc.).

The highest levels of teleoperator workload were observed in the trials where the tele-operator had to drive the shuttle remotely. The average workload score across all the trials in which the teleoperator only monitored the shuttle (that operated either in automated mode, or manually by the on-board operator) was much lower.

**Passenger Experience**

A user acceptance survey (110 respondents) was conducted among the participants who took a ride in the automated shuttle (in automated mode). The survey was developed by University College London, Ghent University, and the City of Helmond to study citizens' attitudes towards automated shuttles and their willingness to use this mode of transport in the context of last mile mobility. The most relevant outcome of the survey:

- More than 80% of the participants were very or somewhat satisfied with their overall journey experience (see Fig. 2).
- Almost 90% of the participants felt very safe or somewhat safe.
- 76.4% of the participants have complete or great trust in the current automated vehicle technology. Not surprisingly, the level of trust is higher in the automated vehicle technology that will be developed in the future (84.5%).
- Most of the free-form comments in the survey were positive - the participants expressed how much they enjoyed the experience of riding an automated shuttle.

## 2.3 Conclusion

Overall, the participants of the FABULOS and LivingLAPT demonstrations in Helmond largely expressed positive attitudes towards automated shuttles and satisfaction with their rides. The citizens of Helmond feel that they already trust the current automated




**Fig. 2.** Satisfaction level of passengers (blue = highly satisfied, purple = very dissatisfied)

technology. The willingness to use automated shuttles for their last mile trips varied across the participants. However, the short duration of the demonstrations didn't allow participants and other road users to get used to an automated shuttle and their behaviour might be less natural compared to demonstrations with long durations. In addition, the demonstrations showed that some improvements of the automated shuttle service are necessary to offer a quality of service (speed, comfort, perception of (social) safety) at least equivalent to the current conventional public transport.

To be able to implement automated public transport services any time soon, the environment (or route) where the service will be operated should correspond to the current (technological) capabilities of automated vehicles. Automated vehicle suppliers have identified the characteristics of the environment in which the automated vehicle is capable to drive in automated mode: the Operational Design Domain (ODD). There seems to be one commonality in the ODDs: the easier the environment (without (or with as few as possible) unpredictable situations), the easier it is for an automated vehicle to drive in automated mode.

## 3 Next Steps

### 3.1 Automated Public Transport Services in Helmond

Considering the limited capabilities of automated vehicles to drive in complex ODDs and after consulting the national vehicle authority, the City of Helmond chose a stepwise approach to implement automated public transport services. Starting in an area where an automated public transport service can safely be provided and technological solutions (e.g. max speed close to the speed limit (30–50 km/h), remote supervision (thus no on-board operator)) can be developed and tested. The best area to start in is an easy environment; a route in an area with only conventional motorized vehicles, no situations with pedestrians or cyclists on the route, a route on which vehicles have right of way, and an area with a need for public transport solutions. Later, automated public transport service operations will be implemented in more complex environments.

One of the areas just outside the one mile-range from the train stations is the industrial area BZOB (the 'greyish' industrial area South East of Helmond in Fig. 1, chapter 1.1). BZOB houses 90 companies and 7100 employees and is not connected yet to any public transport mode (the nearest bus stop is 800 m away from the edge of BZOB). The result is that currently 78% of the employees use a private car to go to work. 19 Companies

(representing ± 1500 employees) are actively participating in an initiative whose goal is to change the travel behaviour of the employees to the usage of alternative transport modes. Analyses among these employees show that there is a need to travel to and from BZOB (from a survey carried out in a study on travel and work-related behaviour in BZOB [5] and a study on the needs for public transport and shared transport modes in Helmond [6]). For employees not living within cycling range from BZOB, the City of Helmond will make public transport more attractive by connecting BZOB with Helmond's central train station and surrounding towns. From Q3 in 2024, a bus at line 320 with a capacity of 80 passengers will halt at a new bus stop located at the edge of BZOB. More than a bus stop, it will be a mobility hub, facilitating multimodal travels. A last-mile automated public transport service will operate throughout BZOB connecting the mobility hub with the industrial area hotspots.

In August 2023 the City of Helmond launched a tender for the procurement, for 7 years, of a zero-emission automated public transport service, which will cover the last mile in BZOB. The project is expected to start in January 2024 with the preparation of the automated public transport service. It is expected to have an automated public transport service operational within the first year and a half of the project. The intended result upon completion of the full project is to have an operational automated public transport service (thus no need for an on-board operator) in the entire BZOB area. This service will provide at the latest in year 7 an on-demand service picking people up or bringing people to the mobility hub and connecting 320 bus line.

### 3.2 Impact of CCAM Passenger Solutions

In September 2022 a new Horizon Europe project in which Helmond participates started: MOVE2CCAM [7]. This project aims at exploring the multi-systems impact of CCAM passenger and freight solutions. The project will define use cases, business models and KPIs through co-creation activities with the "MOVE2CCAM Satellites" (i.e. organizations and citizens), and developing an impact assessment tool that will enable the evaluation of CCAM interventions' impact on different aspects.

In addition to initial workshops with organizations and citizens, an AV demonstration will take place in Helmond (Nov. 2023) to study the reactions and expected impacts of stakeholders and citizens who have actual experience with CCAM solutions and compare these to those who have not. This study will be a follow up of the LivingLAPT user acceptance survey and targets end user groups such as women and disabled people.

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# Prioritizing Buses in Smart Cities: A Stochastic Optimization Approach

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**Abstract.** This paper describes the development of an optimization model that considers the travel times of buses and traffic patterns to minimize deviations from planned schedules for routes across a network in a European city. Traffic congestion is a significant challenge which negatively affects the on-time performance and reliability of bus services. To address this issue, smart traffic management systems such as SCATS (Sydney Coordinated Adaptive Traffic System) are implemented to enhance traffic flow. While SCATS allows buses to request priority at road junctions controlled by traffic signals, conflicts may arise when different buses have opposing requests. To address this, we use a stochastic optimization approach to determine an optimal time-specific traffic interference solution that network owners can impose, such as signal phasing, to minimize schedule deviations for buses throughout the entire network.

**Keywords:** public transport · smart cities · bus reliability · stochastic optimization

## 1 Introduction

In a highly congested European capital city, public bus transport service providers are faced with the constant challenge of ensuring the actual on-time arrival of buses at bus stops by preventing deviation from the planned schedule, whether buses arrive too early or too late. In this particular city's operating environment, the majority of the deviations are delays, where buses arrive late at stops. There is also the phenomenon of "ghost buses," where buses that are scheduled to arrive never actually do.

In order to better support bus transport service providers, we develop an optimization model where buses are given priority to minimise schedule deviations by preemptively controlling traffic light signals which then clears traffic

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congestion ahead of buses. The approach also incorporates an overall view of the network, ensuring that changes in traffic signals is optimal for the network as a whole. The model can be utilized as part of a 'smart mobility' solution, a core element of a 'smart city's' centralized traffic solution [1], with applications in disruption management.

We illustrate the problem using a simplified $3 \times 3$ grid network with two bus routes, as shown in Fig. 1. In this network, each node in the network corresponds to a traffic intersection. There are two bus routes: Route 1 (red) which traverses along 1–4–5–6–9, and Route 2 (blue) which traverses along nodes 3–2–5–8–7. Nodes 4 and 6 are bus stops on Route 1, and nodes 2 and 8 are bus stops on Route 2.

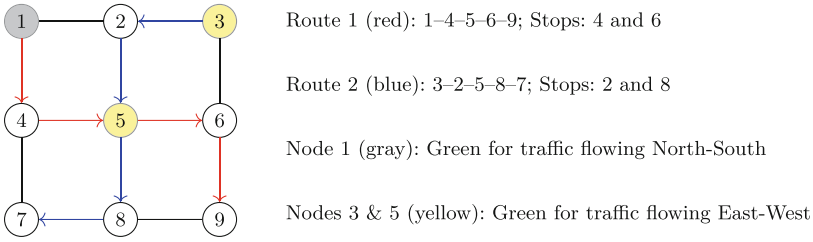



**Fig. 1.** Example $3 \times 3$ grid network with two bus routes. (Color figure online)

Suppose that the wait time at a red signal is set at 0.5 min, and a fixed delay of 0.25 min occurs when the bus makes a left or right turn at an intersection. Consider three scenarios based on the traffic conditions, each of which occurs with a probability 0.2, 0.5, and 0.3, respectively. Table 1 provides the planned and actual arrival times for Route 1 and Route 2.

Denote movements in North-South/South-North directions as 'NS' and movements in East-West/West-East directions as 'EW.' Assuming that the buses depart on time, an optimal arrangement of signal phases in this example network permits a green signal for NS traffic (red for EW) at node 1 and green signals for traffic flowing EW (red for NS) at nodes 3 and 5. The remaining signal phases in this simplified example network do not have an impact on the schedule adherence. Note that this is because Route 1 must move from node 1 to 4. At node 5, which is the only node where both routes cross paths, the EW movement of Route 1 is given priority to the NS movement of Route 2. This traffic signal configuration is optimized over the different traffic scenarios.

The remainder of this paper is organized as follows. Section 2 presents a review of the related literature. Section 3 introduces a stochastic optimization model to minimize deviations from bus planned schedules. We conduct computational studies of the optimization model on randomly generated grid networks and discuss the results in Sect. 4. Some concluding remarks and the future research directions are provided in Sect. 5.

**Table 1.** Actual versus planned time of bus arrivals at designated bus stops.

| Route 1 | | | | | Route 2 | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Node | Planned Time | Actual Time | | | Node | Planned Time | Actual Time | | |
| | | S1 | S2 | S3 | | | S1 | S2 | S3 |
| 4 | 0.5 | 0.35 | 1.16 | 2.64 | 2 | 1 | 0.34 | 1.63 | 2.55 |
| 6 | 2.5 | 1.29 | 5.16 | 8.17 | 8 | 3 | 1.79 | 5.33 | 8.37 |

## 2 Literature Review

The European Commission defines *smart city* as "a place where traditional networks and services are made more efficient with the use of digital solutions for the benefit of its inhabitants and business" [2]. An intelligent transport network (or smart mobility) is one of the core elements in a smart city. In this section, we will provide an overview on current state of developments in intelligent transport systems that are most relevant to our work. For a more comprehensive review on intelligent transportation systems and signal control, see [3] and [4].

Concerning real-time traffic control, studies in the literature have explored dynamic programming [5], a multi-objective agent-based approach in which the traffic signals are modeled as intelligent agents [6], and a hybrid model that utilizes a vehicle location, arrival prediction, and priority selection algorithm [7]. Recent studies have also investigated machine learning approaches to manage traffic signals [8,9].

With respect to managing traffic flows over the network, Sun et al. [10] developed a bi-level programming model to optimize the signal time cycle with bus priority, minimizing passenger and private vehicle delays at an intersection. Wong [11] focused on optimizing traffic signal timings at intersections using a group-based approach. Adacher [12] employed gradient-based methods and continuously updates system states to minimize the weighted sum of vehicle delays. Lee and Wang [13] proposed an adaptive traffic signal control method to minimize the total person-based delay instead of vehicle-based delays at intersections.

This article contributes a traffic signal control problem with bus priority considered. Existing work in the literature have focused on managing signal phases in real-time or minimizing the delays of one or multiple modes of transport. Our work seeks to improve the reliability of the public transport system by maximizing schedule adherence. That is, in addition to delays, we aim to minimize the penalties imposed when a vehicle is early. The proposed solution approach also allows the consideration of various traffic scenarios, allowing a network owner to control signal phases across the network preemptively and prevent schedule deviations from occurring.

## 3 Problem Formulation

We define a network $G = (N, A)$, where $N$ represents the set of nodes (intersections) and $A$ represents the set of arcs (two-way streets). Let $R$ be the set of all

bus routes. For each route $r \in R$, define $N^r$ as the set of nodes and $S^r$ as the set of bus stops on route $r$, where $S^r \subseteq N^r$. In addition, $V^r$ denotes the set of nodes in $N^r$ such that a bus must move NS to arrive at a node in $V^r$ (Recall that NS denotes both North-South and South-North movements). For instance, in Fig. 1, $V^1$ contains node 4 as Route 1's movement from node 1 to node 4 corresponds to a NS movement. Similarly, $H^r$ denotes the set of nodes in $N^r$ such that a bus must move EW on route $r$ to arrive at a node in $H^r$. Analogously, we use $C^r$ to denote the set of intersections at which the bus must make a left or right turn on route $r$.

Let $d_1$ be the amount of time a bus must wait at a red signal, and $d_2$ the amount of additional time taken when making a turn. Define $a_i^r$ as the scheduled arrival time of a bus on route $r$ at node $i \in N^r$, for each $r \in R$. We also define $K$ as the set of all possible scenarios. Let $p^k$ denote the probability associated with scenario $k \in K$ such that $\sum_{k \in K} p^k = 1$. For each scenario $k \in K$, $\delta_{ij}^k$ represents the actual time taken to traverse arc $(i, j) \in A$.

We use a binary variable $x_i$ to represent the traffic signal phases at each node $i \in N$, where $x_i = 0$ corresponds to a green signal for EW traffic (red for NS traffic) and $x_i = 1$, otherwise. Define $t_i^{r,k}$ as the bus on route $r$'s actual arrival time at node $i$ in scenario $k$, $\forall r \in R, i \in N^r, k \in K$. Model (1) minimizes the expected value of total schedule deviation across the network.

$$\min \sum_{k \in K} \sum_{r \in R} \sum_{j \in S^r} p^k \left( u_{1j}^{r,k} + u_{2j}^{r,k} \right) \tag{1a}$$

$$\text{s.t. } t_j^{r,k} = t_i^{r,k} + \delta_{ij}^k + d_1 x_i \qquad \forall k \in K, (i,j) \in Y^r : j \in V^r, r \in R \tag{1b}$$

$$t_j^{r,k} = t_i^{r,k} + \delta_{ij}^k + d_1 (1 - x_i) \qquad \forall k \in K, (i,j) \in Y^r : j \in H^r, r \in R \tag{1c}$$

$$t_j^{r,k} = t_i^{r,k} + \delta_{ij}^k + d_2 \qquad \forall k \in K, (i,j) \in Y^r : j \in C^r, r \in R \tag{1d}$$

$$a_j^{r,k} - t_j^{r,k} = u_{1j}^{r,k} - u_{2j}^{r,k} \qquad \forall k \in K, (i,j) \in Y^r, r \in R \tag{1e}$$

$$t, u \geq 0 \tag{1f}$$

$$x \in \{0,1\}^{|N|}. \tag{1g}$$

Constraints (1b)–(1d) ensure that the actual arrival time at node $j$ is the sum of the actual arrival time at node $i$, the actual time taken to traverse arc $(i, j)$, and any delays incurred on a route for each traffic scenario. Note that constraints (1b) and (1c) correspond to NS and EW movements, respectively. Thus, traffic can only flow without any delay due to red singals in either NS or EW movements at a given intersection, which is enforced through the use of binary variables $x_i$. Constraint (1c) corresponds to when a bus makes a turn. Also observe that the expected total schedule deviation is given by $\sum_{k \in K} \sum_{r \in R} \sum_{j \in S^r} p^k \left( |a_j^{r,k} - t_j^{r,k}| \right)$, which is replaced with objective function (1a) through the introduction of $u$-variables and constraints (1e)–(1f) to obtain a mixed-integer linear program. The objective function (1a) minimizes the weighted difference between the actual versus planned arrival times at all bus stops across the network.

The model can be expanded to be multi-modal with minor modifications to the objective function and additional variables. For this purpose, we can define variables $w^r$, for each $r \in R$, as the relative importance (i.e., priority) of any route of a particular mode of transport (e.g., taxis, personal cars, and bicycles). The revised objective function is given by $\sum_{k\in K}\sum_{r\in R}\sum_{j\in S^r} p^k w^r \left(u_{1j}^{r,k} + u_{2j}^{r,k}\right)$. As other modes of transportation like taxis, personal cars or bicycle do not contain fixed stops along their routes, we consider their origins and destinations as the stations and the expected arrival times at the origin and destination, where applicable, are used as scheduled arrival times. Note that with the introduction of variables $w$, we also permit the differentiation of traffic flows at route level, enabling system owners to prioritize traffic at known bottlenecks in the network.

## 4 Preliminary Experiment

The preliminary experiments were conducted on a Dell vPRO equipped with 10 physical cores, an Intel Core i7 Processor, and 32 GB of RAM. The model was implemented using Pyomo library and CBC solver [14].

The experiment was conducted on a $50 \times 50$ grid network with a set of three bus routes $R = \{1, 2, 3\}$. We consider the set of scenarios $K = \{1, 2, 3\}$. Each scenario occurs with probabilities 0.6, 0.3, and 0.1, respectively. The actual travel times $\delta_{ij}^k$ across arc $(i, j) \in A$ were randomly generated following uniform distributions in $[1, 4]$, $[4, 6]$, and $[6, 10]$ for scenarios $k = 1$, 2, and 3, respectively. We set $d_1 = 0.5$ and $d_2 = 0.25$.

Ten replications of this experiment were conducted and the results are reported in Table 2. For each route and scenario, Table 2 reports the planned arrival time and actual arrival times in minutes in columns *Planned Time* and *Actual Time*, respectively. Column *Deviation* reports route $r$'s deviation from schedule for each bus stop $i$ in each scenario $k$, which is given by $(|t_i^{r,k} - a_i^{r,k}|/a_i^{r,k}) \times 100\%$. Under *Planned Time*, *Actual Time*, and *Deviation*, columns *St 1*, *St 2*, and *St 3* correspond to the 1st, 2nd, and 3rd bus stop, respectively, on each route. At optimality, the objective function value representing the total expected schedule deviations of the entire network is 174.7 min.

Scenario 1 represents the arc travel time planned arrival times for buses at their stop stations under normal traffic conditions. Scenarios 2 and 3 represent heavy traffic and ultra-heavy traffic conditions, which have longer travel times. The deviations between actual and expected times in the most likely scenario (Scenario 1) are minimal. As travel times of the arcs increase in the second scenario, these deviations also grow larger. In the least probable scenario where travel times are significantly longer, the deviations become notably significant. However, by considering the probability of all scenarios, the overall performance of the traffic signal model is optimized across all defined scenarios.

In addition, we also conducted experiments to understand how the objective function value changes when the probabilities associated with different scenarios change. The modified probability for scenario $k$ is reported under column $p^k$, for each $k = 1, 2, 3$, in Table 3. In this set of experiments, five replications were

**Table 2.** Network performance under an optimal signal phasing solution.

| Route | Scenario $k$ ($p^k$) | Planned Time | | | Actual Time | | | Deviation | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | St 1 | St 2 | St 3 | St 1 | St 2 | St 3 | St 1 | St 2 | St 3 |
| 1 | 1 (0.6) | 30 | 60 | 70 | 30.9 | 57.8 | 69.2 | 3% | 3% | 1% |
| | 2 (0.3) | | | | 43.8 | 95.6 | 117.0 | 46% | 59% | 67% |
| | 3 (0.1) | | | | 72.7 | 157.8 | 190.0 | 142% | 163% | 171% |
| 2 | 1 (0.6) | 25 | 50 | 65 | 25.7 | 53.5 | 60.2 | 3% | 7% | 7% |
| | 2 (0.3) | | | | 44.3 | 91.2 | 114.1 | 77% | 82% | 75% |
| | 3 (0.1) | | | | 68.7 | 153.81 | 177.9 | 175% | 208% | 174% |
| 3 | 1 (0.6) | 35 | 60 | 75 | 38.3 | 60.4 | 64.3 | 10% | 1% | 14% |
| | 2 (0.3) | | | | 46.48 | 95.69 | 104.5 | 33% | 59% | 39% |
| | 3 (0.1) | | | | 64.0 | 152.6 | 167.5 | 83% | 154% | 123% |

conducted and the objective function values (i.e., weighted time deviations over the network) were obtained, whose average is reported under column *Average Objective Function Value* in Table 3.

**Table 3.** Mean network time deviation under varying scenario probabilities

| ID | $p^1$ | $p^2$ | $p^3$ | Average Objective Function Value |
|---|---|---|---|---|
| 1 | 0.90 | 0.05 | 0.05 | 69.7 |
| 2 | 0.60 | 0.30 | 0.10 | 177.5 |
| 3 | 0.33 | 0.33 | 0.33 | 368.8 |
| 4 | 0.10 | 0.40 | 0.50 | 499.0 |

As previously mentioned, the first scenario pertains to normal traffic conditions, characterized by lower values of travel time between arcs. In the second and third scenarios, travel times escalate due to heavy and ultra-heavy traffic conditions. Consequently, with the decrease in the probability of the first scenario, the total delay for all buses increases, in accordance with expectations for heavier traffic conditions.

## 5 Conclusion

We proposed a stochastic optimization model that specifically prioritizes buses in traffic signal phasing and optimizes the performance of all bus routes over the network. For future research, we plan to extend the current model to account for multiple time horizons to enhance its practicality and applicability. Different penalties for earliness and tardiness may be considered, as is usually the case in practice. As the proposed model in this article is risk-neutral, we may also

consider different risk levels in future studies to adapt to different profiles of network owners. Finally, we plan to apply the model in a highly-congested urban European city to evaluate its practicality and needs for further developments, while benchmarking its performance against current best practices.

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# Technology Development Towards Autonomous, Connected and Safe Mobility of People and Goods in Urban Environments

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**Abstract.** It is an essential requisite in order to achieve safe autonomous driving in urban environments, to address the mobility from a multidisciplinary approach. In this sense, technological development is crucial in both passenger and goods transport. Within Integra project, in which the work described here is framed, autonomous and connected driving is addressed from a dual perspective: urban environments and logistics environments. Thus, its activity is structured around the following lines of action: (1) improvement of perception technologies, (2) optimisation of communication technologies, (3) redesign of occupant damage mitigation technologies and (4) development of new delivery solutions. This paper summarizes the most critical aspects of each of these lines and the considerations to be taken into account to ensure the implementation of autonomous and connected driving in complex environments. In doing so, it takes into account the particular conditions of urban environments and their implication for the deployment of autonomous mobility.

**Keywords:** Autonomous Driving · Urban Environments · Perception · Occupant Safety · V2X · Goods Transport

## 1 Introduction

Full self-driving automation is the next big mobility-related disruptive innovation not just for the technology development it implies, but also for the benefits it brings to the people and goods transport [1]. In the midst of the transition to decarbonisation, the autonomous and connected driving has as much potential to reduce energy consumption, through more efficient driving, as it does driving stress because it does not require a driver. Another potential benefit is related to cost reductions in the logistics sector and shorter delivery times.

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From the societal point of view, fully autonomous and connected driving has potential to enhance road safety by eliminating human errors. So much so that [2] have estimated that driverless cars may reduce traffic fatalities by up to 90% by mid-century. However, seen from the technological side, there is still a long way to go before we see autonomous vehicles on the roads, especially in urban environments.

The complexity of urban environments, with numerous actors creating situations of enormous variability and technical complexity, raises many difficulties to deploy safe autonomous solutions. In this sense, Integra project, born of collaboration between four Spanish R&D centres, is focused on developing technological solution that enable a ultra-safe level 3–4 autonomous driving in complex urban environment, from a holistic approach, considering both passengers and goods transport. To this end, the project addresses the following interdisciplinary areas: autonomous driving functionalities, connectivity, occupant safety and autonomous goods delivery.

## 2 Autonomous Driving Functionalities

While the success of autonomous driving in urban environments depends on many factors, one of the most important falls on the autonomous driving functionalities have a correct and accurate perception of the environment. To achieve this, it is critical that perception algorithms have access to several groups of data sources. Specifically, to the following data sources: (i) environment real data provides by the integrated sensors; (ii) environment real data provided by external sensors and (iii) context annotated data provided by virtual reconstructions of the real world.

In the framework of INTEGRA project, work was done to exploit these three categories to the highest level in order to address the particular conditions of the urban environments. As a result, the following difficulties were identified:

- Due to the topology of the cities, there are many regions of interest that can be occluded by buildings, vehicles or other items. Consequently, onboard sensors might be insufficient for detecting all kind of dangerous situations.
- With respect to localization, urban scenarios quite often include spaces with low satellite coverage or with GNSS signals affected by multipath disturbances.
- Perception obstacle detection algorithms must be very sensible to the presence of Vulnerable Road Users (VRUs) and robust against false positives.

To address them, the following solutions were considered:

- A group of cooperative sensors, in order to complete the perception of vehicles.
- A LiDAR-based positioning system to improve localization.
- A specific module for classifying and precisely positioning the VRUs and vehicles in relative 3D coordinates by using a vision-based system.

### 2.1 Functions Considerations for the Algorithms

In parallel, the driving functions will have to take decisions on their own. It is therefore important that the SW architecture of the functions includes the “Path Planning” module, the “Control” module and the “Actuation” block.

After studying it through several use cases, it is critical that in urban environments the following workflow is followed:

- The information from the surroundings of the vehicle, captured by sensors, is processed by the perception layer, which enters the "Path Planning" module. In this layer, all the information is organized and enriched according to the needs the "Behaviour Planning" block.
- In the "Behaviour Planning" block, the information is used to execute functionalities such as lane change and speed adaptations.
- Finally, the "Control" module calculates lateral and longitudinal action to be performed by the vehicle's actuator actions according to the instructions of the previous block.

## 3 Connectivity

Complementing the above, the future of driving also relies on facilitating the communication between vehicles, especially in urban environments due to their complexity. The ability to receive information from other vehicles is essential to achieve safe driving. Thus, within Integra project, OMNeT + + and SUMO simulators were coupled in order to evaluate the enhancement in driving safety facilitated by Vehicle-to-Everything (V2X) communications.

After several simulations based on real rather than synthetic mobility data with different urban scenarios, it was observed that the most significant parameter for a safe urban autonomous driving is the position error perceived by the vehicles, due to the lack/loss of V2X messages. Briefly, this error is defined as the difference between the current position of one vehicle and the position known by its neighbors.

One example is show in Fig. 1, which plots the position error perceived by the vehicles involved in a collision scenario when they drive at 60 km/h. These values are presented in function of time, being the first error, a little before second 12. At this point, the distance between both vehicles is large and several messages are lost. Later on, nearly no message is lost.

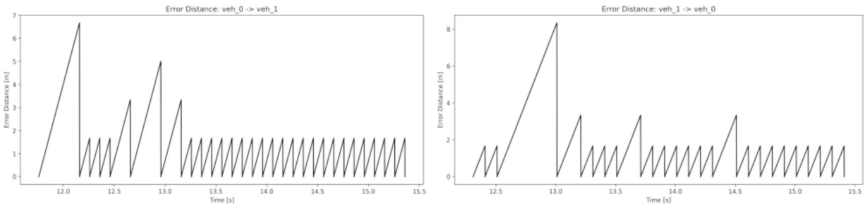



**Fig. 1.** Position error of the vehicles involved in the collision when driving at 60 km/h.

Subsequent larger errors are caused by the consecutive loss of messages, which normally occur when vehicles are apart and have buildings between them.

To obtain these results, a framework was developed that allows capture of real vehicle behavior from traffic video cameras. Graphically, Fig. 2 illustrates an example of the detection and tracking results of several combined traffic cameras from which information is obtained to feed the simulators.



**Fig. 2.** Tracking results for the combination all cameras from the US 101 database [3].

In parallel to the described simulations, another parameter to take into account in terms of connectivity is location data. Presently, standalone GNSS systems are prone to errors exceeding 1 m due to interferences. These inaccuracies are particularly pronounced in urban canyons, where GNSS may produce errors in the tens of meters. To address this challenge the join use of 5G-NR technology and GNSS-based localization was explored within Integra project.

See in the Fig. 3 the performance of 5G-NR versus stand-alone GNSS in three simulation environments: urban, suburban, and rural.

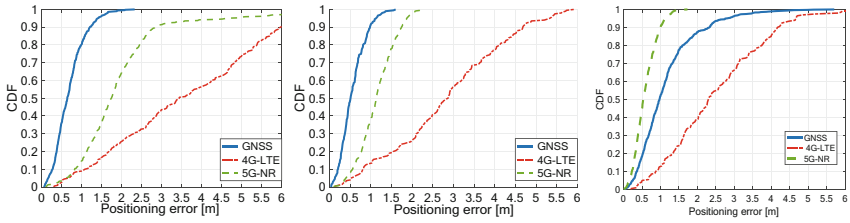



**Fig. 3.** CDF Position Error in three scenarios (rural, suburban and urban).

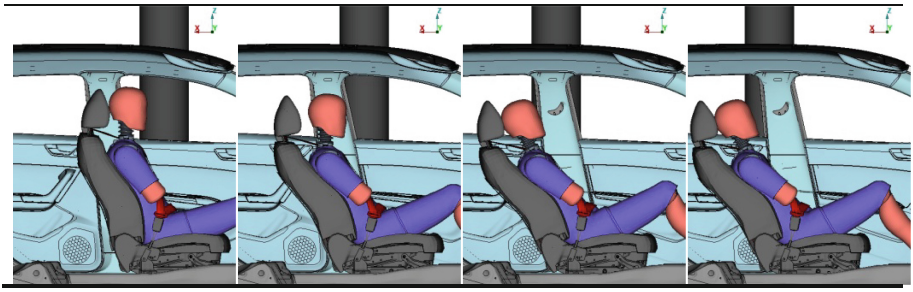
Note that GNSS performs considerably better than cellular systems in environments where there are a large number of visible satellites for users (rural and suburban). On the other hand, in urban environments, the error in position estimation through GNSS begins to increase due to the loss of visible satellites. In contrast, 5G-NR benefits from a high density of nodes, which results in a reduction of positioning error.

## 4 Occupant Safety

The deployment of autonomous driving in urban environments must go hand in hand with a number of readjustments of the occupant protection system. Unfortunately, the entry of autonomous driving does not guarantee the eradication of all accidents. Thus, it is important that in the event of accident the occupant is provided with an appropriate restraint system.

From this point view and with an eye on the progress of the Advanced Driving Assistance Systems (ADAS), the positions listed in Table 1 will be usual in the near future. Consequence of the greater freedom of movement that involves increasing the level of automation of driving, the occupants face a safety issue: the bad performance of the restraint systems due to different positions from the nominal one.

**Table 1.** Autonomous driving scenarios in the near future.

| Relax | Entertainment | Work | Rest |
|---|---|---|---|
|  | | | |

Integra project addresses this question by first analysing the risks associated with the positions described in Table 1 through crash simulations, and then developing and implementing an algorithm for monitoring the driver's position.

Taking into account the results of the simulations at various crash speeds, it can be seen that the posture of the occupants is the variable which most influences on the correct performance of the protection elements. Consequently, seat-embedded solutions provide the best protection for the occupants, as their position relative to the person in the event of a crash is always the same.

However, in certain positions, even with seat-embedded solutions, simulations shows that restraint system cannot adapt to the occupant's pose. In these cases the driver is required to modify his or her posture. Within Integra project, work was proceeded on a deep learning algorithm capable of predicting 33 key points on the driver's body and from them estimating the driver's pose, with a view to applying it to adaptive restraint systems in the near future.

## 5 Autonomous Goods Delivery

Finally, while occupant safety was mentioned above, autonomous driving also requires a number of actions in the field of goods transport in order to maximize safety. On this road, there are several important lines of action that range from guaranteeing the integrity of the goods to designing an optimal and safe vehicle that helps to reduce the delivery times. The following methodology has been used in the Integra project to address these challenges:

### 5.1 Technical Characterization of Urban Delivery Routes and Smart Mobile Locker Design

In order to know the vibrations that the goods are subjected to during the distribution, a total of 15 last-mile routes were monitored in four Spanish different cities. The study was carried out with the same type of delivery van and a data recorder (DR) device, to identify linear accelerations (vertical vibration). The Fig. 4 shows the maximum envelope curve

that was obtained. Based on the severity of interurban routes (PSD) monitored, a smart mobile locker design was also developed (Fig. 5).




**Fig. 4.** Envelope of maximum PSD curve obtained from the 15 routes under study.

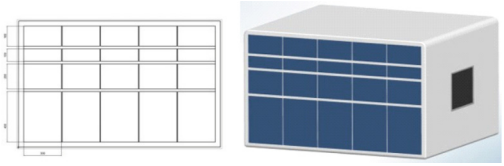


**Fig. 5.** Smart mobile locker design.

In parallel, a vibration test was developed to simulate the reality of the monitored last mile distribution routes and to generate further synthetic data to support the design development.

## 6 Conclusions

To recap, the deployment of autonomous driving in urban environments is not imminent. In order for the autonomous driving to become a reality in cities, the appropriate technology must be first available and a safety level equal to or higher than the current one must be guaranteed. In this context, the success of smart mobility in urban environments lies in the following key aspects: the correct and accurate perception of the environment, the proper performance of V2X communications, the availability of an appropriate restraint system and the development of vehicles adapted to the characteristics of the environment. Working along these lines ensures the implementation of autonomous and connected mobility both in urban environments and in specific logistics environments, where the application of high safety systems is necessary.

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# The Case for Automated Buses: The MultiCAV Project and the Didcot Garden Town Urban Extension

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**Abstract.** Most sustainable urban transport strategies include an expanded role for public transport amongst their measures. New technologies have often been presented as a means of making public transport more attractive when compared to other travel options. Integrating attractive transit with new development is also presented as a technique which can encourage public transport use. The present paper considers these three principles in the context of the MultiCAV project, which tested automated buses (AB) in Didcot (UK), a town scheduled for significant expansion. MultiCAV is one of the few automation projects to test urban buses capable of providing mass transit in a range of urban and peri-urban road environments. Findings are presented from evaluative research including surveys and interviews with potential users, actual users, safety operatives, and the project delivery team. It is found in the case of MultiCAV that automation technology has a high degree of capability, but is not yet sufficiently mature to operate a schedule service in complex road environments shared with general traffic without human assistance for specific tasks. Additionally, a solution for the tasks currently performed by drivers beyond the driving task also needs to be identified. Passenger acceptance of automation was found to be strongly influenced by the condition that an operative is onboard. If early applications of ABs were to be on segregated busways this would reduce or remove some of these barriers. Segregation would also give the services priority, capitalising on the cultural value of high-technology public transport, and increasing appeal relative to the private car. Such an approach would be particularly relevant for new development areas where segregation would be relatively easy to achieve.

**Keywords:** Automated buses · Transit-oriented development · Public transport

## 1 The Case for Automated Urban Buses

### 1.1 Public Transport Technologies for Sustainable Development

That development should be ‘transit oriented’, relatively dense, diverse in its mix to create different kinds of travel opportunity, and designed to be attractive for active travel and public transport use, is one of the established principles of urban planning [1].

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Similarly, investment in high-technology public transport schemes such as Light Rail Transit (LRT) and Guided Busways has been widely considered as a driver of urban regeneration processes [2, 3]. As well as providing a form of public transport which is seen to be more effective in attracting users from cars [4], 'centrepiece' public transport schemes can offer an aesthetical and cultural significance for the public that is not always sufficiently valued by 'rationalist' planners [5]. Indeed, there are circumstances in which aesthetic, marketing and imagery bear great importance; failure to factor them into transport planning decisions can lead to poor outcomes [6].

LRT has been particularly valued by urban practitioners as a means to modernise and rejuvenate decayed spaces [2], within a wider strategy aimed at building competitive world-class cities [7]. LRT has been presented as a clean, sustainable and modern means of transport, and sometimes contrasted with buses against these attributes [2, 8]. Busways and guided bus technology also have strong proponents, though. It is argued they offer the potential to deliver similar benefits to LRT for a much lower capital cost. They are also identified as being quicker to deliver and more flexible over time. However, it has also been argued that they may be less attractive to passengers than rail systems and lack their strong contribution to a city's image [4].

Into this context emerges the potential for automated vehicles (AVs), operating either on segregated busways or on roads shared with general traffic. The AV entails a complex technology that might also shape urban imageries. However, interest is also driven by the potential for a significant reduction in operating costs if drivers are not required, potentially facilitating a higher level of service and/or lower fares.

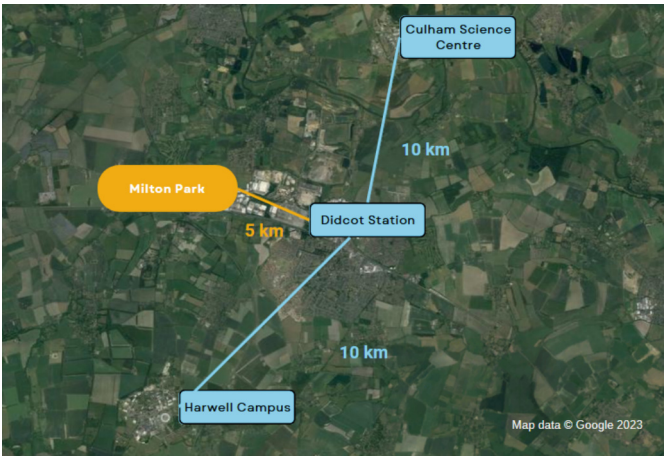



**Fig. 1.** Concept for Autonomous Public Transport Services in Didcot Garden Town. (Basemap source: Google Maps™)

An example of a stakeholder community attracted by the potential of AV buses was that for 'Didcot Garden Town' [9], a spatial-economic planning strategy to increase the population of Didcot, UK from 30,000 to 45,000 and add 20,000 jobs. The vision was to create a sustainable science and technology city incorporating the existing

internationally-renowned research facilities at Harwell and Culham and the technology business cluster at Milton Park (Fig. 1). A sustainable transport system to underpin transit-oriented development was seen as essential. The Garden Line (shown in blue) was proposed as a segregated route for active travel and AVs. Another to Milton Park (shown in orange) would involve AVs using existing roads.

During MultiCAV the orange route became the basis of a trial of an automated bus (AB) service. The remainder of the paper considers the experiences of the project which delivered that trial, in terms of lessons learned for the operating team and user reactions.

## 2 Experiences from the MultiCAV Project

### 2.1 Automated Public Transport at Didcot, UK

There have been many trials globally of automated small-capacity 'shuttle' or 'pod' vehicles, with novel forms of passenger compartment, and speeds limited to 20–25 km/h. Such vehicles do not meet the crash test performance, operating capabilities, or capacity of the typical urban bus. Few automation projects have sought to adapt existing road-going buses. A demonstration in Malaga (Spain) deployed a 60-seat electric AB on a 5 km route, operating at 11 km/h [10]. The CAVForth project operated a diesel-powered AB service using 43-seat buses on a 15 km route mainly on extra-urban highways near Edinburgh (UK) [11].

MultiCAV [12] in Didcot deployed an automated electric Mellor minibus. The service carried members of the public over a period of seven weeks on a 5 km route between Milton Park Business Park and Didcot railway station (Fig. 2). The AB operated at up to 65 km/h in mixed traffic, sharing roadspace with pedestrians, cyclists, cars, vans, other buses and heavy goods vehicles. The general-purpose roads included features such as traffic light control and roundabouts. Fares could not be charged. Passengers were requested to wear safety belts (not a normal feature of urban buses in the UK) and no standing was allowed. In other respects (timetables, stops, integration with digital travel information) the project delivered an AB within a typical urban bus service.

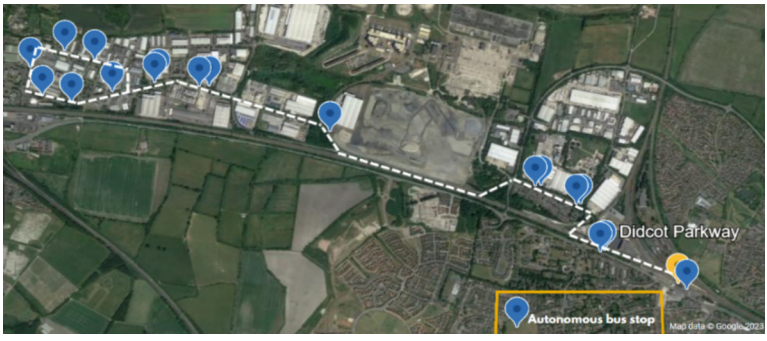



**Fig. 2.** Route of Autonomous Bus Trial Service in Didcot. (Basemap source: Google Maps™)

In line with UK Government AV trial guidelines, and to provide a human interface with the passengers, a human operator was present in the driving seat, ready to take control. The operators were briefed to give primary consideration to safety, but also the passenger experience, so interventions were also made to ensure the journey was not delayed, or to avoid AV behaviours that, whilst still safe, might lead to discomfort. A sign reading 'AUTO' was illuminated in the passenger cabin to indicate when the bus was operating under automation.

The authors undertook evaluative research with the following objectives:

- To evaluate user (and non-user) perceptions and experiences of the electric AB,
- To examine the experiences of safety operatives,
- To understand limits to AV technology readiness,
- To consider potential future applications.

### 2.2 Study Methods

Table 1 provides a summary of how the research engaged with different participants. The research was conducted following UWE Bristol ethical approval (references FET.19.10.014 and FET-2122–96).

**Table 1.** MultiCAV social research activities.

| Target study population | Data collection approach |
|---|---|
| Potential users | Surveys of Milton Park employees at different times 2020–2023 |
| Actual users | On-board self-completed survey of experiences during travel |
| Actual users | Post-journey interviews to deepen understanding |
| Safety operatives (drivers) | Interviews following weeks of in-cab experience |
| AB service delivery team | 'Learning journey' interviews near beginning and end of project |
| AB service delivery team | Workshop enabling the comparison of professional experiences |

### 2.3 Principal Findings

Prior to the AB service, a survey of Milton Park employees (n = 863) found 74% agreed that "I would be happy using an AV if there was an operator onboard". However, this dropped to 45% if the same question was posed but in the absence of an operator.

During operation, a survey of AB users (n = 119) identified 90% to be daily or frequent bus users, mainly commuters. A similar number indicated their alternative travel option would have been a bus. Just 13% reported using the service "just to try" the AB.

Apart from the finding that 72% found the electric bus quieter than their normal diesel bus experience, the performance of the bus in terms of smoothness when driving was not seen as different overall: about half of users rated it about the same, the other half were split as to whether it was smoother or "jerkier". Regarding safety, over 90% agreed

that they felt safe on the AB "because there was a human operator on board". More users reported feeling safe when the bus was travelling at low speed (88%) compared with high speed (72%).

Users were asked to rate the AB's driving performance compared with a human driver for five different journey events. Figure 3 shows that for all events most respondents thought the performance was similar. For those that recorded a difference, in all cases except "approaching and leaving junctions" the AB was rated more highly.

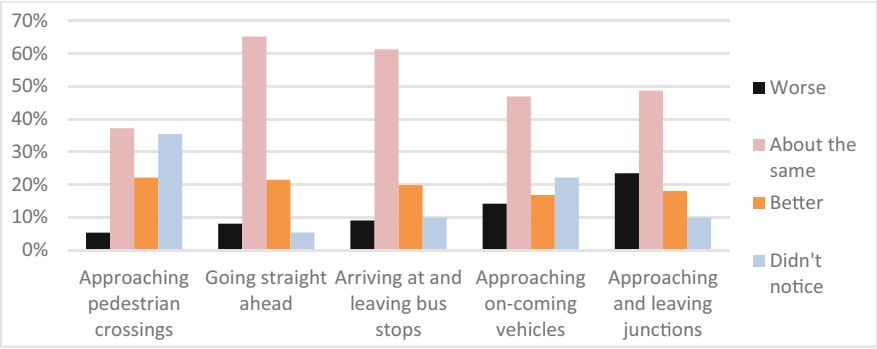



**Fig. 3.** Ratings of autonomous driving compared to human driving for five journey events.

The findings from the qualitative interviews with users showed strong positive attributions towards the new technology, but also a sense that "it was just another bus". There was also some disappointment that the safety operative had to intervene to manage unexpected events, such as temporary roadworks, or particularly challenging situations, such as joining a roundabout in busy but high-speed traffic. In addition, an explanation for the lower ratings of AB performance at junctions was revealed: the bus could be seen to be over-cautious compared with the typical human driver; the latter being more willing to take calculated risks.

The safety operatives were a team of six bus drivers seconded from their normal duties in a busy urban environment on the western fringe of London. They reported a high level of satisfaction with the training they had received to convert to operating the electric AB. After some initial apprehension due to the novelty of the task, they had found the experience to be positive and enjoyable. They also reported their confidence in the autonomous system grew, due to three factors: their longer exposure, a perception that the technology had improved during the trial (driving more like a human and requiring fewer interventions), and that their interactions with the technicians had increased their own understanding and lead to adjustments in system operation.

## 3 Relevance of MultiCAV Experiences to Future Applications

Within a user community relatively engaged with new technologies, MultiCAV demonstrated that an AB can be experienced as overall equivalent to a human-driven service. Indeed, the familiar nature of the vehicle meant that the generation of positive 'futurist'

associations was limited. Nonetheless, there was an expectation for a human operative to be onboard, although the overall positive evaluations also provide some support for potential future unstaffed operation. The 'caveat' is that significant barriers remain to be overcome. The technology at the time of study was not fully mature. Operator interventions were necessary to overcome issues with the 'machine-readability' of the environment [13], such as wind-blown vegetation impinging on the carriageway. Whilst the AB was capable of all necessary manoeuvres, being able to perform them on roads where some humans do not drive to the highway code remains a constraint.

A further constraint for ABs is that the bus driver performs functions other than driving. In the UK these include a legal responsibility to ensure the safe travel of mobility-impaired passengers. A solution such as bookable human assistance or a 'carebot' could be necessary to ensure all passengers can board, travel, and alight AB services.

Interviews with the experts who delivered the AB service confirmed the view that it would be easier in the short term to overcome the issues relating to on-road interactions through the use of segregated busways. Segregation will also ensure that ABs are not delayed by traffic congestion, which will otherwise remain as a deterrent to bus use. With the right image and branding, the combination of high technology and priority also offers the potential for the high cultural attributions discussed in the introduction; conditions important for attracting new passengers to public transport from private cars.

ABs on segregated carriageways present an intermediate investment option with the potential for high levels of service and low operating costs without the high cost of providing mechanical guidance. Given the difficulty of delivering segregated alignments in the existing built environment, they offer a particularly relevant solution for new-build developments. A hybrid solution would be for ABs to be unstaffed on busways where they can be provided, but as they enter urban areas where road conditions are more complex and segregated alignments unavailable, for a safety operator to join.

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# Transition to Remote Train Control: Challenges and Best Practices for Collaboration in the Digital Age

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**Abstract.** This paper studies the collaborative and managerial aspects of remote control of trains and trams. In the transport industry, increasing societal pressures have pushed organizations to revolutionize their operations by going digital. Indeed, contemporary societies require that transport firms optimize their services in order to meet the growing challenges and needs of the modern world. Our study is based on mapping published experiences and expected consequences of remote train control (RTC). The identified initiatives yielded valuable insights into the potential challenges associated with RTC and we provided best practices to address obstacles and navigate the changes in the work context for various stakeholders. We found that misunderstandings in the driver´s roles can cause quality of services issues during the transition to RTC. The prospect of changing roles for operational staff raises concerns. The achievement RTC will be contingent upon the involvement and collaboration of diverse stakeholders.

**Keyword:** ATO · Project Management · RTC

## 1 Introduction

The advent of automation has precipitated profound transformations across numerous industries, significantly altering their operational paradigms. It has been claimed that automation in the railway sector is still in its embryonic stage, but it holds the potential to perform crucial tasks (Besinovic et al., 2022). Currently, the escalating imperative for railway organizations to recalibrate and transform their operations has arisen in light of societal pressures (Singh et al., 2021). One possibility to tackle these challenges is the introduction of Automatic Train Operations (ATO). However, the use of ATO in an open-world railway context may encounter challenges. Alternative approaches are being explored, such as Highly Assisted Driving, which includes RTC (Gadmer et al., 2022). While RTC offers solutions to certain issues, it also introduces complexities that necessitate careful consideration. For instance, RTC has been observed to exacerbate the

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monotony of train driving, leading to detrimental effects on drivers' attention (Anceaux et al., 2019) and it has been found to increase the cognitive workload for various stakeholders (Gadmer et al., 2022). Consequently, it is imperative to assess the specific needs and business requirements associated with the implementation of RTC. The primary objective of this paper is to identify and communicate the consequences associated with the deployment of RTC to decision makers and stakeholders involved. The scope of these consequences encompasses benefits, costs, as well as managerial barriers related to RTC. We assessed previous studies on the effects of RTC on issues such as challenges, staffing requirements, service capacity and reliability. The identified initiatives yielded valuable insights into the obstacles associated with RTC and we provided best practices to address barriers and navigate the changes in the work context for various stakeholders. The scope of the collected studies includes all types of track-based transport. The identified research encompasses cases studies, literature reviews, empirical and conceptual papers. This study is related to the flagship project FP2 R2DATO under the Europe's Rail Joint Undertaking. The project aims to grasp the opportunity offered by digitalization and automation of rail operations.

## 2 Challenges for Remote Train Control

RTC generates major impacts in the railway industry, since the dynamics of collaboration among stakeholders is transformed due to team members required to engage in endeavors with a machine agent (Pacaux-Lemoine, Gadmer and Richard, 2020). The remote operator, being separated from the train, lacks the capacity to autonomously gather environmental information and respond to it and in the absence of direct access to the train real time conditions, he/she becomes dependent on an advisory system. This system will gather information, conduct thorough analyses and formulate predictive outputs regarding the driving process, which will serve as inputs for the remote operator actions (Pacaux-Lemoine, Gadmer and Richard, 2020). This creates multiples challenges for railway organizations. It was found that remote operators exhibit delayed signal detection, attributed to the combined effects of system latency and engine response latency, making interpretation challenging (Paglia et al., 2021).

Furthermore, the operator's ability to cooperate and interact with assistance systems is severely impaired by the fact that their needs and exigencies are rarely assessed (Gadmer et al., 2021). Karvonen et al. (2011) conducted a study to assess the effects of metro automation on train drivers and explored strategies to leverage their expertise in enhancing the automation process. They identified that disregarding the responsibilities and knowledge held by the drivers during the transition towards ATO could yield adverse impacts on service quality and create safety issues. Since it is frequently assumed that former drivers will transition to the role of remote operator, it is critical to comprehend their responsibilities and activities to specify the modifications that must be applied so that RTC can be attained (Gadmer, Pacaux-Lemoine and Richard, 2021). Traditionally, train drivers represent the first layer of operational resilience since they are the first one to perceive, communicate and act upon any irregularity (Brandenburger and Naumann, 2018). Thus, even if RTC holds the potential to augment the resilience of operations by supervising, controlling, and intervening remotely in cases of disruptions, new operational strategies must be developed to truly attain this potential (Gadmer et al., 2022).

When introducing RTC, organizations need to define how and when the authority to make decision regarding the control of the train is going to switch from one entity to another. This transitional process is incremental in nature since it will entail deliberations and investigations involving multiple stakeholders (Gadmer et al., 2022). For example, the driver may need to perform physical tasks during unforeseen events, such as an evacuation. In that situation, the duties assigned to the driver includes engaging with traffic control to strategize the optimal approach and communicate it to the passengers (Jansson, Olsson and Fröidh, 2023).

In brief, the introduction of RTC significantly impacts the railway industry. Collaboration dynamics are perturbed as team members engage with automated machine agents. While RTC has the potential to enhance operational resilience, novel strategies must be developed to fully capture this benefit. The transition of decision-making authority requires careful planning and stakeholder involvement. The next section will outline the project management best practices to respond to these challenges and ensure a smooth transition towards RTC.

## 3 Best Practices for Introducing Remote Train Control

As illustrated by the implementation of RTC, the integration of new technologies is reshaping the work context of projects, as well as project management processes. The impact of these processes will be predominantly experienced by project team members, thus, project managers and organizational leaders must acknowledge the challenges it entails and take appropriate actions (Manerwick and Manerwick, 2020). Zimmer (2019) contends that digitalization cannot be accomplished through a single comprehensive effort, but rather necessitates the undertaking of diverse digitalization projects across all organizational levels. This means that railway organization must not pursue RTC independently, but create a conducive environment that fosters stakeholder learning, as they will be required to explore new alternatives, reallocate resources, and cultivate new capabilities and routines (Brady and Davies, 2016). When establishing a project teams composed of human and machine agents, Ngereja and Hussein (2021) assert that top management support is crucial, as it necessitates displaying leadership through financial means by investing in training, fostering a collaborative culture, encouraging employees to seek assistance, and supporting mentoring programs for both managers and employees. The formulation of these teams implies that top-down definition of roles of team members must be substitute by an evolutive bottom-up approach that is driven by the team, which entails frequent change management (Manerwick and Manerwick, 2020). Coordination between team members and managers will be essential to enable the coupling of human and machines (Schneider et al., 2021).

To achieve this coordination, throughout the course of the transformation, stakeholders' exigencies must be prioritized and accentuated. It is thus fundamental that organizations identify internal and external stakeholders that are most affected by their digitalization endeavors, as well as a complete understanding of the impacts on their roles, needs and expectations (Papavasilou and Gorod, 2022). When introducing RTC, stakeholders and more precisely train drivers need to be involved and considered at each phase of the project. Papavasilou and Gorod (2022) suggest consulting them by organizing co-design session and by engaging in beta and pilot testing, as well as obtaining

feedback post implementation and to adjust accordingly. These efforts should also be supported with consultation by experts who will analyze stakeholders' roles and evaluate emerging needs at each stage of the project, while establishing a clear and structured engagement and communication channel between the project team and the managers (Papavasilou and Gorod, 2022). By doing so, railway organizations will align the goals of RTC with the interests and needs of train drivers and other stakeholders. Collecting and analyzing emerging exigencies throughout the progression of the project as the potential to facilitate the adjustment process in response to technological and environmental changes (Romualdo da Costa Filho and Penha Ferreira da Silva, 2021).

This was observed by Karvonen and colleagues (2011) who attested that drivers have unique abilities to react in metro environment. Therefore, when introducing automation, new arrangements have to be made to compensate the lost vantage point of drivers. The arrangements include properly understanding their roles in order to determine how can an automated system fulfill them, especially since these types of systems excel only at handling monotonous tasks, which do not require complex problem-solving skills (Karvonen et al., 2011). On that matter, Jansson, Olsson and Fröidch (2023) found that multiples roles of the drivers are currently not addressed in the conventional grade of automation levels description. They consequently introduce a revised model with six main areas where the driver has a substantial role: Detect, Report, Inspect, Adjust, Manage passengers, and Respond to train orders. By analyzing and understanding each of these areas, railway operators and infrastructure managers can implement the arrangements described by Karvonen et al. (2011) to tackle the challenges associated with deploying ATO and capture the benefits (Jansson, Olsson and Fröidch, 2023). Rio Tinto exemplified this process with their AutoHaul project, which is a driverless heavy haul long distance train operation. A remote team performs activities that were previously drivers' tasks. They monitor the onboard status of the trains and process all notifications, the objective is to switch from drivers to pilots (Yusuf et al., 2020).

In pursuance of the deployment of automated metro, Denisenkov, Denisenkova and Polyakova (2020) developed a six stages implementation model that optimizes business processes and improves the quality of transportation services by guiding the introduction of digital technologies. The first two stages relate to technical aspects, such as updating the infrastructure. In the third stage, the organization start utilizing advanced technologies, which requires forming implementation strategies, creating support teams, updating documentation and training personnel. The fourth stage focuses on *Automated Business Process Management Systems*, which involves working groups with relevant internal and external stakeholders. Stage five involves adapting business processes through audit, leading to restructuring and updated documentation. Stage six introduces a unified system for real-time business process management using digital technologies, resulting in improved safety, efficiency, and passenger experience for metro systems (Denisenkov, Denisenkova and Polyakova, 2020). This model is in line with project management literature that suggest that including a broad range of stakeholders into the decision-making processes implies that several business procedures will be transformed and, thus, project managers that will oversee the implementation of RTC will have to rejuvenate their skills to adequately support the new organizational approach (Manerwick and Manerwick, 2021). The implementation of RTC is reshaping project environments

and processes in the railway industry, which primarily affects project team members, necessitating proactive actions from organizational leaders, since digitalization requires a multifaceted approach across organizational levels.

## 4 Conclusion

RTC impacts various aspects of the railway sector, such as collaborative dynamics, operational resilience, and stakeholder involvement. The adoption of RTC mandates the thorough analysis of collaborative strategies in light of coordination between human and machine agents. While RTC holds the potential to bolster operational resilience, its optimal utility necessitates the formulation of novel project management practices, the change in decision-making processes entails careful planning and the active participation of multiple stakeholders. The engagement of train drivers is cardinal in shaping the implementation process. Recognizing their distinctive competencies and responsibilities is pivotal for transitioning to automation. Successful deployment relies upon an evolved project management paradigm that focuses on bottom-up delineation of roles and continual change management. By resolving these considerations, railway organizations can successfully implement RTC and capitalize on its transformative capacity.

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# Trustworthy Automated Driving Through Qualitative Scene Understanding and Explanations

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**Abstract.** We present the Qualitative Explainable Graph (QXG): a unified symbolic and qualitative representation for scene understanding in urban mobility. QXG enables interpreting an automated vehicle's environment using sensor data and machine learning models. It leverages spatio-temporal graphs and qualitative constraints to extract scene semantics from raw sensor inputs, such as LiDAR and camera data, offering an intelligible scene model. QXG can be incrementally constructed in real-time, making it a versatile tool for in-vehicle explanations and real-time decision-making across various sensor types. Our research showcases the transformative potential of QXG, particularly in the context of automated driving, where it elucidates decision rationales by linking the graph with vehicle actions. These explanations serve diverse purposes, from informing passengers and alerting vulnerable road users (VRUs) to enabling post-analysis of prior behaviours.

**Keywords:** Scene Understanding · Symbolic AI · Qualitative Reasoning · Explainable AI · Automated Driving · Connected Mobility

## 1 Introduction

Artificial intelligence (AI) methods are at the core of automated driving (AD) and connected mobility. However, passing control to an AI-based system and trusting its decisions requires the ability to request explanations for these decisions [10]. Societal acceptance of AD significantly depends on these AI models' trustworthiness, transparency and reliability [9]. Still, this is an open challenge as many of the state-of-the-art deep learning (DL) models are opaque and not inherently explainable by themselves [2].

In recent years, several Explainable AI (XAI) methods with a focus on automated driving have been proposed. Following [2], they fall into three main categories: a) *Vision-based XAI* related to highlighting the area of an image that

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influences a perception model towards a certain output [10]; b) *Feature-based importance scores* quantify the influence of each input feature on the model output; and c) *Textual-based XAI* that aims to formulate explanations as intelligible arguments using natural language processing [6]. Unfortunately, automated support for multi-sensor and video-based scene explanation is still restricted to quantitative analysis, e.g., saliency heatmaps [10].

In this work, we approach qualitative methods for scene understanding by using *Qualitative Explainable Graphs (QXG)* and, based on this representation, a novel method for action explanation. A QXG captures the spatio-temporal dynamics of a scene via qualitative algebras, i.e., a description of the relative positions (e.g., pedestrian north of ego car), a qualitative distance (e.g., pedestrian far from ego car) and their direction towards each other (e.g., ego car approaching static pedestrian). From these graphs, interpretable machine learning models are trained to provide justification for taken actions. Our results on the real-world nuScenes dataset [4] show that the QXG can be efficiently constructed incrementally in real-time and that it serves to correctly explain actions.

## 2 Background & Related Work

*Qualitative Calculi* A *qualitative calculus (QC)* is a computational method for analyzing qualitative connections among physical attributes, such as position, velocity, and acceleration, independently of precise quantitative data [5]. QC can be parameterized by a qualitative algebra tailored to temporal dynamics, spatial relationships, or a combination of both [1,11]. For automated driving, qualitative reasoning is utilized through ontologies [13] and neurosymbolic online abduction [12]. This enables encoding complex driving scenarios and traffic dynamics, especially when obtaining precise measurements is challenging or unfeasible. QC are commonly used in spatio-temporal reasoning to describe the relations between sets of objects in a space or over time, e.g. the positioning, distance, or orientation of vulnerable road users (VRUs) in relation to a vehicle.

In this work, we rely on four qualitative calculi [5] for all spatial aspects:

1. **Qualitative Distance Calculus ($QDC$)** [11] focuses on representing and reasoning about distances between objects in a qualitative manner, without relying on precise metric measurements.
2. **Rectangle Algebra ($RA$)** [11] provides a qualitative relative positioning of objects represented as rectangle rather than as points, i.e., involving spatial dimensions. It is a two-dimensional extension of the Allen's interval algebra [1] and valuable for describing object orientations and spatial relationships.
3. **Basic Qualitative Trajectory Calculus ($QTC_b$)** [5] deals with qualitative representations of object trajectories and their interactions. It enables reasoning about the motion and paths of objects without the need for detailed numerical data. It shall be noted that the heading needs to be inferred temporally and is, unlike the other calculi, not a pure spatial relationship.

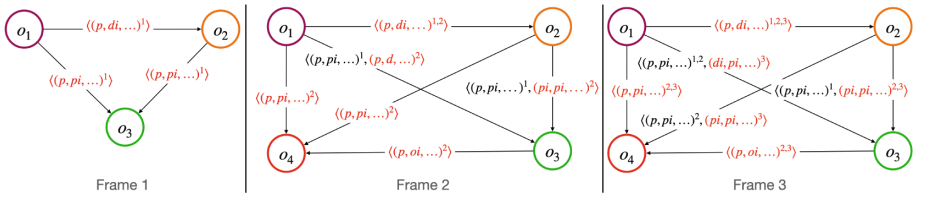



**Fig. 1.** Illustration of the successive construction process of the QXG over multiple frames. For simplification, only the rectangle algebra relation is depicted.

4. **Star Calculus** [11] is a qualitative calculus designed to represent and reason about spatial regions and their relationships. It is useful for describing regions of influence, zones, and coverage areas in automated driving scenarios. We apply $STAR_4$ which divides the surrounding into 4 quarters.

*Qualitative Scene Understanding* Scene understanding involves gathering and organising spatial and temporal information regarding objects, including vehicles, VRUs, and static elements, across a sequence of frames [14]. At its core, scene understanding encompasses perception tasks like object detection and image segmentation [8]. In qualitative scene understanding, we operate at a higher level, focusing on the qualitative depiction of a scene, emphasising objects and their temporal and spatial relations.

In the context of automated driving, a scene is formally represented as a sequence of $n$ frames, depicted as $\mathcal{S} = \langle f_1, \ldots, f_n \rangle$. Object detection and tracking, as part of this process, involves detecting objects in a given frame $f_k$ within $\mathcal{S}$, determining their bounding boxes, and tracking their movement relative to previously detected objects in preceding frames. We assume a set of $m$ detected objects, denoted as $\mathcal{O} = \{o_1, \ldots o_m\}$, to be present in $\mathcal{S}$, where each object $o_i$ appears in at least one frame $f_j \in \mathcal{S}$.

Scene understanding primarily focuses on assessing the situational context. Its outcome can be used for decision-making, trajectory prediction, or providing explanations and analyses of various aspects within the scene.

## 3 Qualitative Explainable Graph

The Qualitative Explainable Graph (QXG) is a scene representation format describing qualitative spatial-temporal relations among objects in a scene[1]. The graph representing a scene $S$ is composed of one node per object in $\mathcal{O}$ with edges $\mathcal{V}$ between objects that appear jointly in at least one frame $f$ (Fig. 1).

The QXG captures the relation between two objects over the temporal course of a scene through spatial relations and their changes. The selection of the spatial calculi is a parameter of the QXG and, depending on the needed granularity and

[1] The QXG was first described in [3]; in this work we extend it to a more complete representation with multiple qualitative calculi.

or use case requirements, alternative calculi may be considered. In the context of this work, we describe the relation between objects by a mixture of the four calculi mentioned above to capture the necessary spatial information. Through the combination of these calculi, we cover the relevant aspects to understand and explain scenes through qualitative graphs. Nevertheless, the formulation of the QXG and its usage is generally independent of the specific calculi chosen as long as they are expressive enough to cover at least the relative positioning and distance of objects, although extra calculi [5] might be desirable, depending on the use case, to enrich the representation.

## 4 Action Explanation

The QXG offers a unified qualitative representation of scenes and their object dynamics, enabling post-hoc explanations of actions taken by individual actors without recreation of the graph or retraining of the method. These explanations consist of object-pair relation chains that justify why an action was taken, i.e. a rationalization, considering an external perspective.

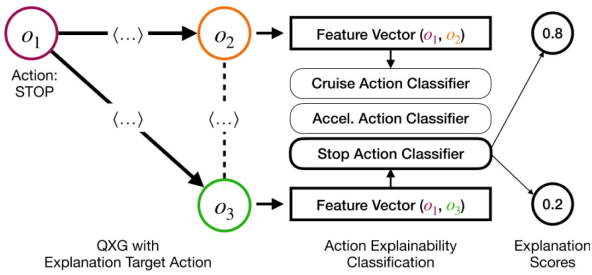
To approach action explanation, we frame the task as a one-against-all classification problem. Our method is trained on a labelled dataset comprising QXGs and annotated actions, using the real-world nuScenes dataset [4] for QXG generation from LiDAR data. During training, annotated QXGs form a training dataset. For each action in a scene, we extract the $t$ most recent object-relation chains, creating joint feature vectors that describe the explanation context. These feature vectors are generated for the acting object and all other objects that appeared in the same frame in the last $t$ frames. We train one-class classifiers for each action in the dataset. These classifiers assess the likelihood of a given object-pair relation chain causing a specific action against all other actions.

During the explanation stage, we require a QXG and an action to be explained. Object-pairs involving the acting object are scored by the action's classifier. The pairs with the highest scores represent the most plausible explanation for the acting object's behaviour. This approach allows us to flexibly adjust the explanation scope by altering the classifier score threshold. Additionally, by employing interpretable classifiers like tree-based models, we can provide decision paths as supplementary context for the highest classification scores.

## 5 Experiments

We assess the action explanations using 850 QXG-represented scenes from the nuScenes dataset [4]. The QXG is built incrementally, frame-by-frame from the top LiDAR view, which is computationally efficient. Remarkably, even for frames with the maximum number of 160 objects, construction remains efficient, taking less than 50 milliseconds, thus achieving real-time QXG generation.

Random forests are trained as the interpretable action explainability classifiers on 595 scenes. Our evaluation results on 255 held-out scenes, summarised in




(a) QXG action explanation process: From the action-annotated QXG the previous relations are extracted and classified according to the target action.

| Action | Precision | Recall |
|---|---|---|
| Cruising | 89.7 % | 89.7 % |
| Accel. | 89.2 % | 89.2 % |
| Stopping | 90.6 % | 90.6 % |
| Average | 89.8 % | 89.8 % |

(b) Classifier Results

**Fig. 2.** An overview of the explanation process and results for the trained action explanation classifiers.

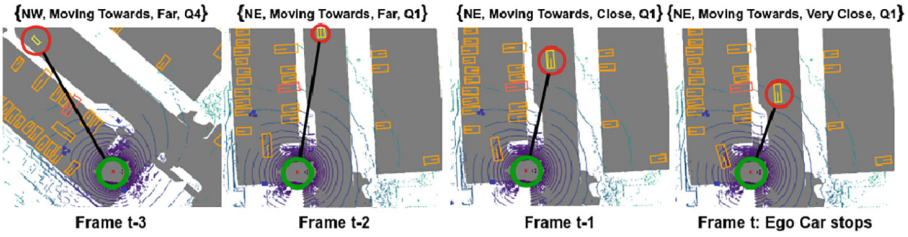



**Fig. 3.** Example action explanation overlaid on the LiDAR view: The car circled in red approaches the ego car, as captured by edge relations between these two objects above the images. Calculated from the specified calculi, the relations rationalise the stopping. NW: North west, NE: North east; Order of relations: $RA$, $QTC_b$, $QDC$, $STAR_4$.

Fig. 2b, employ Precision and Recall as key metrics, gauging prediction correctness and sensitivity, respectively. Notably, Precision and Recall exhibit identical values, as we are dealing with a one-class classification scenario, and our test cases are abundant.

To provide an illustrative example, Fig. 3 showcases an explanation for an ego car's decision to halt at a parking lot intersection, prompted by the approach of a yellow car. While there are many objects (depicted in yellow), the action explanation correctly highlights the approaching car as the main incentive for the stopping maneuver. Figure 3 was generated using nuscenes-devkit [4] and google's draw.io which are open source softwares.

## 6 Conclusion

Establishing a symbolic and qualitative comprehension of the vehicle's surroundings enhances communication not only with internal decision-making AI but also with other vehicles, VRUs, and external auditors, thereby bolstering system safety and reliability [7]. In this paper, we have introduced the Qualitative

Explainable Graph (QXG), which is a spatio-temporal representation of automated driving scenarios that can be constructed incrementally in real-time. The key advantage of employing a qualitative scene representation lies in its capacity for introspection and in-depth analysis. Action explanations can be performed by training interpretable tree-based classifiers from QXGs and we showed that this can be efficiently performed on the real-world nuScenes automated driving dataset. In future work, we will deepen the use of QXGs for AI in CCAM [7], such as vehicle-to-vehicle scene understanding, intelligible explanations for VRUs, and advanced message-passing techniques to enhance the action explanation process.

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# Acceptability of Automated Vehicles in Portugal: Profiling Prospective Users

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**Abstract.** The continuous development of advanced driver assistance systems is paving the way for the deployment of autonomous vehicles. Until then, manual vehicles and partially automated vehicles (AVs) will co-exist. Past experience has shown that the deployment of new technology must consider users' acceptability and adoption. This is the case of AVs, that must provide safety and comfortable travel experiences. To evaluate acceptability profiles towards AVs, this study analyses the determinant factors of AVs acceptability to identify different Portuguese population clusters. A questionnaire was developed to explore prospective users' representations regarding benefits and expectations, risks and concerns, previous experience with automated driving technology, and preferred use cases for AVs. A cluster analysis was performed using the k-means algorithm and, after, chi-square tests characterized cluster membership. In the end, acceptability profiles were compared for different use cases using ANOVA post-hoc tests. Three clusters of prospective users were identified: objectors, ambivalents, and enthusiasts. Driving pleasure, safety, reliability of the technology, and data privacy are prevailing negative factors while improved road safety, reduced emissions, and non-driving tasks possibilities favor acceptability. Sociodemographic characteristics, like income, education, place of residence, and self-perception about the adoption of new technologies reflected the main differences between clusters.

**Keywords:** automated vehicles · perception · clustering · acceptability

## 1 Introduction

Automated vehicles (AVs) promise to radically change mobility of people and goods, improving road safety and traffic management, supporting climate actions, and promoting benefits for individuals and society as a whole [1]. Nevertheless, those benefits must

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be perceived by potential users, and must be bigger than the perceived risks. In other words, the success of the technology depends on societal acceptability [2, 3]. Moreover, AVs implementation requires considerable legal and business adaptation. For these reasons, research must focus on the evaluation of acceptability from the perspective of different users, in different contexts [4].

One practical application of AV technology is the idea behind truck platooning, where trucks resort to vehicle-to-vehicle (V2V) communications to travel closely in convoy. The deployment of such technology demands understanding the representations of truck drivers, logistics companies, road operators and regulators about the technology [5]. In a first approach, and to access the acceptability of AVs, not limited to freight transport, this study aims at unveiling the perceptions about AVs, in general, and investigates what acceptability profiles emerge from these perceptions.

Using the Portuguese context as a support of our research, we have developed a comprehensive questionnaire. Data collected from the questionnaire was then treated and analyzed using statistical tools, from which resulted three users' clusters. After presenting materials and methods, we characterize the three profiles in the results section, together with some concluding remarks.

## 2 Materials and Methods

Our study comprised the development and application of an online questionnaire for data collection, followed by a statistical analysis of the questionnaire results to identify and characterize AVs acceptability profiles and the determinant factors of AVs acceptability.

The questionnaire was composed by more than 70 items to explore prospective users' representations about AVs: benefits and expectations (e.g., the possibility to perform secondary tasks during automated driving), risks and concerns (e.g., system limits, system failures, loss of control over the driving activity), previous experience with automated driving technology, and preferred use cases for AVs. Some of the questions addressed sociodemographic characteristics (gender, age, education, job, income, location), self-perception on the use of technology, and mobility habits. The preferred use cases aimed at assessing situations where respondents were more prone of using AVs, but can serve as an estimation for the adoption. The considered use cases were: intention to use a full automated vehicle, stated preference of a full automated vehicle over a non-automated vehicle, being comfortable with using a full automated vehicle for family trips, and intention to use and automated bus.

After data treatment process, the first analysis performed aimed at identifying different identify different Portuguese population clusters. At this stage, we performed a cluster analysis using the k-means algorithm to group the respondents according to their driving and mobility habits, knowledge/previous experience about AVs, and perceived risks and benefits, measured using a 5-point Likert scale. After, we used chi-square tests to characterize cluster membership based on their characterization regarding demographics, self-perception on the use of technology. Lastly, we compared the acceptability profiles defined, in the first stage, by the cluster analysis against the acceptability levels measured for the different use cases, using ANOVA post-hoc tests.

In total, 501 respondents (51% male, 49% female) aged between 18 and 81 years participated in the survey (Table 1). The participants were well distributed in terms of

education levels, with all levels of education (high school, bachelor's degree, master, PhD) having between 20 and 30% representation in the sample. More than two thirds (70%) live in rural areas and are employed. Concerning participants' self-perception towards the use of technology, 59% prefer to wait a while and be aware of other's opinions, 36% are early adopters, and 6% stated they are not prone to technological changes.

**Table 1.** Sample characterization.

| | Variable | % |
|---|---|---|
| Gender | Female | 50,7% |
| | Male | 49,3% |
| Age | [18–35[ yo | 37,8% |
| | [35–50[ yo | 36,0% |
| | [50–99] yo | 26,2% |
| Education | Basic education | 1,6% |
| | High school | 20,0% |
| | Bachelor's Degree | 28,9% |
| | Master's degree | 25,7% |
| | PhD | 23,8% |
| Occupation | Employed (salaried workers) | 68,5% |
| | Self-employed | 6,8% |
| | Unemployed | 1,4% |
| | Retired | 3,4% |
| | Student | 20,0% |
| Income | Up to 2 national minimum wages | 34,3% |
| | Between 3 to 4 national minimum wages | 42,1% |
| | 5 or more national minimum wages | 23,6% |
| Residential area | Predominantly urban area | 70,3% |
| | Medium urban area | 22,0% |
| | Predominantly rural area | 7,8% |
| Use of technologies | Willing to use new technologies as soon as they are available | 35,5% |
| | Prefer to wait a while and be aware of other people's opinions | 58,7% |
| | Not very adept at technological change | 5,8% |

## 3 Results

The clusters analysis performed resulted in three clusters of prospective users: *objectors*, *ambivalents*, and *enthusiasts*. Naturally, the *enthusiasts* reported self-perception fits the behavior of early adopters, while *ambivalents* are late adopters, and *objectors* do not support huge technological advances.

The objectors stated that they enjoy driving more than the other groups and showed higher concerns with the safety and reliability of the technology (system limits and system failures), as well as with data privacy. On the other side, the enthusiasts highlight possibility of performing non-driving tasks while traveling as a benefit of AVs, and they also believe that automated driving technology can improve road safety and reduce emissions. *Ambivalents*, on their turn, are concerned about road safety, but at the same time perceive benefits in performing non-driving tasks. This type of contradiction suggests that this group needs more information about the true impacts of AVs.

In relation to the sociodemographic characteristics, income, education, place of residence, and self-perception about the adoption of new technologies reflected the main differences between clusters. *Objectors* are concentrated in rural areas, and have lower incomes, while enthusiasts, referring to early adopters, are concentrated in urban areas, have higher education levels (masters' degree and PhD) and higher income. Gender, age, and professional situation (student, employed, unemployed, or retired) did not seem relevant for the acceptability profiles.

## 4 Discussion and Conclusions

The sociodemographic characteristics of the identified profiles suggest that AVs acceptability follow the patterns of other technologies, with three well-distinguished groups from technology averse to technology, late adopters, and early adopters. This study also presents the characteristics of these groups concerning their representations about AVs in terms of road safety, travel-time savings, reduction of gas emissions, possibility of performing non-driving tasks, technology limits and reliability. Considering participants preferences about AVs, the three clusters were characterized as *objectors*, *ambivalents*, and *enthusiasts*. Accordingly, participants reported intention to use is lower in the *objectors* group and higher in the *enthusiasts* group, in all use cases assessed in this study.

The questionnaire results contribute to a better understanding, not only of the acceptability profiles, but also about potential adoption of AVs. These results can be later used in the design of guidelines to increase AVs acceptability, target at *objectors* and *ambivalents* of important contributions. Namely, policymakers should focus on the reducing the risks perceived by those two groups, and remove any doubts regarding the perceived benefits. The design of the guidelines, for policymakers and manufacturers are possible future research. Still, narrowing our research by focusing on specific vehicles such as heavy vehicles for freight transport can also contribute to assess the acceptability of truck platooning, by professional drivers and the impacts for the driver profession.

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# Safety Demonstration Framework of Automated Road Mobility: Methodological and Governance Aspects of the Scenario-Based Approach

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**Abstract.** Automated road transport mobility will develop only if fundamental conditions are fulfilled: acceptance by users and citizens, economic sustainability, contribution to a more sustainable mobility and last but not least, demonstration of its safety. Fulfillment of these conditions needs to be addressed by policymakers through regulations, standards, guidance, assessments and stakeholders' involvement. France built its regulatory framework on this balance by assuming safety will be the main factor for other conditions for the development of automated road transport systems to be reached. This paper presents the safety demonstration framework, methods and tools for the development of automated road mobility. The main guiding principle underlying this safety-first based framework lies in the scenario-based approach aiming at the best possible coverage of driving situations that such systems should be required to encounter and address safely. This paper will present two aspects of this approach, articulated with conventional safety demonstration activities: scenario generation approach based on layers and its articulation with ODD description and OED definition.

**Keywords:** automated road mobility · safety demonstration principles · scenario-based approach

## 1 Context of an Approach

### 1.1 International Basis

Automated driving systems (ADS) with high levels of automation require setting commonly and widely accepted and applied high-level safety rules and efficient validation framework to ensure safety.

Within the UNECE World Forum for Harmonization of Vehicle Regulations (WP.29), a dedicated group under Working Party on Automated/Autonomous and Connected Vehicles (GRVA) is working on safety validation tools and methods (VMAD). Despite the path to regulation has not been done yet, the informal working group delivered their first document in June 2021 as a reference on safety validation methods and tools for vehicle type-approval [1]. This first publication at the UN level opens the global approach that national and regional authorities will have to follow. In particular, the

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Master document on New Assessment and Test Methods (NATM) considers six pillars to demonstrate safety of a vehicle, among which is the scenario catalogue. By providing the foundations of a robust safety validation framework in a repeatable, objective, evidence-based and technology neutral manner; the scenario-based approach is defined as to be the starting point to help to systematically organize safety validation activities in such a way. Moreover, the question of ensuring a holistic and dense coverage of traffic situations is central. Finally yet importantly, NATM guidelines closely associate two concepts: scenarios and operational design domain (ODD), in which the system is designed to operate safely. The effectiveness of a scenario-based approach is presented through the correspondence between the scenario catalogue and ODD real-world driving situations that can reasonably be expected to occur in the ODD.

On this basis the need to have international standards gathering and merging international knowledge on scenarios is pushed by the international community of experts. The aim of establishing both international and national standards on scenarios lies in the need of harmonizing practices and considerations around what is considered as one of the most important topic to address regarding safety but also one of the most difficult to properly address regarding the variety of systems and ODDs. In this context, an international standard is developing at ISO under the TC22/SC33 committee. The project's scope under discussions is composed of a set of five standards on scenarios [2].

At the European Union (EU) level, the challenge of regulating the safe operation of automated driving systems (ADS) has been made. The European Commission (EC) published last year the first international regulation 2022/1426 on ADS for vehicle type-approval [3]. This regulation relies heavily on scenarios that are relevant for the system. Scenario generation is described as it should cover "reasonably foreseeable" traffic situations and it goes further by considering that scenario parameter should not be limited to values already observed in documented databases.

### 1.2 National Doctrine on Automated Road Mobility

The national doctrine on automated road mobility is supported by the national strategy, revised in 2022 for 2025 [4]. Since 2018, France has built its framework on three principles – safety, progressivity, and acceptability. These three pillars are intended to both preserve road users and vehicles' integrity and promote confidence in automated driving systems, being aware that the more people trust, the more they use. To fulfil this aim it appeared relevant to rely on the strength of a complete legislative and regulatory framework.

The French regulatory framework on automated mobility entered into force in September 2022. The legislative basis of automated road mobility in France comes from the "Loi d'orientation des mobilités" (LOM) of December 24, 2019, and Ordinance no. 2021–443 from April 14, 2021 which define roles and responsibilities of automated systems and drivers or human supervisors [5]. The regulatory package for the deployment of automated road transport systems is composed of Decree no. 2021–873 from June 29, 2021, which defines a global process to demonstrate safety, putting safety demonstration at the center of the loop, which leads to consider the foundation of a performance- and progressive-based approach. Such an approach is reinforced by recent academic work on demonstrating safety of automated vehicles, on which it is possible to rely [6].

## 2 Scenario-Based Approach: The Core of Safety Demonstration

### 2.1 Rationale Underlying an Approach

The interest of the scenario-based approach, within the national context, relies on three main, complementary logics (a) a logic of covering the space of possibilities, which meets the objective of not having omitted cases, characterizing the search of representativity; (b) an essentially probabilistic logic regarding their potential (very) high criticality, giving life to the concept of "edge-cases"; and (c) a careful and restrictive logic, considering a set of driving situations in which the (static) environment gives possible addressable hazards characterized with complex interactions.

The scenario-based approach, among safety demonstration activities regarding automated road transport systems' deployment, aims to address the relevant level of details for an ADS depending on its capabilities, while remaining technology neutral. Indeed assessing safety of a specific system requires sizing precisely the set of scenarios by combining approaches focusing respectively on the vehicle, the system in which it will be integrated, the route on which it will be deployed (at a local level). That is to say, the scenario-based approach has the virtue to proportionate safety demonstration to the ODD, including ODD boundaries.

Based on NATM requirements [1], working on scenario generation to assess vehicle safety, and more generally system safety constitutes a pillar that is (a) more precise, in particular by taking into account ODD limits attached to the use cases; (b) more complete, in particular by using risk analysis to fill the gaps in traffic hazards analysis; (c) more diverse, in particular through the accumulation of feedbacks or the addition of other scenario description axes as the use cases mature (e.g. remote intervention, interactions with law enforcement officers and/or first responders).

### 2.2 Guiding Principle of Such an Approach

The scenario-based approach being at the core of safety demonstration, defining clear and common principles on the methodology is a key element. A national doctrine has been launched, based on a guiding principle linked to the notion of "reasonably foreseeable". The reasonably foreseeable concept has to be seen as the notion of what is conceivable, in the sense that any situation that might occur within the entire ODD has to be taken into account. The contribution relies on defining the reasonably foreseeable principle as referring to a global safety demonstration principle related to scenario generation, regardless of the type of scenarios and independently of the scenario selection process, to provide an "exhaustive" coverage of traffic situations that might occur and that are conceivable for the specific system in its ODD.

### 2.3 Scenario Generation

Based on a large literature review on scenario-based approaches [7–9] that emerged at the international level through projects, work showed the potential and, at the same time, complexity of multiplying axes of scenario description.

The question of the opportunity of standardizing scenario description is complex. On the one hand, considering that, the scenario approach is subsidiary to the description of ODDs and should aim at the maximum exhaustiveness of possible scenario descriptors, the standardization of descriptors may seem inappropriate. On the other hand, the idea that scenario generation is a cumulative process of expertise and/or data makes the standardization of descriptors meaningful.

It is assumed that the proposed doctrine and method presented here, shared and supported by national industry is one possible logical arrangement. The proposed scenario-based approach is based on the combination of five layers (Table 1):

**Table 1.** 5-layer model introduced in the national work.

| | |
|---|---|
| 1 | Static driving environment (including road geometry, signage and legibility) |
| 2 | Nominal intended manoeuvre |
| 3 | Hazards and events including both precursor events (external) and system failures and functional insufficiencies (internal) |
| 4 | Response |
| 5 | Hazards affecting response (environmental conditions and visibility masks…) |

The strength of this approach is to be able to answer the principle of scenario coverage, by avoiding omitting certain types of events. The power of such an approach is accountable to the power to combine these axes and to precise them through attributes. The resulting living process amounts to saying that working on scenario generation is worth working on scenario descriptors.

The combinatory-based approach pushes to consider the two-level loop along scenarios: managing the scenario catalogue from both knowledge- and data-based methods, supplemented by creating new combinations from descriptor combination itself (Fig. 1).

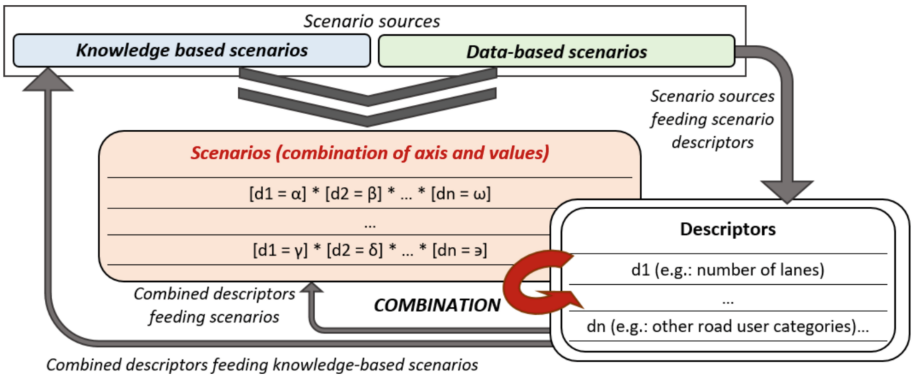



**Fig. 1.** National scenario-based approach as a living process and its articulation with the combinatory-based approach regarding scenario sources.

### 2.4 Link Between ODD and Scenarios, Scenarios and Descriptors

The notion of scenario completeness alone might lead to consider an infinite number of scenarios. In that perspective, the concept of representativity plays a great role, especially in conjunction with ODD consideration. The scenario approach should also address the question how to move from ODD and OED(R) to scenarios that give life to a set of descriptive bricks. The search for completeness in the lists of descriptors is the key to move from inert elements to sets of characteristics intended to build a scenario.

French approach based on scenario generation and on completeness does not seek to describe neither characterize triggering conditions of hazards in a specific ODD while it may freeze the ODD itself and reasonably foreseeable situations linked to it. Otherwise, it aims at clarifying driving situations translated in scenarios related to an ODD and addressable hazards relevant in its ODD. Having saying that, creating scenarios on driving situations based on a specific ODD, regarding possible addressable events, means having to consider ODD description and OED definition themselves.

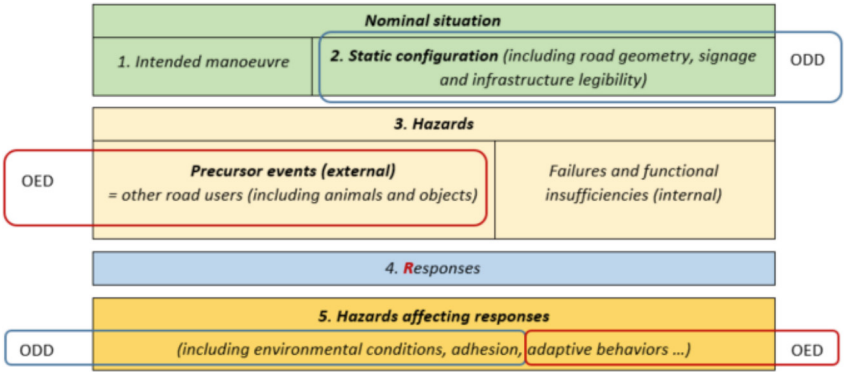



**Fig. 2.** Layers of scenario generation presenting the power of "descriptors" and the complementarity between ODD description and OED definition (leaving aside failures and functional insufficiencies).

Based on that, there is a need to build a scenario methodology to move forward from a possible infinite (functional) scenario generation process to its intersection with ODD description and OED(R) definition, enabling to qualify, classify and prioritize logical to concrete scenarios to be included in testing procedures. In that case, it is worth mentioning that ODD consideration through its descriptors has to be linked with OED descriptors (see Fig. 2) as they constitute a set of the reasonably foreseeable conditions. As a result, all these considerations place ODD has a central element when building a scenario generation process, and put in the middle the concept of descriptors.

This ties in with the idea that the search of completeness within the scenario-based approach, carried out by the notion of a sufficient list of descriptors is the key to move from inert elements to sets of characteristics intended to build a scenario. Hence, making the link between these two important notions is a possible way to move from a theoretical approach named scenario generation to a concrete approach characterized by its

intersection with ODD description. The latter process aims to provide a finite number of concrete scenarios for testing procedures.

Moving from scenario generation, based on the combination of descriptors that might lead to a non-quantifiable number of scenarios, to scenario testing that means a fully discretization of the space of scenarios, reflects moving from a generic ODD to a specific ODD (called operational domain (OD)), instantiated by hazards and events.

Starting from bounded, discretized space of ODD descriptors, the approach lies on the principle that building a finite list of scenarios is possible. The logic of completeness, translated in the notion of scenario coverage focuses on three major areas: (a) to bring out the so-called unavoidable or generic scenarios, which by their frequency are representative of road traffic and existing situations, and which demonstrate a potential severity that justifies an interest regarding safety; (b) to target edge case scenarios, first at the critical axis limits, generally characterized by an extreme severity, then designed from unknown descriptors; and, (c) with the idea of reflecting cautiousness behaviors.

## 3 Next Step

French regulatory framework is built on a global safety demonstration process. The scenario-based approach is the starting point of the national doctrine on safety demonstration, linking all the interrelated approaches involved in safety demonstration.

Scenario generation has been the first step towards safety validation principles to allow assessing vehicle and system safety. Scenario generation is an enabler to define clear and shared methodologies within safety demonstration but it goes beyond scenario generation to move forward to operational design domain definition to operational domain description. The way a scenario is described and generated has to be articulated with the way a system's environment is described.

That being said, to move forward from scenario generation, the detailed approach aims to propose a discretization method that can be applied to physical testing for system validation, whether in the homologation phase or the validation phase specific to local deployment on a route. In this context, considering ODD remains the step forward.

Assessing safety through standardized and shared methods, capable of proving their completeness, inter alia, may be seen as a methodological work done in relationship with inputs from industry, but also as a work where governance of an ecosystem remains central, in particular in the objective of road safety in a user-centered perspective.

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# CCAM for the Users; Matching the User Needs with Vehicle Capabilities in ULTIMO Project

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**Abstract.** The goal of ULTIMO Horizon Europe project, is to create the very first economically feasible and sustainable integration of AVs for Mobility as a Service (MaaS) public transportation and Logistics as a Service (LaaS) urban goods transportation. To do this, a user centric holistic approach is adopted, to ensure that all elements in a cross-sector business environment are incorporated to deliver large-scale on-demand, well-accepted, shared, seamless-integrated and economically viable Connected and Cooperative Automated Mobility (CCAM) services. In this concept, this paper presents the work performed to bridge the needs of the users with the vehicles' potential. To do this, extensive research has been performed in identifying the requirements of all involved actors, including existing research findings, conduction of interviews, co-creation workshops and round table discussions, along with market survey for specifying the existing vehicle capabilities and experts' consultation for matching the requirements with the capabilities. This provides a tool to pilot sites for identifying the requirements their vehicles satisfy or choosing the appropriate vehicles according to the requirements existing (or planned) to be treated at site. Moreover, it could serve vehicle manufacturers for developing further capabilities for their vehicles, as well as planners and PTO's in developing their strategies.

**Keywords:** automated · connected · cooperative · inclusive · users · transport

## 1 Introduction

The ULTIMO [1] Horizon Europe project aims to create the very first economically feasible and sustainable integration of AVs for Mobility as a Service (MaaS) public transportation and Logistics as a Service (LaaS) urban goods transportation. ULTIMO aims to deploy in three sites in Europe, 15 or more multi-vendor SAE L4 [2] AVs per site. A user centric holistic approach, applied throughout the project, ensures that all elements in a cross-sector business environment are incorporated to deliver large-scale on-demand, door-to-door, well-accepted, shared, seamless-integrated and economically

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viable CCAM services. The target is operation without safety driver on-board, in a fully automated and mission management mode with the support of innovative user centric passenger services. The work presented in this paper is addressing the following aims:

- Engage passengers and users in autonomous mobility to ensure their input and perspective;
- Create a passenger-centric, accessible on-demand public transport system for all, addressing diverse mobility patterns and social groups;
- Improve travel comfort, trustworthiness, and safety throughout the journey, from planning to reaching the destination;
- Enhance mobility for passengers, especially those with limited access to public transport;
- Emphasize user interaction with mobility services and vehicle interaction with the environment, including testing new technologies like sensors, connectivity, AI, and addressing vulnerable road users;
- Promoting Public Transport Operators' (PTO) and Public Transport Authorities' (PTA) needs for on-demand transport and autonomous vehicles;
- Proactively communicate passenger requirements to the development of new services and evaluate their implementation.

## 2 Methodology

The methodology followed in this work has been developed around three axes: first, to identify the needs and requirements of the involved users and actors, second to specify the vehicle capabilities and, finally, to provide a match between the two.

To achieve an accessible user experience that meets the needs of all users, including those who are potentially vulnerable, the human-centered design process for interactive systems (ISO 9241–210) [3] has been utilised. Representation of relevant stakeholders, including younger and older persons and their families and disabled colleagues was pursued, to ensure continuous reflection on user needs. In addition to building on existing research, further user research has been conducted, including interviews, site visits, workshops, evaluations, and data science measurements, to ensure a fully informed approach by user perspectives, including also co-creation workshops with PTOs, manufacturers, fleet managers, and passenger groups. In terms of vehicle capabilities, extensive market analysis has been performed by project experts, identifying the related capabilities currently offered by AV manufacturers. Finally, for the matching between requirements and capabilities, a survey with the use of a dedicated template has been performed, involving different project experts, representing the views of vehicle manufacturers, PTOs, users, OEMs, services providers, equipment providers, etc.

## 3 Passenger and Other Actors' Requirements and Needs

### 3.1 The ULTIMO User Journey

User Journeys are focused on the user and what they see and what they do. They describe at a high level of detail exactly what steps users take to complete a specific task within a system or service. In ULTIMO, the User Journey identifies the key interactions that

the user has with the service, and it helps us to better understand the touchpoints that need to be considered to create a positive user experience with our ULTIMO services. It has been developed and updated by ULTIMO PTO/PTA partners having many years of experience with operating automated vehicles and Demand Responsive Transport (DRT) services, consisting of three main phases Pre-Trip, Trip and Post-Trip, each of them including further steps and activities, i.e.:

- The Pre-Trip phase describes everything that happens before a person uses the central service "Take me from A to B". It contains the steps "Informing oneself/Deciding", "Planning, Booking, Paying", "Getting to Pickup Point", "Waiting at the Pickup Point" and "Connecting to Vehicle" (Fig. 1).




**Fig. 1.** Pre-Trip phase in User Journey

- The Phase Trip contains all direct touchpoints the passenger has with the vehicle: "Boarding the vehicle", "Travelling", "Incident during trip" (as an optional step), and "Disembarking/Switching transportation" (Fig. 2).




**Fig. 2.** Trip phase in User Journey

- The User Journey is not over once the passenger has arrived at destination. Phase Post-Trip covers the step "Reviewing the experience" with all possible activities after a trip e.g., rating or sharing their experience.

### 3.2 The Passenger Requirements

In order to avoid duplication, work started with the requirements already collected in previous EU projects INDIMO [4] and AVENUE [5], e.g., in Geneva, Vienna, Berlin and City of Luxembourg. To verify and update these requirements for the case of long term using of the service, additional interviews were conducted within ULTIMO project,

considering different user groups, e.g. students, adults, etc. Specific focus has been given to persons with special needs, to identify their expectations, needs and requirements regarding public transport in general and DRT-Services in particular.

A total of 205 user requirements were collected [6]. The user requirements are assigned to the steps of the User Journey as described above. In particular:

- *Informing/Deciding (4)*, e.g. "The user shall have access to complete information on the service and the vehicle"
- *Planning/Booking/Paying (47)*, e.g. "The user shall be able to book recurring trips"
- *Getting to pick-up point (11)*, e.g. "The user shall be provided with an accurate and accessible description of how to find their pick-up point"
- *Waiting at pick-up point (9)*, e.g. "The system shall provide a time estimate of how far away the vehicle is"
- *Connecting to vehicle (6)*, e.g. "The vehicle shall be clearly marked as a service from the PTO/PTA"
- *Boarding the vehicle (29)*, e.g. "When using a wheelchair, the user shall be able to securely fix the wheelchair in the vehicle"
- *Travelling (59),* e.g. "The user shall receive the reasons for slowing down or stops"
- *Incident (11)*, e.g. "The user shall be able to talk directly to customer service in case of an incident or any concerns"
- *Disembarking/Switching (21),* e.g. "The vehicle shall check if it is safe before it opens the doors for passengers to disembark"
- *Reviewing (8)*, e.g. "The user shall be able to provide feedback on the service"

### 3.3 Other Actors' Requirements

Further to passengers, requirements have been identified also for the needs of PTO/PTAs, LaaS and Vehicles.

The PTO/PTA requirements were gathered in several working sessions between the ULTIMO PTO/PTA partners. Most PTO/PTA requirements are related to the topics Fleet Management, Monitoring, Remote operation and Communication. Equally critical are considerations such as special needs, passenger safety, and data protection. In total, 68 requirements have been identified [6].

Within the aim of ULTIMO project, is to explore via real life validations, how the excess capacity of public transportation vehicles can be used for non-public transportation services (nPTS) by third parties. In this context it aims to propose a new model, where the Autonomous Vehicles' extra capacity, in principle low passenger needs' times, will be used for non-public transportation, like last urban logistics and non-public passenger transportation. To collect the requirements for such applications, consultation with logistics experts took place, resulting to the identification of 68 relevant requirements [7].

Vehicle requirements encompass several subcategories, with the most mentioned ones including hardware specifications, interior, safety, security, and V2X (Vehicle-to-everything). Vehicles shall detect discrepancies in occupied seats compared to registered passengers. For the convenience of passengers, the vehicles shall have handles for passengers to hold on to. In-vehicle screens shall be designed for easy readability, and display specifications shall ensure that individual station names or message words are

displayed clearly and for a minimum duration. Adequate space shall be provided for passengers with wheelchairs, mobility aids, or strollers, as well as means to secure them. In total, 68 vehicle requirements were identified [6].

## 4 Vehicle Capabilities

What is necessary for automated driving and, consecutively, for the implementation of use cases and the satisfaction of user requirements, is the equipment of the vehicles with the appropriate capabilities. Within ULTIMO, it has been attempted to identify the capabilities that are necessary for automated driving, along with their current availability in the market. To do this, a relevant survey has been undertaken among project partners. As a result, the vehicle capabilities have been recognized in three main categories, with relevant subcategories [6]:

- Hardware specifications: *Vehicle dimensions* (height, length, width, weight, etc.), *Technical specification*s (top speed, turning diameter, ground clearance, battery capacity, door width and height, operation temperature, etc.), *Carrying capacity* (passengers, cargo, other), *Passenger services* (stop request button, pax counting system, ticket verification system, loudspeaker, etc.), *Accessibility and comfort* (ramp, audio guidance to doors, passenger information system, heating/cooling/air conditioning, etc.), *Passenger Safety* (assistance systems for visually and/or hearing impaired, seatbelts, emergency stop button, first aid kit, etc.), *Autonomous driving hardware* (sensors, computer)
- Software specifications: *Operational Design domain, autonomous driving system* (traffic lights, roundabouts, speed signs, road blocking obstacles, etc.), *Remote capabilities* (safety operator, fleet management), *Connectivity* (V2I, V2X, etc.)
- Other specifications: *Legal and regulatory* (type of license of safety operator, speed authorization, etc.)

## 5 Matching What the User Needs with What the Vehicle Offers

Having defined the requirements and vehicle capabilities, as described above, the next step was to try to match them, i.e., to identify which vehicle capabilities are necessary in order to satisfy each of the set requirements.

Thus, to match the requirements with the vehicle capabilities a set of matrices have been built. Each matrix addresses the requirements of each category (per User Journey step, plus other actors) to match with the vehicle capabilities. In order to collect the required input and match the vehicle capabilities with the requirements, these matrices have been shared with ULTIMO experts, with the aim to gather different views, from the point of the vehicle manufacturers, the PTOs, the users, the OEMs, the services providers, the equipment providers, etc.

The gathered inputs have been synthesized in one overall set of matrices, providing all the vehicle capabilities that are considered necessary for each of the identified requirements. This resulted to a total of 12 tables including the vehicle capabilities assigned to each of the set requirements. [6].

At this stage the aim was to provide a compendium of the desired vehicle capabilities (among the ones identified) for each of the requirements, so that the latter could be optimally met. Thus, the capabilities addressed are not vehicle, nor pilot specific. At later stages of the project work, and upon having finalised the pilots' set up, use cases to be addressed and vehicles to be used in each pilot, it would be possible to specify which are the capabilities actually available and, thus, the requirements that can be satisfied.

## 6 Discussion and Conclusions

Within the overall concept of ULTIMO, to integrate AV deployment in MaaS and LaaS applications, a primary and crucial step is to investigate how AVs can align with what the users would expect by this innovative service. Having defined the requirements and vehicle capabilities, we have attempted a first matching between them, to find which vehicle capabilities are necessary in order to satisfy each of the identified needs and requirements.

At this first version, we are not focussing on specific pilots and/or vehicles and use cases. The results can serve for the pilot sites to identify the requirements their vehicles could satisfy, and vice versa, to choose the appropriate vehicles according to their intended service. Moreover, it could serve vehicle manufacturers for developing further capabilities for their vehicles, as well as for planners and PTO's in developing their strategies towards AV operated MaaS and LaaS implementation. Of course, this is not exhaustive nor complete; in a later stage, and as the pilot planning within ULTIMO shall be further specified, requirements and capabilities may be more specific and even enriched and the matching between the two could be more targeted and complete.

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# Automated Mobility-On-Demand Services in the Less Dense and Rural Area

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**Abstract.** The development of Cooperative, Connected and Automated Mobility (CCAM) represents major challenges for local authorities, particularly in less dense and rural areas where there is a lack of public transportation. The main purpose of this paper is to describe the development of an automated mobility on-demand service, which will be implemented beginning September 2023 in La Rochelle, France. This paper describes the automated mobility on-demand system (bus, infrastructure and supervision centre) and the conditions for its smooth integration with the local existing MaaS (Mobility as a Service) system. This new service aims at providing a small/medium sized city like La Rochelle with an efficient last-mile transport service - to and from existing mobility hubs - complementing the existing public transport.

**Keywords:** Cooperative · Connected and Automated Mobility · rural and suburban area · MaaS · integration · evaluation

## 1 Introduction

Urban mobility focuses on big economic, environmental and social challenges related to urbanization, densification and car-dominated mobility. Local authorities implement different transport policies in order to increase the attractiveness of the public transport which is considered as a sustainable mode of transport. However, public transport has difficulties in answering first- and last-mile connectivity problems [1] and substitutes for private cars being more comfortable, convenient, and flexible, especially for combining multiple activities within a journey [2]. Recent advances in technology and engineering in the Cooperative, Connected and Automated Mobility (CCAM), have led to increasing expectation and anticipation of new and innovative modes, such as Mobility-on-Demand (MOD) and Automated-Mobility-on-Demand (AMOD) services, as potential sustainable urban mobility solutions, even more so in less dense and rural areas where there is a lack of public transportation. This paper is structured as follows: definition of MOD and AMOD systems in the context of MaaS, and a description of the implementation of AMOD in La Rochelle, France.

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## 2 Literature Review

### 2.1 Automated Mobility on Demand (AMOD)

AMOS is a combination between automation (technology aspects) and sharing (behaviour aspects). The concept of MOD is based on the principle that transportation is a commodity where modes have economic values that are distinguishable in terms of cost, journey time, wait time, number of connections, convenience, and other attributes [3]. New technologies and the continuous use of smartphones have opened the possibilities for more convenient, affordable, fast and safe options in urban transportation. This has led to the emergence of MOD systems, such as Uber and Lyft, which aim to provide fast and reliable mobility that is catered to individualistic needs [4].

MOD ensures more flexibility with respect to two-way rental systems, and provide personal, anytime mobility, in contrast to traditional taxi systems or alternative one-way ridesharing concepts such as carpooling, vanpooling, and buses. MOD is suggested as a solution to improve mobility in low-density and suburban areas [5] with 5 conditions of good integration with the public transit existing services: fare payment integration, physical infrastructure, schedule integration, data sharing, and app-integration. Autonomous driving holds great promise for MOD systems because robotic vehicles can rebalance themselves, autonomously reach charging stations when needed, and enable system-wide coordination aimed at throughput optimization. Furthermore, they provide a personal mobility option to those who do not drive, and potentially increase safety [6]. Finally, compared to MOD, AMOD services have certain unique advantages including its potential in improving road safety, higher throughputs, and lower operating costs [2] with the significant impact on individual accessibility and residential relocation patterns [7].

### 2.2 Mobility as a Service (MaaS)

The concept of Mobility-as-a-Service (MaaS) has become an important area of study when it comes to addressing transportation issues to improve people's mobility. It is defined as: "a framework for providing a portfolio of multimodal mobility services that places the user at the centre" [8]. It involves, among other things, developing new models that integrate digital solutions to enhance traveller service while promoting sustainable transportation systems. The MaaS framework can encompass any combination of multi-service, multimodal offerings, and non-transport-related services, including private car usage and parking, whether subsidised or not by the public sector. Furthermore, it's important to emphasise that MaaS is not merely the integration of digital technology into transportation but rather the creation of a new model that incorporates existing systems with the customer at the core of services.

It is imperative to design a model for MaaS that considers the existing system (public service, for example) and models as well as user comfort. This issue echoes the work of [8, 9] in which they identify a number of challenges ranging from the overall underestimation of problems related to establishing effective collaboration and trust among the various stakeholders involved in MaaS, to the difficulties in developing attractive service offerings for customers, and even to the recognition of the need for public intervention and support for sustainable MaaS solutions, for example, from governments.

On another hand, developing new services such as those based on Autonomous vehicles (AVs) raises the question of the integration of these services. We could go further and question the overhaul of the existing model to rethink it differently. To deal with the integration question, [9] propose a classification of MaaS integration that considers both increasing [10] and decreasing [11] levels of integration. [12] explains that the development of automated vehicles technology takes place along two dimensions: (i) the driving automation dimension; (ii) the connectivity dimension. Thus, the framework proposed by [9] can help to effectively address the integration of autonomous vehicles into the existing MaaS (Fig. 1).

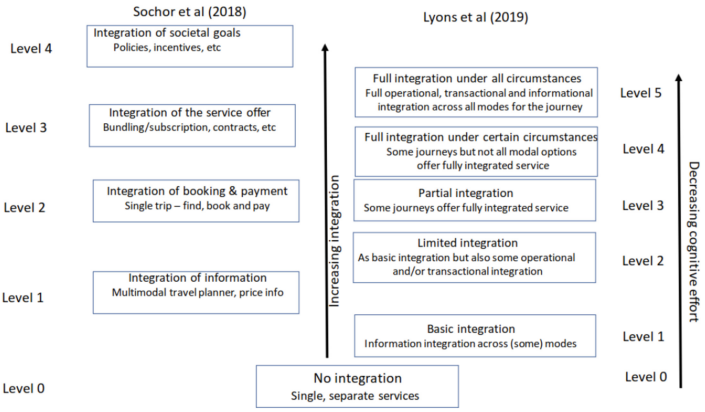



**Fig. 1.** Classification of MaaS integration [9]

This integration will make possible the sharing of AVs, encouraged by factors including 24-h availability, wide vehicle choice, no driving licence required, high safety, service personalization, on-demand instant response, and a non-car oriented community. This outcome depicts conditions in which AV's could enable the MaaS concept of shared, on-demand mobility [13].

## 3 Automated Mobility-On-Demand Service in Less Dense Area

### 3.1 The Context of La Rochelle Urban Community

On the French Atlantic coast, La Rochelle Urban Community comprises 28 municipalities around the city centre with a total population of 175 608 inhabitants (2021). The city has launched several novel initiatives—notably a goods delivery service by electric vehicle, an electric car-sharing system and even solar electric shuttle boats to transport passengers across the city harbour, which have been converted from experiments to permanent services.

La Rochelle's first short term showcase using automated transport in the city centre began in 2008 in the CityMobil project and had a strong impact on inhabitants and

decision-makers. A further demonstration of fully automated vehicles in real-life conditions was organised in 2011, including cybercars circulating for the first time in an urban open environment with interactions with pedestrians and cyclists.

Questionnaire responses showed that inhabitants believed in the development of such vehicles for public transport purposes in the future. After this successful experiment, La Rochelle participated in the CityMobil2 project as a demonstration site in 2014–2015 [14]. A main conclusion of this experiment was to encourage legislative changes to allow for permanent automated transport systems, rather than short term demonstrations.

La Rochelle's current public transportation system includes the following services: buses (including four bus rapid transit lines), shared bicycles, shared cars, ferry boats, commuter trains, ride sharing, park and ride, and on demand shuttle service (MOD). A total of three MOD lines each serve a specific zone, with a limited time window and currently have low ridership (less than 7 trips per day).

### 3.2 Yélo DETA Project

La Rochelle's latest innovative project in the field of autonomous public transport builds on the lessons learned in the past, with the objective of creating a fully MaaS-integrated, on-demand, autonomous service in suburban La Rochelle. Yélo DETA (Yélo Se Déplacer En Transport Automatisé) is a three-year project supported under the Call for Projects "Automated road mobility, connected and low-carbon service infrastructures" from the French Ministries of Industry and Digital Transition and Telecommunications. The focus is on suburban areas which currently have major gaps in terms of service capabilities: infrequent service, limited/absent off-peak service, limited connections to existing hubs, lack of suburb-to-suburb links. Indeed, the MOD service being developed during the YéloDETA project improves the existing MOD service overall (Table 1).

**Table 1.** Comparing existing and new MOD service in suburban La Rochelle, France.

| | Current MOD | YeloDETA |
|---|---|---|
| Driver | Yes | No |
| Origin/Destination restrictions | One of three hub stations | None |
| Availability [H/week] | 16 to 32 | 78 |
| Reservation restrictions | At least 2 h before trip | None |
| MaaS integration | No | Yes |
| Objective | Bring suburban passengers to hub stations to get to city centre. | Bring suburban passengers to hub stations to get to La Rochelle city centre. Allow for inter-suburban trips using any available bus stop. |

The objective of the Yélo DETA project is to develop and provide a first real-time Automated-On-Demand Transport service to respond to different challenges:

(i) to improve connections between the suburban towns, (ii) to offer a service for first and last kilometres to and from already existing hubs, (iii) to offer a complete transport solution integrated in local MaaS in order to accelerate modal transfer, (iv) to demonstrate economic, social and environmental viability of this service.

The differences between the Yélo DETA project and the past experiments are illustrated in Table 2. The main novelty of the Yélo DETA project is to go beyond a short experiment and implement of a real service, integrated with the local MaaS.

**Table 2.** Characteristics of 4 experiments with AVs carried out in La Rochelle, France

| | Demonstration | CityMobil | CityMobil 2 | YeloDETA |
|---|---|---|---|---|
| Year | 2008 | 2011 | 2015 | 2023 |
| Duration | 1 month | 3 months | 6 months | 2 years test phase |
| Vehicles [qty] | 1 | 1 | 6 | 4 |
| Vehicle capacity | 2 | 4 | 12 | 10 |
| Vehicle max speed [km/h] | 3 | 5 | 20 | 60 |
| Road type | Closed | Open, city centre | Open, city centre | Open, low density suburban town centres, and highways |
| Other road users | None | Cyclists, pedestrians | Cyclists, pedestrians, cars | Cyclists, pedestrians, cars |
| On board operator | Yes | Yes | Yes | Phase 1: Yes<br>Phase 2: No |
| MaaS Integration | No | No | No | Yes |
| On demand service | No | No | No | Yes |
| Objectives | Showcase new technology in a public square | Test AVs in an open urban environment. | Idem CityMobil, including interactions with cars. Evaluate the acceptance of the technology by all stakeholders. | Idem CityMobil 2, open suburban environment at speeds up to 60 km/h, without an on board operator.<br>Provide on demand service to be integrated with the MaaS Estimate the modal shift to new services. |

## 4 Conclusions

Integration of AMOD with traditional transportation modes can be achieved through the Mobility-as-a-Service (MaaS). AMOD emphasizes the commodification of passenger mobility and goods delivery and transportation systems management, whereas MaaS primarily focuses on passenger mobility aggregation and subscription services. Recently, AMOD and MaaS have been converging even more, as the public and private sectors increasingly emphasize concepts of integrated mobility.

This article describes the real-time Automated Mobility On Demand service in the Yélo DETA project in La Rochelle. This service will ensure the link between the public transport and the last and the first km. The new Yélo DETA MOD service is designed to better meet the needs of habitants, with the objective of 4 shuttles at level 4 of automation, without an on-board operator, at a maximum speed of 60km/h in rural areas and without any specific infrastructure.

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# Transforming Ridesharing: Harnessing Role Flexibility and HOV Integration for Enhanced Mobility Solutions

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**Abstract.** While dynamic ridesharing has been extensively studied, there remains a significant research gap in exploring role flexibility within the many-to-many ridesharing scheme, where the system allows for several pickups for drivers and multiple transfers for riders. Previous works have predominantly assumed that all participants own a car and have focused on one-to-one arrangements. Additionally, there is a scarcity of research on integrating High Occupancy Vehicle (HOV) lanes and mathematical modelling. This study addresses these gaps by presenting a novel Mixed Integer Linear Programming (MILP) model that allows for role flexibility irrespective of car ownership and considers the implications of HOV lanes. Computational analysis highlights the benefits of incorporating role flexibility and accommodating non-car-owning participants in many-to-many ridesharing systems. Yet, excessive role shifts may create imbalances, impacting service to non-car owners. Further research should explore these correlations.

**Keywords:** Dynamic Ridesharing · Mixed Integer Linear Programming · Ride Matching · Role Flexibility · High Occupancy Vehicle

## 1 Introduction

Urban traffic congestion presents several challenges, including longer travel times, increased fuel consumption, higher emissions, and adverse environmental and health impacts. Expanding infrastructure and investing in public transit can be expensive and sometimes impractical in densely populated areas. While congestion pricing and alternative transportation modes exist, they may fall short in less densely populated areas. High-Occupancy Vehicle (HOV) lanes, dedicated for multi-occupant vehicles [1], effectively reduce congestion by promoting ridesharing and public transit. These lanes enhance traffic flow and serve as key strategies to tackle this issue, especially on busy freeways [1, 2]. HOV lanes in places like Beijing, Hong Kong, and California have shown significant benefits, including reduced travel times and improved traffic flow [3]. Carpoolers also enjoy incentives like reduced toll charges, motivating more people to use high-occupancy transportation modes and thereby reducing overall road congestion [4].

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Dynamic ridesharing systems with non-employee or non-contractor drivers also aim to alleviate congestion. They facilitate connections between travelers with compatible itineraries and schedules on short notice. Within ridesharing systems, an array of matching and transfer strategies exist. Some studies focus on one-to-one matching, where each rider is paired with a single driver capable of accommodating one passenger at a time [5]. A more comprehensive ridesharing approach involves a many-to-many scheme, where the system accommodates multiple stops for drivers and potential transfers between drivers and riders [2]. Another aspect of ridesharing systems is the role of participants as being driver or rider, which are typically defined upon trip registration. While some studies consider role flexibility [5, 6], the assumption is that all participants possess personal vehicles and thus have no preference, or that the system adheres to one-to-one frameworks. Similarly, studies on HOV [4] lack flexibility in participants roles, focusing on hired drivers and simplified one-to-one schemes. This study aims to fill these gaps by introducing a Mixed Integer Linear Programming (MILP) model for HOV lanes with a many-to-many approach and considering comprehensive role flexibility among participants. Ridesharing with multiple passengers in a vehicle may offer cost savings, and when combined with HOV lanes, it provides time-saving benefits.

## 2 Problem Description and Mathematical Formulations

We consider a dynamic ridesharing system that operates on a transportation network $\mathbb{G} = (\mathbb{N}, \mathbb{E})$, where $\mathbb{N}$ denotes nodes and $\mathbb{E}$ represents edges. Participants $\mathbb{P} = \{\mathbb{C} \cup \mathbb{NC}\}$ register their trip details and preferences are divided into car owners $\mathbb{C}$, and non-car owners $\mathbb{NC}$. Given the role-flexibility of the problem, individuals who take on the role of drivers $d$ form a subset $\mathbb{D} \subseteq \mathbb{C}$. Meanwhile, those who register as non-car owners or car owners but are assigned passenger roles constitute the set of $r$ riders $\mathbb{R} \supseteq \mathbb{NC}$. Each participant's travel data includes submission time $s_p$, origin $o_p$ and end $e_p$ locations, earliest departure $ED_p$, latest arrival times $LA_p$, with car owners specifying car capacity $Q_d$ and a notification deadline $\Delta_p$ for potential matches. We represent HOV nodes as $\mathbb{N}_H \subset \mathbb{N}$ and define $\mathbb{E}_H$ as the edges present in the sub-graph of $\mathbb{G}$ induced by $\mathbb{N}_H$.

To adapt to the dynamic nature of the problem and accommodate continuous information arrival we employ a rolling horizon strategy [5]. This involves periodic re-optimization of a static problem formulation at specific times based on incoming trip announcements. Prior to model solution, we perform preprocessing to account for users' spatiotemporal constraints. This narrows down the available nodes and links for each participant, leading to a reduced search space and facilitating the identification of viable and non-viable pairings of drivers and riders. We define the set of accessible nodes for participant $p \in \mathbb{P}$ as $\mathbb{AN}_p = \left\{i \in \mathbb{N} : T_{s_p,i} + T_{i,e_p} \leq LA_p - ED_p\right\}$, with $T_{i,j}$ denoting the shortest trip time between locations $i$ and $j$. Also, we establish sets of mutually accessible nodes for each participants-driver pair, denoted as $\mathbb{AN}_{pd}$, and their corresponding accessible links $\mathbb{AE}_{pd}$. Viable matches $\mathbb{RD}$ between riders and drivers, are based on overlapping accessible links and time constraints. It is important to note that due to transfer allowances a complete path or time overlap is not necessary. A match exists if $\mathbb{AE}_{pd} \neq \varnothing$ and $\neg\left(LA_d \leq ED_p \| LA_p \leq ED_d\right)$. To account for potential wait times, we introduce constraints into the model that synchronize meeting times at pickup and

transfer points, all the while maintaining onboard riders' schedules. To formulate this problem, we define the decision variables as outlined in Table 1.

**Table 1.** Decision Variables

| Variable Description | |
|---|---|
| $x_{i,j}^{p,d}$ | Binary variable if driver $d$ serves participant $p$ from $i$ to $j$ |
| $y_i^{p,d}$ | Binary variable if driver $d$ picks up participant $p$ at node $i$ |
| $z_i^{p,d}$ | Binary variable if driver $d$ drops off participant $p$ at node $i$ |
| $\mu^p$ | Binary variable if participant $p$ is matched |
| $\delta^d$ | Binary variable if driver $d$ provide drive service |
| $\kappa_i^d$ | Number of people in vehicle $d$ after serving node $i$ |
| $u_i^d$ | Counter on node $i$ in the path of driver $d$ |
| $\tau_i^p$ | The time at which participant $p$ visits node $i$ |

In the notation provided, we formulate the many-to-many flex-role ridesharing problem within a network that includes HOV as follows.

$$\max \sum_{p} \lambda_p \mu^p - \sum_{i,j} \sum_{p,d} t_{i,j} x_{i,j}^{p,d} \tag{1}$$

$$\sum_{j \in \mathbb{AN}_d} x_{o_d,j}^{d,d} = \delta^d \qquad \forall d \in \mathbb{C} \tag{2}$$

$$\sum_{i \in \mathbb{AN}_d} x_{i,e_d}^{d,d} = \delta^d \qquad \forall d \in \mathbb{C} \tag{3}$$

$$\sum_{i \in \mathbb{AN}_d} x_{i,j}^{d,d} = \sum_{k \in \mathbb{AN}_d} x_{j,k}^{d,d} \qquad \forall d \in \mathbb{C}, \forall j \in \mathbb{AN}_d \backslash \{o_d, e_d\} \tag{4}$$

$$\sum_{d \neq p, d \in \mathbb{C}} \sum_{j \in \mathbb{AN}_{pd}} x_{o_p,j}^{p,d} = \mu^p \qquad \forall p \in \mathbb{P} \tag{5}$$

$$\sum_{d \neq p, d \in \mathbb{C}} \sum_{i \in \mathbb{AN}_{pd}} x_{i,e_d}^{p,d} = \mu^p \qquad \forall p \in \mathbb{P} \tag{6}$$

$$\sum_{d \neq p, d \in \mathbb{C}} \sum_{i \in \mathbb{AN}_{pd}} x_{i,j}^{p,d} = \sum_{d \neq p, d \in \mathbb{C}} \sum_{k \in \mathbb{AN}_{pd}} x_{j,k}^{p,d} \qquad \forall p \in \mathbb{P}, \forall j \in \mathbb{AN}_{pd} \backslash \{o_p, e_p\} \tag{7}$$

$$\sum_{d \neq p, p \in \mathbb{P}} x_{i,j}^{p,d} \leq Q_d x_{i,j}^{d,d} \qquad \forall d \in \mathbb{C}, (i,j) \in \mathbb{AE}_{pd} \tag{8}$$

$$\sum_{d \in \mathbb{C}} x_{i,j}^{p,d} \leq 1 \qquad \forall p \in \mathbb{P}, (i,j) \in \mathbb{AE}_{pd} \tag{9}$$

$$x_{i,j}^{p,d} \leq \delta^d \qquad \forall p \in \mathbb{P}, d \in \mathbb{C}, (i,j) \in \mathbb{AE}_{pd} \tag{10}$$

$$\delta^d + \mu^d \leq 1 \qquad \forall d \in \mathbb{C} \tag{11}$$

$$y_i^{p,d} \leq \sum_{j \in \mathbb{AN}_{pd}} x_{i,j}^{p,d} \qquad \forall p \in \mathbb{P}, d \in \mathbb{C}, i \in \mathbb{AN}_{pd} \tag{12}$$

$$2y_i^{p,d} - 1 \leq \sum_{j \in \mathbb{AN}_{pd}} x_{i,j}^{p,d} - \sum_{j \in \mathbb{AN}_{pd}} x_{j,i}^{p,d} \leq y_i^{p,d} \qquad \forall p \in \mathbb{P}, d \in \mathbb{C}, i \in \mathbb{AN}_{pd} \tag{13}$$

$$2z_i^{p,d} - 1 \leq \sum_{j \in \mathbb{AN}_{pd}} x_{j,i}^{p,d} - \sum_{j \in \mathbb{AN}_{pd}} x_{i,j}^{p,d} \leq z_i^{p,d} \qquad \forall p \in \mathbb{P}, d \in \mathbb{C}, i \in \mathbb{AN}_{pd} \tag{14}$$

$$\sum_{i \in \mathbb{AN}_{pd}} y_i^{p,d} = \sum_{j \in \mathbb{AN}_{pd}} z_j^{p,d} \qquad \forall p \in \mathbb{P}, d \in \mathbb{C} \tag{15}$$

$$u_j^d \geq u_i^d + x_{i,j}^{d,d} - \left|\mathbb{AE}_d\right|\left(1 - x_{i,j}^{d,d}\right) \qquad \forall d \in \mathbb{C}, (i,j) \in \mathbb{AE}_d \tag{16}$$

$$u_j^d \geq u_i^d + 1 - |\mathbb{AN}_d|\left(2 - z_j^{p,d} - y_i^{p,d}\right) \qquad \forall p \in \mathbb{P}, d \in \mathbb{C}, i,j \in \mathbb{AN}_{pd} \tag{17}$$

$$\kappa_j^d \leq \kappa_i^d + \sum_{p \in \mathbb{P}} y_j^{p,d} - \sum_{p \in \mathbb{P}} z_j^{p,d} + M_1\left(1 - x_{i,j}^{d,d}\right) \qquad \forall d \in \mathbb{C}, (i,j) \in \mathbb{AE}_d \tag{18}$$

$$\kappa_j^d \geq \kappa_i^d + \sum_{p \in \mathbb{P}} y_j^{p,d} - \sum_{p \in \mathbb{P}} z_j^{p,d} - M_1\left(1 - x_{i,j}^{d,d}\right) \qquad \forall d \in \mathbb{C}, (i,j) \in \mathbb{AE}_d \tag{19}$$

$$\kappa_i^d \geq n_H - Q^d\left(1 - x_{i,j}^{d,d}\right) \qquad \forall d \in \mathbb{C}, (i,j) \in \mathbb{AE}_d \cap \mathbb{E}_H \tag{20}$$

$$\tau_i^d + t_{i,j} \leq \tau_j^d + M_{i,j}^d\left(1 - x_{i,j}^{d,d}\right) \qquad \forall d \in \mathbb{C}, (i,j) \in \mathbb{AE}_{pd} \tag{21}$$

$$ED_d\left(\delta^d + \mu^d\right) \leq \tau_i^d \leq LA_d\left(\delta^d + \mu^d\right) \qquad \forall d \in \mathbb{C}, \forall i \in \mathbb{AN}_d \tag{22}$$

$$ED_p\mu^p \leq \tau_i^p \leq LA_p\mu^p \qquad \forall p \in \mathbb{P}, \forall i \in \mathbb{AN}_p \tag{23}$$

$$x_{i,j}^{p,d}, y_j^{p,d}, z_i^{p,d}, \mu^p, \delta^d \in \{0,1\} \qquad \forall d \in \mathbb{C}, \forall p \in \mathbb{P}, i,j \in \mathbb{AN}_{pd} \tag{24}$$

$$\kappa_i^d, u_i^d \in \mathcal{N}, \tau_i^p \in \mathcal{Z}^+ \qquad \forall d \in \mathbb{C}, \forall p \in \mathbb{P} \tag{25}$$

Objective function (1) maximizes total matches and minimizes travel time, with $\lambda_p$ as the travel time for the fastest route from origin to destination, and $t_{i,j}$ as edge travel time. Constraint (2) ensures the departure of drivers from their origins, while constraint (3) guarantees their arrival at their destinations. Constraint (4) fulfills flow conservation for the driver's path. Constraint (5) directs riders out of their origin and (6) ensures that they

end their trips at their destination. Constraint (7) indicates flow conservation for riders. Moreover, these constraints enable passengers to transfer between drivers, creating a many-to-many scheme. Constraint (8) ensures vehicle capacity and the prerequisite that a driver must travel along a link for a rider on that link. Constraint (9) guarantees single-driver assignments for each step of a rider's path. Constraint (10) mandates car owners to be assigned as drivers before providing service to others. Constraint (11) states that car owners can either provide a ride service or receive it. Constraint set (12) states that a pick follows and immediate travel to the next node. Constraint (13) checks the feasibility of pickup at node $i$ by driver $d$. This requires that incoming edges at $i$ sum to zero, while outgoing edges sum to one. Constraint (14) monitors the possibility of drop-offs, ensuring that a source node only has outgoing flow while a destination node only receives incoming flow. Constraints (15)-(17) ensure meaningful orders for pickups and drop-offs. Constraint (15) guarantees that each pickup corresponds to a drop-off. Constraint (16) act as the counter on nodes visited by driver $d$ as they cross edges, tracking progress along the route. For pickup-drop-off order, constraint (17) ensures pick up location $i$ have a higher counter than drop-off point $j$. Constraint sets (18) and (19) limit the number of passengers on board after serving node $j$. The coefficient $M_1$ is set to $M_1 = Q^d + \sum_{p \in \mathbb{P}} 1$. Constraints (20) enforces a minimum passenger requirement for HOV lane access. Constraint (21) relates departure times at nodes and its subsequent immediate node, where $M^p_{i,j} = LA_p - ED_p + t_{i,j}$. This also prevents subtours. Constraint (22) and (23) ensures adherence to time windows for participants. Constraint sets (24) and (25) describe the type of variables.

## 3 Methodology

To compare the time savings from HOV and Flex roles, we utilize the New York City Taxi Trip dataset [7], which contains coordinates, timestamps, and trip durations. We randomly selected ~ 17k requests, with ~ 8k from non-car owners and ~ 9k from car owners. To address missing departure and arrival time in data, we follow literature [2] practices by adding or subtracting a random time between 0 and 5 min from the pickup and drop-off times. To identify accessible nodes within a user's time frame, we employ Yen's shortest path algorithm [8] and analyze the first 10 shortest paths. We obtain map data using the *OpenStreetMapX* package [9]. The map contains 40490 nodes and 12,242 edges, from which we randomly set 785 edges to have HOV lanes (see Fig. 1). A minimum of 2 occupants is required for HOV lane access. The system operates from 9:00 am to 07:00 pm, and we employ a rolling horizon [5] with a 5-min period for all experiments. All models are implemented in Julia v1.8.3 and solved using ILOG CPLEX v22.1.0 on a laptop with a Core (TM) i7 processor and 16 GB of RAM.

## 4 Results

Table 2 summarizes findings, with values averaging over the horizon. The '%Match' represents served participants to non-car owners, while '%Shift' is the ratio of car owners served by others. Combining role flexibility with HOV lanes achieves the lowest objective function. However, role flexibility alone achieves a higher %match, likely due to HOV




**Fig. 1.** HOV lanes in the Manhattan area (Image produced with OpenStreetMapX [9]; MIT licensed.)

**Table 2.** Effect of HOV and Role Flexibility on Matching

| Model | Objective | % Match | % Role Shift |
|---|---|---|---|
| Flex Role-HOV | 1164.13 | 80.62 | 27.87 |
| Flex Role-No HOV | 1489.12 | 89.12 | 29.80 |
| No Flex Role-HOV | 2666.74 | 60.14 | – |
| No Flex Role-No HOV | 3153.18 | 59.41 | – |

access requirements that limits combination of users can travel together. Role flexibility enhances total matches compared to inflexible models, but it is influenced by the driver-passenger ratio. We sometimes achieve 112% matches, serving all non-car owners and 12% of car owners through role shifts. However, in other cases, more role shifts can lead to imbalances, affecting service levels to non-car owners.

## 5 Conclusion

Role flexibility improves total matches in both HOV and non-HOV scenarios, with its effectiveness tied to the driver-passenger ratio. Further research on the correlations among role flexibility, role shifts, participant ratios, and service levels is an interesting avenue for future research.

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# FP2 R2DATO: Stepwise Approach for the Autonomous Tram

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**Abstract.** Throughout the history of transportation, very few inventions have had the same impact as rail transport. One of the oldest and most established means of transportation, railways, still provides efficient transportation of freight and passengers, but they stand to benefit from cutting-edge technology. The Europe's Rail FP2 R2DATO project (GA 101102001) is developing technologies in several fields of digital automated up to autonomous train operation seeking a new paradigm in how the rail system is operated, increasing safety, flexibility, capacity, performance and reducing energy consumption and costs.

These technologies can be applied to all rail segments including urban light rail. Future trams will benefit from new functionalities including remote control, ATO or perception systems. After collecting operational use cases and operational rules from key players of the urban operating community in Europe, FP2 R2DATO activities on tramway will focus on the remote control operation first, which will allow an operator to drive the vehicle from the office, avoiding the need of getting physically to the tram. This feature is intended to be used in daily operation in depots to support the train preparation, its retirement from service or for shunting within the depot. A first demonstrator is planned in 2024.

**Keywords:** Autonomous · connected · tramway

## 1 Introduction

Automation, digitalisation and artificial intelligence are changing the world and, of course, also the transport system. Automated trains have been operating in closed environments (subways, people-movers, etc.) for decades and now the first steps are being taken to make this also possible on the mainline rail under ETCS. On the other hand, the automotive sector is moving steadily towards the autonomous vehicle, through the use of increasingly sophisticated sensors and artificial intelligence routines. In the middle of both worlds are trams. Even though they are rail vehicles, they share the operational environment with road users.

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This opens the door to benefiting from the advantages and strengths of both sectors to facilitate and simplify the tramway operation, making it safer, more effective and sustainable.

The aim of the flagship project FP2 R2DATO (GA 101102001) [1] under the Europe's Rail Joint Undertaking frame is to take the major opportunity offered by digitalisation and automation of rail operation and to develop the Next Generation ATC[1] and deliver scalable automation in train operations, up to GoA4[2] for 2030, in order to maximise the infrastructure capacity on the existing rail networks, increase flexibility, punctuality and resilience while reducing operational costs. First tangible results of FP2 R2DATO are expected to be delivered by 2025, for key enabling technologies, contributing to the required transformation of the European railway system, including urban light rail.

Hence the FP2 R2DATO project is the perfect vector for the development of innovative solutions for the next generation of highly automated European trams, aiming at the following key advantages identified in the project by the group of urban rail operators led by UITP:

- Streamlining routine tram operations: automation is practiced at overseeing repetitive tasks like shunting, washing, and self-diagnostics within depot and non-commercial areas where public access is restricted. This not only increases efficiency but also minimises human intervention in everyday operations.
- Revitalising depot management: ATO systems offer the potential not only to operate the tram fleet within depots efficiently but also to redefine the perspectives on personnel roles and responsibilities. Confronting the challenges of workforce scarcity, ATO can facilitate the diversification of personnel tasks and the introduction of innovative roles like remote tram operators. This multi-pronged strategy optimises the utilisation of available resources.
- Enhancing safe and efficient tram operation: ATO systems are designed to provide comprehensive support for tram operators, ensuring safe and efficient driving during regular operations, while still retaining the role of the driver for critical decision-making.

## 2 Methodology

One of the major difficulties in developing automated functions for trams is that, unlike the mainline, there is no single interoperability or regulation, and no common operational rules. This means that in principle each tramway operator would have a customised solution tailored to their needs, dramatically increasing the cost of automated functions and their development time. Even in the automotive sector, despite the freedom of choice in driving, there are more or less common rules in Europe, making it possible for a Portuguese person to drive in Portugal, Germany or Sweden indiscriminately. For this reason, the development proposed in R2DATO consists of the following phases:

1. Collection of use cases, through UITP, from the main European tramway operators.

[1] Automatic Train Control.

[2] Grade of Automation 4: Unattended operations.

2. Selection of the most relevant use cases and search for maximum harmonisation between operators.
3. Design and implementation of the necessary technical enablers, and integration in vehicles and test and validation environment.
4. Demonstration in different operational contexts: Depot and commercial service.

In addition, a progressive implementation and deployment of the automatic functionalities associated with the chosen use cases is defined, making it possible to have simple functions validated from the first phases of the project to add new, more complex functionalities later on.

Therefore, the development has been grouped into three major demonstrators:

1. Remote tram driving in depot.
2. Autonomous driving in depot (GoA4).
3. Highly assisted driving in commercial service (equivalent to SAE L3 [2]).

All development shall follow the procedures of EN50126, EN50128 and EN50129. The necessary safety documentation for approval of modifications to the trams will be produced and both the Norwegian Railway Authority and the Norwegian Public Roads Authority have been involved from the beginning of the project.

## 3 Use Cases

To facilitate these objectives, UITP and the group of operators embarked on the task of defining operational use cases and requirements that align with the current operational norms of their respective networks. Given the diversity of operating conditions and regulations among the member networks, the exercise aimed not only to aggregate operational rules and use cases but also to extract universal principles that could accommodate various scenarios without delving into complex procedural specifics.

Operational use cases are established by addressing two key questions:

1. Contextual Automation: where can automation meaningfully enhance daily operations?
2. Operational behaviour: How should trams behave in response to environmental cues and aligned with the network's operational norms?

The former question concerns instances where automation, remote driving, or autonomous operations can succeed the role of an onboard driver or provide the drivers an advanced support. The latter concerns to standardising operational rules, thereby enabling the smooth integration of decision-making processes facilitated by automation.

Among the spectrum of automation-assisted use cases, the following were chosen as a priority for depot operations:

1. **Remote shunting**: the process of moving trams between tracks within a depot, encompassing tasks like track switching and negotiating crossings for parking, maintenance, or washing purposes. Shunting may involve switching points, signals, and crossings to ensure safe and efficient movement within depot. Automation, particularly autonomous operations, holds potential in optimising shunting efficiency and track allocation.

2. **Pre-departure readiness**: This encompasses diverse applications of ATO, including:
   - Automated pre-departure checks: leveraging ATO to execute elements of pre-trip checks traditionally performed by tram drivers or depot personnel. One of the examples of such us cases is wheel profile examination.
   - Remote tram system control: enabling telecommand manipulation of tram systems such as doors, HVAC, and acoustic signals.
   - Autonomous depot driving: facilitating autonomous tram movement within depots, fostering efficient tram deployment at the start of shifts.
3. **Remote washing procedure**: applying automation and remote control to rationalise tram washing routines, focusing on external cleaning within depot premises. Additionally, the concept of autonomous washing introduces a higher degree of system autonomy.
4. **Vehicle replacement shunting**: addressing the strategic management of replacing trams in and out of service. This involves V2X[3] communication, a scope wherein information exchange between several trams and infrastructure.

In conclusion, the activity, driven by the synergistic efforts among urban rail operators, attempts to establish a reasoned foundation for the integration of ATO systems within the complex framework of tram and light rail networks by defining the beneficial use cases. The fundamental challenge of this exercise lays in the dual requirement of formulating harmonised use cases while simultaneously accommodating the contextual operating nuances that need parametric considerations in ATO systems. Although the area of depot operations demonstrates notable commonalities, it is in the orchestration of unification across the operational ("street" level) landscape that the true complexity of the endeavour becomes manifest.

## 4 Technical Enablers

Figure 1 depicts the required technical enablers to achieve the expected tram automation:

**Remote Driving**: Remote driving from a remote operation centre. Based on low latency video streaming and remote static and dynamic telecommands.

**ATO**: Automated driver functions such as traction, brake and driving commands based on system consigns.

**Environment Perception**: Objects, signalling, path and landmark detection, classification and tracking by new generation sensors.

**Connectivity**: Ground to train communication for telecommands and operational information, for video streaming and data transmission. V2X communication with other trams, cars, scooters, infrastructure, etc.

**Autonomous and Automated Functions**: Configurable sequences, environment assessment, decision making and control improved capabilities.

[3] V2X communication refers to the exchange of information between vehicles and other entities, such as infrastructure, other vehicles, or pedestrians, to enhance overall safety and operational efficiency in transportation systems, based on the 3GPP standards.

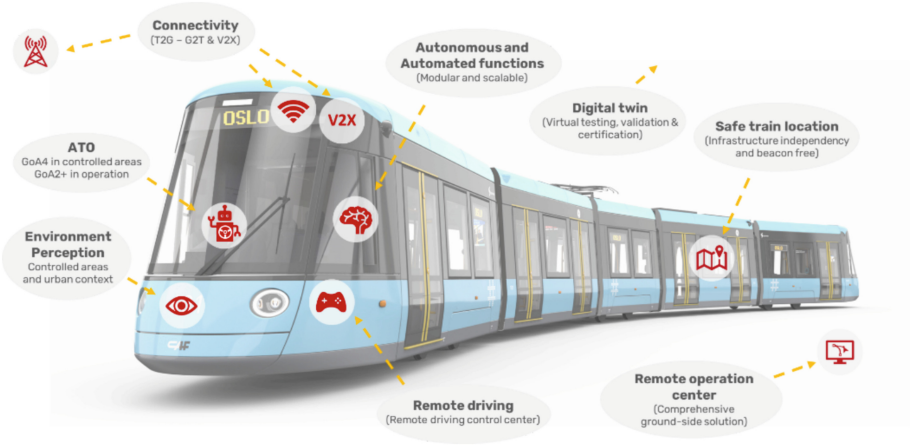



**Fig. 1.** Technical Enablers

**Safe Train Location**: Accurate positioning and precise speed measuring. Location in all operational scenarios complying with challenging requirements.

**Remote Operation Centre**: Centralized and configurable solution to enable remote driving, telecommands, fleet monitoring and sequences programming. High level of configurability and adaptability.

The implementation of automated functionalities will be modular and scalable. This will allow the validation of single functionalities, but also complex scenarios made of sequential (or parallel) previously validated ones.

## 5 Testing and Demonstration

### 5.1 Location

The testing and demonstration will take place in Oslo, with the support of the local tramway operator Sporveien Trikken. Two depots, in Holtet and in Grefsen, will be used for the first two demonstrators.

While the track yard in Holtet is open air, the whole of Grefsen is covered. This will allow testing and validation of the technical enablers under different environmental conditions. For example, Holtet (see Fig. 2) is exposed to inclement weather such as snow or fog, in Grefsen there is no possibility to rely on GNSS for tram positioning. Light conditions and train-to-ground transmission conditions are also different at the two locations. In terms of commercial operation, Sporveien Trikken currently serves 6 lines, each with different characteristics and operational needs. While some share the roadway with cars, other sections share the roadway with pedestrians.

One of the lines, in the direction of the Holtet depot, is segregated and therefore allows testing in a more controlled environment. All in all, the set of locations and types of operation will allow for extensive validation of the automated functions.




**Fig. 2.** SL18 tram exiting the workshop building at Holtet depot under snowy weather

### 5.2 Vehicles

For this development two SL18 trams (CAF URBOS 100 type) of Sporveien Trikken have been modified. The modification consists of the integration of perception sensors and new computer and communication equipment. The integration has been designed in such a way that the trams can be in commercial service while they are not being tested, as there is a total electrical disconnection of the new devices by means of a switch, leaving the trams in their original functional state. The design also allows for the variation of the sensor suite over time, to adapt to the needs of perception and to be able to integrate new generation sensors that may appear in the coming years.

### 5.3 Testing Concept

Test cases with their test protocols will be developed on the basis of priority use cases. Necessary measures resulting from safety studies shall be implemented. Each of the use cases is associated with performance indicators that are to be improved by automation and therefore these indicators must be measured and compared with the current situation without automated functions. Among others, automatic depot operation is aimed at increasing productivity and reducing costs, while advanced driving assistance in commercial service is aimed at improving safety, operating efficiency and facilitating the driver's tasks.

Test cases will capture both the successful paths of the use case and those that end in failure, as well as test the safety measures in specific test cases. Where possible, the system will be stressed in order to find a reliable and safe operation envelope.

The tests will be carried out in campaigns in between which there will be time to evaluate the results and implement improvements as necessary, until a sufficient level of maturity and reliability is reached in all deployed functions.

## 6 Planning

This ambitious design, implementation and technology demonstration plan for the scenarios and use cases will last until the end of 2028 as can be seen in Fig. 3. The preliminary work has already been done. Indeed, the TAURO project (GA 101014984) [3] provided the fundamentals for the remote driving of trams in depot (specification and architecture) and validated the use of perception sensors for tram positioning in a real operational environment. These results were presented in a form of poster during the previous edition of the Transport Research Arena in Lisbon.

The R2DATO project will end in May 2026, fully covering the demonstrator on remote driving and the first steps for the validation of the unattended autonomous driving, both in depot.

The successor of R2DATO, also part of the Europe's Rail initiative, is planned to start in December 2025, and the second wave of demonstrators will be included. It will comprise the completion of the unattended autonomous driving in the depot, and based on it, the demonstration of the advanced driver assistance system under commercial service in the city of Oslo.

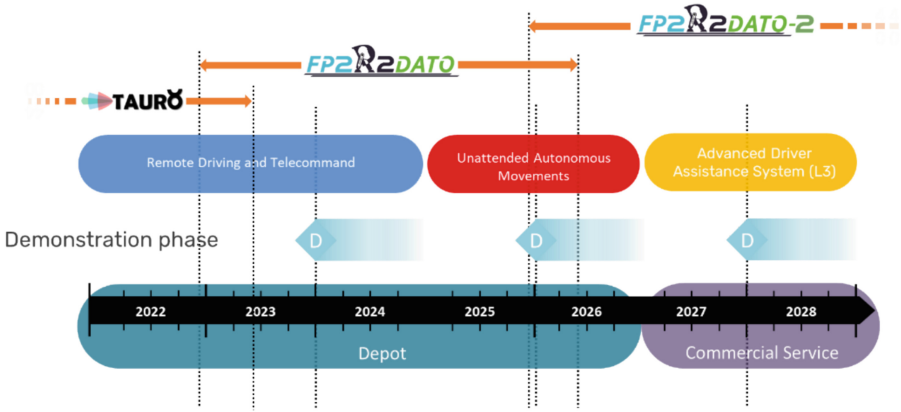



**Fig. 3.** Planning

## 7 Conclusions and Next Steps

Tramways should not stay behind in the race for automation. While they can benefit from the progress in the automotive sector and the experience of rail automated metros, they also face specific difficulties, such as the diversity in operational procedures and regulations. The Europe's Rail FP2 R2DATO is collecting and harmonizing operational use cases for the future European highly automated tramway system, which will then be implemented and demonstrated in the city of Oslo, under two scenarios (depot and city) and three applications (remote driving in depot, unattended autonomous movements in depot and highly assisted driving in commercial service).

By the time of the Transport Research Arena in 2024 the first application will be already under tests for several months giving the opportunity to present the first results during the conference.

With the support of the Europe's Rail Joint Undertaking and the UITP members the validated specifications and operational procedures for the future highly automated tramway should become a European standard smoothening the progressive deployment of such technologies for the benefit of the European citizenship.

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# Future Roundabouts Relying on 5G, Edge Computing and Artificial Intelligence

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**Abstract.** The paper focuses on the behaviour of cooperative, connected and automated vehicles (CCAVs) with the aim of improving traffic flow and safety and providing adequate comfort to vehicle occupants. The study is part of AI@Edge project, founded by the Horizon Europe framework programme. AI@Edge focuses on leveraging AI and Edge computing to enhance 5G networks. The simulation environment is a single-lane mini-roundabout, calibrated on the basis of experimental measurements to accurately replicate the behaviour of human-driven vehicles. A cooperative Deep Reinforcement Learning (DRL) policy, exploiting Proximal Policy Optimization (PPO), was developed to optimize the behaviour of CCAVs while negotiating the roundabout. To assess the effectiveness of this policy, a dynamic driving simulator coupled with a microscopic traffic simulator and a graphical simulator was employed. This comprehensive approach included both simulated human-driven vehicles (HDs) and CCAVs, alongside a real human driver. Tests indicate that human drivers respond positively to scenarios with a higher percentage of automated vehicles, due to an enhanced sense of safety and comfort. Quantitative analysis of the policy also demonstrates the capability of CCAVs to reduce fuel consumption and optimize traffic flow.

**Keywords:** CCAM · Artificial intelligence · Deep learning · Edge computing · 5G · Roundabouts · Human driver

## 1 Reference Scenario and Simulation

The integration of Artificial Intelligence (AI) into autonomous decision-making systems is a fundamental aspect of the multi-service Next Generation Internet. The European project AI@Edge [1] aims to explore the integration of AI-enabled

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platforms in digital infrastructures, including those dedicated to Cooperative, Connected and Automated Mobility (CCAM). This paper focuses on developing a virtual simulation environment, both in terms of digital infrastructure and vehicle replication. It will be employed to test a Deep Reinforcement Learning (DRL) policy that optimizes traffic flow within roundabouts, while safely navigating CCAVs in a mixed traffic situation with humans-in-the-loop. This specific type of intersection is selected as it is known to be a bottleneck for automated driving. The reference scenario for the simulations is a four-leg single-lane mini-roundabout [2], which is based on an actual roundabout located in Milan. The scenario is reported in Fig. 1.



(a) SUMO network. (b) VI-WorldSim network. (c) Actual roundabout

Fig. 1: SUMO and VI-WorldSim networks and the actual roundabout (Maps Data: ©2023 Google)

The introduction of CCAVs is expected to bring significant improvements in traffic flow, safety and emissions [3]. However, the adoption of CCAVs will be gradual and the period of mixed traffic conditions with CCAVs and human-driven vehicles (HDs) sharing the same infrastructure is expected to be long [4]. Microscopic traffic simulators (MTS) are typically employed for analyzing different networks and traffic conditions. However, due to the complexity of the human being, driver models roughly approximate human behaviour. Therefore, computer experiments with SUMO had to be substantiated with a human-in-the-loop. To this end, SUMO (Simulator of Urban Mobility [5]), was coupled with a dynamic driving simulator and the VI-WorldSim [6] graphical environment. This architecture [7,8] allowed for very accurate replication of the real scenario, thus being able to create an effective Digital Twin.

Three types of vehicles were present in the simulation:

1. CCAVs driven by the DRL policy hosted in the Artificial Intelligence Framework (AIF). They communicate with the infrastructure giving and asking for information (e.g. position and speed) about them and all other vehicles.
2. Simulated human-driven vehicles, controlled by a car-following model, specifically an Intelligent Driver Model (IDM) [9], only sending their data.
3. The ego-vehicle driven by the real human driver in the dynamic driving simulator. The cockpit is equipped with a telematic box that reads data from

the ego-vehicle and transmits it to a 5G radio platform connected to the infrastructure, with the actual communication delay.

All simulations at the driving simulator were performed in real time. A real-time database was in charge of the synchronization of all involved simulation software.

The DriSMi laboratory of Politecnico di Milano [10] conducted the tests using a state-of-the-art cable-driven driving simulator, called DiM400 [11]. The motion is provided by a multi-stage system with redundant degrees of freedom and very low latency. Its cockpit features active seat belts and brake. Noise and Vibration Harshness (NVH) frequencies are reproduced using eight shakers. For more details, please refer to [12].

## 2 Digital Infrastructure and AI Policy for CCAVs

The reference scenario described in the previous section is part of the use case #1 of the AI@Edge project. AI@Edge aims to realize a *connect-compute platform* for creating resilient and secure end-to-end slices. Within AI@Edge broad system architecture, there is a layer, called "network and service automation platform". This platform automates the management of various orchestrators, provides non-real-time intelligence, and ensures the low latency required for the Artificial Intelligence Framework (AIF). Since roundabouts represent a critical situation for AI, Edge computing and 5G [13], this scenario provides a challenging real-world problem to assess the performance of the AI@Edge project's technologies.

### 2.1 Communication Protocol

The connect-compute platform contains the digital infrastructure to run the mobile Edge computing applications [14] and represents one of the most important innovations of the AI@Edge project. In particular, this platform will be used to implement an innovative communication protocol, called Vehicle-to-Network-to-Vehicle (V2N2V). In this protocol, all vehicles are connected to the cloud via a 5G connection. A Multi-access Edge Computing (MEC) server, located near the roundabout and also connected to the network, collects all the provided information and run the DRL policy. As a result, the user is brought closer to the edge of the digital infrastructure. V2N2V combines Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) protocols, optimizing both and reducing the operation and maintenance costs for the vehicle and the infrastructure.

### 2.2 DRL Policy

CCAVs choices are guided by a DRL policy. The Proximal Policy Optimization (PPO) method [15] is used to learn policy parameters. PPO is an algorithm that is based on the Trust Region Policy Optimization (TRPO) algorithm [16], but it offers improved flexibility at the cost of increasing the computational complexity. Both PPO and TRPO optimize policies efficiently by iteratively adjusting

their parameters while maintaining stability during the learning process. PPO employs a dual-step process, involving policy evaluation and policy improvement. During policy evaluation, data is gathered by executing the current policy within the environment, and advantages are computed to measure how favourable the selected actions are relative to expected outcomes. Policy improvement is performed through several epochs of optimization, during which PPO computes surrogate objectives that quantify the change in the policy's performance with respect to the previously considered set of policy parameters. These surrogate objectives facilitate the optimization of the policy by promoting positive action shifts while limiting the extent of any update to improve stability during learning. The objective of the policy is to improve traffic flow and minimise fuel consumption while ensuring safety for any vehicle in the network. Furthermore, the AVs also accounted for the driving comfort of vehicle occupants to also take into consideration the real acceptability of such technology. To this end, the computed advantages are obtained as a function of the lateral and longitudinal jerks, for which thresholds are defined based on experimental data. This led to a comprehensive and functioning motion planning algorithm.

## 3 Experimental Tests

Some experimental tests have been conducted to validate the digital infrastructure architecture and the AI policy. A panel of drivers has been asked to drive in the reference roundabout scenario presented in Sect. 1. Before conducting the tests, an experimental calibration of the scenario was undertaken to validate the accuracy of the roundabout model in comparison to data obtained from the real-world roundabout. The calibration procedure has been implemented in SUMO by comparing the simulation outputs with the acquired data while varying the most relevant parameters of the IDM driver model. At the end of the calibration, the set of driver parameters minimizing the difference between the simulated and measured data has been identified. The panel of participants chosen for the experimental tests consisted of ten drivers without prior subject experience with driving simulators. The panel included 5 female and 5 male, aged between 22 and 33, with driving experience ranging from 1 to 15 years. At the conclusion of each test, the drivers' perceptions were gathered. Following the test, each participant was requested to complete a form aimed at gauging their preferences regarding the proportion of CCAVs in the network, with respect to safety and general preferences. It should be noted that, due to the limited number of participants, these findings are preliminary, and a larger group of drivers should be considered to obtain more accurate information. The results of the preliminary tests are presented in Tables 1, 2, 3 and 4. Specifically, Table 1 and Table 2 report the qualitative results derived from participants' responses, while Table 3 and Table 4 show the quantitative results obtained by evaluating the policy's effectiveness in relation to traffic flow and fuel consumption. Considering quantitative results, the fuel consumption data have been retrieved considering a simulation lasting 3600 s to better appreciate their behaviour over time.

Table 1: Answers to the first question of the survey.

| Regarding safety perception, which of the following statements do you agree with the most? | Number of answers |
|---|---|
| Traffic with 20% of CCAVs was definitely safer | 0 |
| Traffic with 20% of CCAVs was partially safer | 2 |
| Traffic with 20% of CCAVs was partially less safe | 2 |
| Traffic with 20% of CCAVs was definitely less safe | 6 |
| I did not perceive differences | 0 |

Table 2: Answers to the second question of the survey.

| Globally, which of the two scenarios did you prefer? | Number of answers |
|---|---|
| I definitely preferred the scenario with 20% CCAVs | 0 |
| I partially preferred the scenario with 20% CCAVs | 3 |
| I partially preferred the scenario with 80% CCAVs | 3 |
| I definitely preferred the scenario with 80% CCAVs | 4 |
| I cannot say which scenario I preferred | 0 |

Table 3: Normalized consumption and emission scores given a penetration rate of CCAVs, considering a simulation of 3600 s. The worst-performing and best-performing vehicles are used as normalising factors, generating a score between 0, lower fuel consumption and 1, worst performance, for each vehicle.

| % CCAVs | CCAV | | HD | | | |
|---|---|---|---|---|---|---|
| | consumption | emission | consumption | emission | # CCAVs | # HDs |
| 0 | - | - | 0.74 | 0.69 | 0 | 1540 |
| 20 | 0.61 | 0.56 | 0.64 | 0.58 | 308 | 1232 |
| 80 | 0.46 | 0.38 | 0.49 | 0.44 | 1232 | 308 |
| 100 | 0.43 | 0.36 | - | - | 1540 | 0 |

On the other hand, crossing time, defined as the time interval between departure and arrival for every vehicle, has been retrieved during simulations with humans-in-the-loop lasting 100 s.

According to the qualitative results, 80% of the participants perceived the scenario with 80% CCAVs to be safer. Additionally, 70% of the participants preferred the scenario with 80% CCAVs. Moreover, as the number of CCAVs increased, both CCAVs and HDs reduced their fuel consumption and emissions on average, and the average crossing time decreased.

Table 4: Crossing time and number of vehicles that completed their path as a function of the percentage of CCAVs, considering a simulation of 100 s.

| | 0% CCAVs | 20% CCAVs | 80% CCAVs |
|---|---|---|---|
| Average crossing time [s] | 56.26 | 54.49 | 49.01 |
| Maximum crossing time [s] | 87.53 | 83.32 | 79.66 |
| N. vehicles [-] | 35 | 39 | 41 |
| Reduction of crossing time | ref. | 3.15% | 12.88% |

## 4 Conclusion

This paper presents a co-simulation between SUMO and a dynamic driving simulator to investigate the interaction between HDs and CCAVs in a mixed traffic situation. An innovative communication configuration called V2N2V is used to manage data flow. The study focuses on a mini-roundabout and uses a DRL policy to control CCAVs. Preliminary tests show that human drivers preferred and were safer with more CCAVs. Furthermore, CCAVs reduced fuel consumption, enhanced traffic flow, provided adequate driving comfort and boosted the efficiency of HDs. These results validate the test bed employed and give an understanding of future applications, regarding complex traffic administration by AVs. Future research paths include the analysis of more complicated road networks and the use of physiological sensors to subjectively assess the driver.

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# Field Study of FRMCS Use Cases in the 5GRAIL Project

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**Abstract.** Railways currently use the Global System Mobile for Railways (GSM-R) for train operation across the world. The GSM-R is used for voice communication between train driver and control centres, including but not limited to, the Railway Emergency Call (REC) as well as for signalling and control messages of the European Train Control System (ETCS). Based on the fifth generation (5G) of mobile networks and in particular, 3rd Generation Partnership Project (3GPP) releases 17 and 18, the Future Railway Mobile Communication System (FRMCS) is envisioned to replace GSM-R. This modernization step does not only address administrative constraints, e.g., the upcoming 2G equipment obsolescence, but also provides an opportunity for transforming the current train operation through introduction of digitalization and automation technologies in an aim of increasing capacity and efficiency for a sustainable transport. In this paper, we present some highlights of first FRMCS Fields trials that have been realized within the 5GRAIL project which is funded by the EU Horizon 2020 program. These trials were co-led by DB Netz AG in Germany and SNCF RESEAU in France. The aim was to accomplish functional and performance testing in addition to multi-access and cross-border like scenarios. We discuss some results on the testing of the different applications before concluding with lessons-learned and outcomes.

**Keywords:** FRMCS · 5GRAIL · 5G · Railway mobile radio · Mission-critical services · Bearer-flexibility

## 1 Introduction

The Future Railway Mobile Communication System (FRMCS) will be the 5G worldwide standard for railway operational communications, conforming to European regulation as well as responding to the needs and obligations of rail organisations outside of Europe. A major challenge is the update by the European Railway Agency of the Technical Specifications for Interoperability of Control Command and Signalling (TSI CCS) with a full description of FRMCS with respect to interoperability functions. Therefore, the 5GRAIL project [1] aims to verify the first set of FRMCS specifications and standards (FRMCS V1) by developing and testing prototypes of the FRMCS ecosystem. The validation of

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the latest available railway-relevant 5G specifications will be achieved through cross-border emulation trials covering significant portions of railway operational communication requirements and including the core technological innovations for rail expected from 5G release 16 and pre-release 17 [2]. The project will first define functional tests and then work towards the development and evaluation of prototypes, for both onboard (Telecom On-board Architecture (TOBA)) and the infrastructure. The TOBA Gateway (GW) is a core element of the 5GRAIL prototyping activities as it enables multi-application support in the onboard railway communication system [3]. The railway applications include voice-specific services, such as group calls or the Railway Emergency Call (REC), the vital European Train Control System (ETCS), Automatic Train Operation (ATO) and essential additional services like Train Control and Monitoring System (TCMS) or video apps.

Prototypes will be then tested in simulated and real environments, with pilots in laboratories and in the field rolled out in various European locations (France, Hungary, and Germany), to ensure compliance and validation for FRMCS specifications, standards, and performance, and consequently guarantee the time to market for FRMCS deployments. 5GRAIL will finally deliver test report conclusions to potentially update FRMCS version 1 (v1) specifications [4, 5] and to identify implementation constraints.

The objectives of the field trials are to provide a 5G railway field test environment to evaluate technical solutions and prototypes developed as part of this innovative 5GRAIL project. The prototypes developed and lab-tested will be integrated into real railways environment, i.e., rolling stock running on rail tracks with dedicated 5G radio coverage [6, 7], which will allow evaluation of their functionalities and performances. Field tests will demonstrate the usability of 5G to answer railways needs using railways applications and application simulators. Figure 1 illustrates the workflow in the 5GRAIL project, which is decomposed into 8 Work Packages (WPs). Testing is performed in two fields (France and Germany), each having different characteristics.

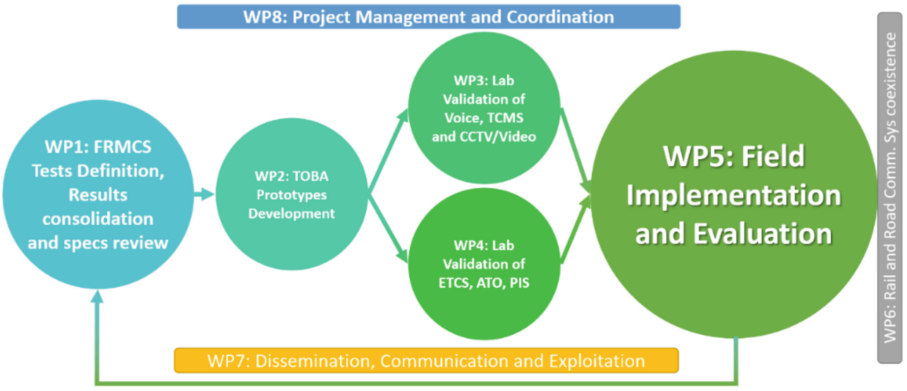



**Fig. 1.** Project Decomposition and Inputs/Outputs of Field Evaluation (Image produced in Paint.net, Freeware)

The summarized objectives are as follows:

- Real-world 5G testing of essential functional requirements for the railways,
- Evaluation of End-to-End functionality and connectivity for selected railways,
- Integration of applications such as Voice via 3GPP's mission-critical push-to-talk (MCPTT) functionalities, or ETCS, ATO, real-time Video, TCMS, etc. via 3GPP's mission-critical data (MCDATA) functions,
- Emulation of FRMCS bearer flexibility and border-crossing like scenarios.

## 2 Testbeds for Field Trials

In SNCF's testbed in France, the test sites consist of a portion of commercial line in sub-urban environments in the Paris region. 5G RAN is deployed as a test network at TDD band n39 encompassing 1900 MHz-1910 MHz band [8] in three sites called: Bourbonnais, Marin and Rive, with reuse of existing GSM-R/GPRS basic infrastructure setup. The CU/DUs and 5G Core are deployed at a local command centre close to the test sites. Train speed is limited to a maximum of 70 km/h.

In DB's testbed in Germany, 5G RAN is deployed as a test network at TDD band n78 (3.7 GHz, using 20 MHz bandwidth) in 8 sites. The 5G Core is operated remotely from a control centre located of a project partner in Hungary via a leased line. Trains run with a speed of 50–80 km/h.

The testing is conducted in parallel in the two fields with different scopes. Some similar initial end-to-end connectivity tests are executed in both test fields to compare the results in different deployment conditions.

## 3 Generic End-to-End Architecture for Field Trials

The generic network architecture of the FRMCS used in the two fields is depicted in Fig. 2. The transport stratum implementing the 5G/FRMCS infrastructure is shown in light blue rectangles. It includes the network elements of the Radio Access Networks (RANs) and 5G Core Networks (5GCs) [2]. The Application and Services strata are shown within the yellow and grey rectangles, respectively. The applications use the On-board Application ($OB_{app}$) and TrackSide Application ($TS_{app}$) interfaces [5]. In case of voice applications, the mission-critical application (MCx) client is realized in the cab radio device and, hence, tight coupled. For data/video applications the MCx client is implemented in the TOBA Onboard GW following the loose-coupling principle. With 5GRAIL's TOBA GW prototype, a parallel operation of mission-critical application with a unified FRMCS onboard system becomes possible.

Table 1 reports a list of FRMCS role in modernizing Railway Communication beyond the state of the art, with the conclusion of the field evaluation.

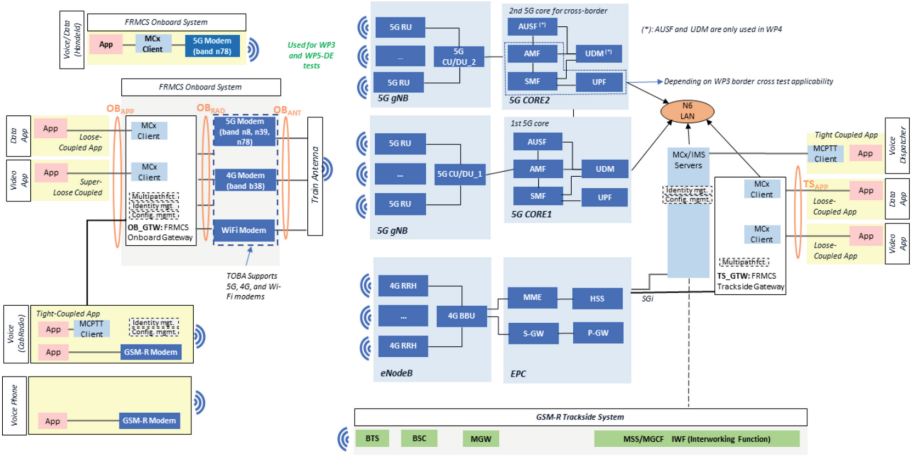



**Fig. 2.** Generic Network Architecture of the Field Testing of FRMCS (Image produced in Paint.net, Freeware)

**Table 1.** 5GRAIL role in modernizing railway communication.

| State of the art | After 5GRAIL |
|---|---|
| GSM-R (2G) | FRMCS (5G) |
| Limited capacity for railway services | Extended capacity for railway services |
| No bearer flexibility for railway applications | Bearer flexibility for railway applications |
| ETCS and ATO circuit-switched interfaces | ETCS and ATO IP interfaces |
| Limitations on ATO | No limitations for ATO |
| No possibility for video critical applications | Video for critical applications |
| Limitations on TCMS applications | TCMS applications |
| Distributed management of telecoms in train | Unified management of train communications |

## 4 Highlights of Some Use-Cases of the Field Trials

Voice, data, and video calls as well as combined use of heterogeneous applications are successfully completed in the two fields. Below, some highlights are listed.

**Voice Communication – Testing P2P Calls, Group Calls and REC (Germany)**
As voice communication plays a significant role in today's railway communications, its migration to 5G-based FRMCS is crucial. In 5GRAIL several voice services have been tested over FRMCS such as point-to-point (P2P) calls initiated by a train driver (using a cab radio) towards a train controller and vice versa, multi-train group calls with FRMCS user groups and mixed FRMCS and GSM-R user groups as well as railway emergency calls (REC) both with only FRMCS users and interworking with GSM-R.

For the first time, a system transition from 2G-based GSM-R to 5G-based FRMCS with service continuation has been showcased.

**Video Communication – Testing Remote Vision Combined with ETCS (France)**
In the remote vision application, a real-time video is transmitted from the train front to the trackside control centres. One objective of testing the remote vision application in 5GRAIL is to add high load on the network and analyse its behaviour, including flows priority management, when multiple heterogeneous applications in term of criticality are used at the same time. In this test, the Remote Vision (RV) is used in parallel with the ETCS application simulator. Note that RV uses High Efficiency Video Coding (H.265/HEVC) adaptive codec to encode the driver's view in the tests, as illustrated in Fig. 3. In practice, it is possible to stream 1280 × 720p (HD ready video) with full driving capacity from 800 kbps. However, the codec is usually set at 1Mbps. As adaptive, it will automatically adjust according to network conditions, as seen in Fig. 4.

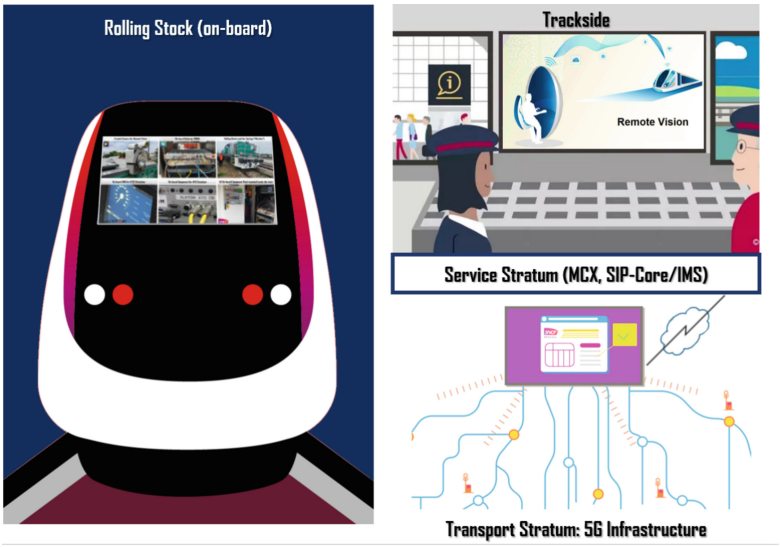



**Fig. 3.** Remote Driving End-to-end simulation (Image produced in Paint.net, Freeware)

**Overall Achievements**
5GRAIL has performed comprehensive test campaigns in the field with 6 weeks drive tests with rolling stock in France and Germany, each. Besides successfully accomplished voice and remote vision tests (as discussed above), also the data tests with ETCS, ATO and TCMS simulators have been realized. For these data applications with rather small bitrates, achieved latencies in the 5G-based FRMCS test networks have been generally low without impact on QoS of the application. This was also true for combined data application scenarios. Another test aspect of 5GRAIL's video testing was the real-time streaming of in-cabin video from train to ground (uplink) as well as the offload of CCTV

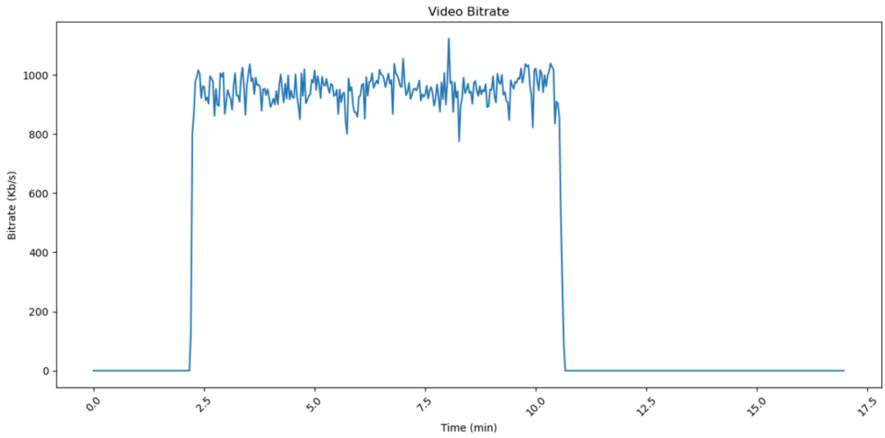



**Fig. 4.** Video Bitrate run at 1Mbps (Image produced in Paint.net, Freeware)

files to trackside servers. For the latter one, a transition between two different 5G bearers has been realized as inter-frequency handover between 5G sub-bands with different TDD patterns and, hence, different achievable uplink bitrates.

## 5 Conclusion

In this paper, we have presented some highlights of the functional and performance testing accomplished as part of the field tests in the 5GRAIL project. This project allowed the railway ecosystem to validate 5G technologies and 5G standalone architecture for a connected and automated mobility (CAM) context. Moreover, it allowed to validate 5G systems to support advanced FRMCS use-cases such as real-time video. 5GRAIL is the first large-scale FRMCS prototyping project. This project is the first step towards FRMCS. Further projects are currently following.

**Acknowledgement.** The project "5G for future RAILway mobile communication system" (5GRAIL) has received funding from EU's Horizon 2020 research and innovation program under grant agreement No. 951725.

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# FRMCS, also a Rail Digitalization Enabler

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**Abstract.** Future Railway Mobile Communication System (FRMCS) will be the 5G SA MCX standard for railway operational communications, conforming to European regulation. It will also fulfil the needs of rail organisations worldwide. UIC (International Union of Railways) is leading the design, standardisation, and is deeply involved for the introduction plan of this telecommunication system, in close cooperation with railways, authorities and suppliers. FRMCS is the successor of GSM-R which is a component of European Railway Traffic Management System (ERTMS), representing around ~130,000 km of coverage of tracks in Europe. GSM-R is however announced to become obsolete soon due to its 2G technology. Therefore, FRMCS, being specified and implemented as a standard, combining 5G transport with Mission Critical (MC) service layer features, is considered as a major trigger for the wide-ranging digitalization of the rail sector, satisfying the increasing demand of data while keeping the high quality of service for critical railways applications, in an interoperability context.

This paper aims to present some insights of the FRMCS introduction plan and provide an overview of the outcomes of 5GRAIL, an EU Horizon 2020 project coordinated by UIC, as part of the FRMCS readiness initiative.

For more information, visit: https://uic.org/rail-system/telecoms-signalling/article/frmcs, 5GRAIL - 5G for future RAILway mobile communication system.

**Keywords:** FRMCS · 5G · MCX · TOBA · REC · Border-crossing · Bearer flexibility

## 1 Introduction

The introduction of FRMCS (Future Railway Mobile Communication System), the GSM-R successor, is mandatory need not only due to the obsolescence of the 2G technology on which GSM-R is based, but also to enable the smart train, via the 3GPP 5G and MCX features. Obviously, the need for this new technology is a prerequisite for the evolution of ERTMS (European Railway Traffic Management System) whilst also being a trigger for the wide-ranging digitalization of the rail sector.

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FRMCS relies on the 3GPP (3rd Generation Partnership Project) technology, 5G Core and Access networks, supporting at minimum the Railway Mobile Radio (RMR) harmonized spectrum for Europe (as per Electronic Communications Committee (ECC) (20)02 decision), and ensuring the relevant functionalities and performance requirements per railway application obtained through the 3GPP Mission Critical Services (MCX).

One key element of this new architecture is the introduction of the so-called FRMCS gateways in the end-to-end communication chain, providing the decoupling between railway applications and telecommunication network, which allows the transport layer to evolve e.g., to a new radio technology without impacting the application layer. Connections between the on-board and the trackside parts of each application go through the two FRMCS gateways, located on both sides of the 5G infrastructure, as described below:

- The On Board FRMCS gateway (OB_GTW), also known as TOBA (Telecom On-board Architecture) is connected to the applications through OBapp interface and to the 5G Radio Access Network, through a set of FRMCS modems.
- The Trackside FRMCS gateway (TS_GTW) is connected to the applications through TSapp interface and to the 5G Core Network.

The usage of these standardized interfaces allows any newly created application to be easily inserted in the FRMCS system.

The below figure presents, as an example, the 5GRAIL[1] project applications integration via On-Board and Trackside FRMCS Gateways (Fig. 1):

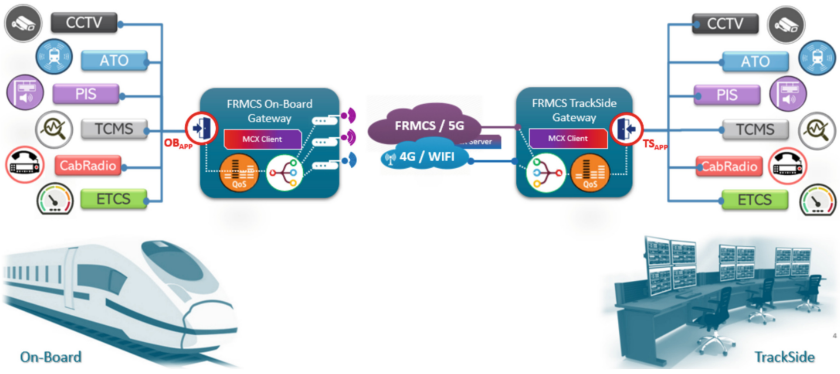



**Fig. 1.** Integration of 5GRAIL applications via FRMCS Gateways [3] Reproduced with permission from Kontron Transportation, copyright Kontron Transportation, 5GRAIL Project 2020–2023.

[1] 5GRAIL: An EU-funded Horizon 2020 5G for Connected and Automated Mobility (CAM).

Moreover, the implementation of FRMCS services is based on one MCX server, located in the infrastructure, and MCX clients, on each side of the FRMCS infrastructure. Railway applications shall use the appropriate client to interconnect both parts of an application, this being one of the key principles of the FRMCS System architecture. There are two integration options for the MCX clients:

- the MCX client is embedded in the application; defined as **tight coupling mode.**
- or the MCX client is embedded in the gateways, defined as **loose coupling mode**.

## 2 Status of FRMCS Introduction

UIC has elaborated a complete plan to introduce FRMCS [1]:

- Thanks to the UIC 3GPP task force, some solutions were standardized starting from R17 and continue in R18 and beyond. Moreover, missing requirements were added to the 3GPP R19 specifications, based on the continuous gap analysis between them and he UIC FRMCS FRS (Functional Requirement Specifications).
- UIC has published well in advance the FRMCS architecture principles and the migration scenarios for ETCS and voice.
- The RMR spectrum was allocated to FRMCS in Europe with the ECC (20) 02 decision.
- 5G FRMCS chipsets in bands n100 (FDD (Frequency-Division Duplexing), Uplink (UL): 874.4-880MHz, Downlink (DL):919.4-925MHz) and n101 (TDD (Time-Division Duplexing), 1900–1910 MHz) have been provided as prototypes and used in 5GRAIL testing activities, also considering high-power UEs prototypes for field testing.

But the major achievement of this introduction plan was the availability of the FRMCS V1 specifications, included in CCS TSI 2023, aiming to deliver a system supporting critical applications (ETCS, ATO GoA2 and voice) using the RMR band. The FRMCS V1 specifications were partly validated in lab and field conditions, by the DG CONNECT funded 5GRAIL project.

### 2.1 FRMCS V2, the Next Steps

The approval of FRMCS V1 specifications has been concluded with the addition of them in the CCS TSI 2023 confirming FRMCS as a subsystem of the ERTMS [1]. FRMCS V2 is in progress to provide together with 3GPP R18 features, a complete FRMCS system to be tested during MORANE-2 European trial, which is expected to focus on field tests with conventional and high-speed lines and under cross-border conditions.

MORANE-2 is a major step that will provide to the railway operators with the first pilot schemes for FRMCS first deployment.

## 3 5GRAIL's Outstanding Achievements, as First FRMCS Demonstrator

The scope of 5GRAIL was to validate FRMCS V1 specifications by defining functional end-to-end tests for a selected subset of FRMCS V1 features to be executed in lab conditions in Hungary, led by Nokia and in France led by Kontron also in field conditions

in Germany, led by DB and in France, led by SNCF. The outcome of them considered as the first FRMCS demonstration provided feedback to the FRMCS V1 specifications, as part of the loopback process but also initiated or enhanced requirements in 3GPP specifications. Moreover, it is considered as an important step for the preparation of FRMCS V2 specifications.

Below, some important achievements of 5GRAIL, impacting the specifications are presented.

### 3.1 Railway Emergency Communication (REC)

The REC is an extremely important communication in railway environment, used in emergency conditions. Therefore, it is considered as a high priority communication and has distinct means for set-up and presentation. REC was not completely specified in FRMCS V1 and the work will continue in FRMCS V2 in parallel with the 3GPP R18 enhancement. However, a thorough assessment of implementation options [4] has been performed and described in the UIC FRMCS FIS V1 specifications which concluded that the Ad hoc Group Communication (AHGC) method with Server based area definition and user determination without required affiliation is the most suitable one, whose target is 3GPP Rel-18. The dynamic area definition based on the initiator's location and the selection and affiliation of the impacted participants (clients) according to their location is a new concept in MCX standards, more focused on the Public Safety Emergency call use cases.

In the framework of 5GRAIL, at Nokia's lab in Hungary [5], the server-based approach with affiliation of the concerned clients based on their continuously updated location report was performed. Although it is not the final AHGC implementation, the role and requirements on the MCX server were very similar, hence interesting outcomes have been provided to the specifications.

### 3.2 FRMCS-GSM-R Interworking

GSM-R – FRMCS Interworking is an important functionality during the coexistence period of both technologies. The specification of the interworking function is an ongoing working item in European Telecommunications Standards Institute (ETSI), so the REC test case performed within 5GRAIL in Nokia's lab is a pre-standard one. It is worth mentioning that the scenario also covers the cross-border situation where neighbour networks have different technologies in use.

The main realization in 5GRAIL was to initiate a REC on the GSM-R network when in the FRMCS system a corresponding REC is established by the CAB radio. Inside Nokia's Mobile Switching Center Server (MSS), the incoming MCX messages defined in 3GPP for Interworking are interpreted and mapped to the GSM-R messages used by a dispatcher originated REC call. The following set-up is used for this test (Fig. 2):

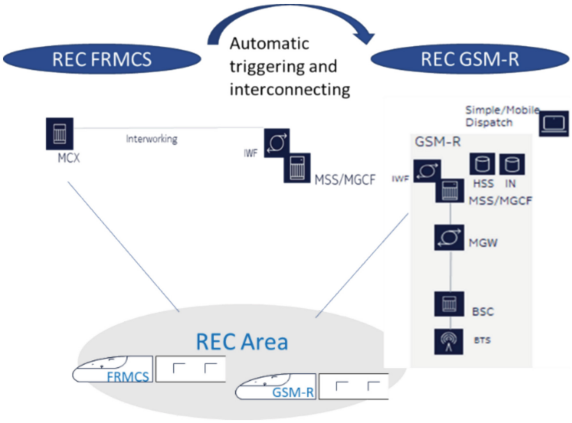



**Fig. 2.** Set-up for GSM-R-FRMCS interworking in 5GRAIL [5] Reproduced with permission from Nokia, copyright Nokia, 5GRAIL Project 2020–2023.

### 3.3 Border Crossing

Trains crossing the border is an essential requirement for FRMCS for the deployment allowing trains seamlessly travelling between the different countries, as currently with the GSM-R system. The implementation of the cross-border is mandatory for the FRMCS to be included in the EU legal frame of TSI. Border crossing was starting to be specified during the preparation of the FRMCS V1 and the work will continue during the FRMCS V2, since it is a particularly difficult topic as it is impacting all the strata. Moreover, some roaming functionalities start to be developed in 5GSA (5G Standalone) ecosystem and were only existing in 5GNSA (non-Standalone).

Cross-border implementation in the scope of 5GRAIL was also a pre-standard one, with two different flavours tested. In Kontron's lab, the multi-connectivity concept was used with the simultaneous usage of two 5G UEs by the On-Board FRMCS gateway of Kontron, achieving a seamless transition from the application point of view. In the same lab, the cross-border was also tested with the On-Board FRMCS gateway of Alstom applying the bearer flexibility with two 5G modems each one configured to a dedicated link and used by the application whenever operational with a given priority, preventing the application of any outage impact [6].

In Nokia's lab, Ng handover was configured using two 5G core systems by Inter Access and Mobility Management Function (AMF), where the active data session was seamlessly moved between the two cores without interruption. Due to the 5GSA capabilities available for 5GRAIL, the two core systems were configured as an intra PLMN setup with one MCX server [6].

The following figure presents the set-up as implemented in both 5GRAIL labs (Fig. 3):

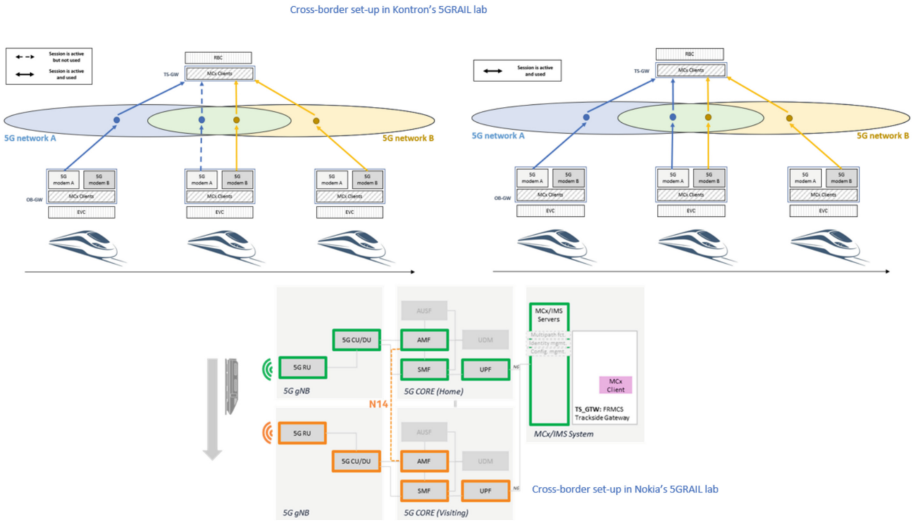



**Fig. 3.** Cross-border set-up in both labs of 5GRAIL [6] Reproduced with permission from Kontron Transportation and DB InfraGo, copyright Kontron Transportation and DB InfraGo, 5GRAIL Project 2020–2023.

## 4 Conclusion

Major steps have been achieved with the finalization of the FRMCS V1 specifications and the first demonstration of them, thanks to the 5GRAIL project. FRMCS V2 specifications and the MORANE-2 will be a challenging and exciting work, leading to mature products ready for the FRMCS pilot systems deployment.

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# 5G Realistic Radio Channel Models for FRMCS Deployment in Railway Environments

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**Abstract.** The Future Railway Mobile Communication systems (FRMCS) is the new system under development, based on 5G-NR, that will replace the GSM-R standard. Its deployment will require the design of new radio engineering tools, which in particular rely on new 3D radio channel models to validate the performance of proposed networking technologies under high-speed conditions, and to perform future radio-planning tasks. The 5GREMORA project aims at developing new measurement-based 3D radio channel models for railways, and demonstrating how new scheduling algorithms can be assessed with those models. The paper outlines the main ambitions of the project; and presents the preliminary results obtained so far.

**Keywords:** 5G · FRMCS · Safe communications · Channel models · Channel sounding · Railways

## 1 Introduction

The Future Railway Mobile Communication System (FRMCS) is designed at European level to answer the increasing needs of Railway in wireless communications. It will be IP based, multi-bearer and resilient to technology evolution and interference. This new system will offer the railway industry a full migration towards 5G as GSM-R becomes obsolete in 2030. Currently, to the best of our knowledge, there is no model of 5G radio channel in the railway frequency bands (RFB) harmonized at European level. 5G railway radio channels in 900 and 1900 MHz bands are not yet characterized and it requires further study. The 5G REMORA project is set up to develop realistic new 5G railway radio channel models enabling FRMCS evaluation and deployment in the railway frequency bands not covered in other 5G related projects. The rest of the paper is

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organized as follows. Section 2 presents the channel sounder systems (CSS) considered. Section 3 details the modelling approach with Ray Tracing. Section 4 highlights the work related to the development of an advanced scheduling technique. Then we conclude.

## 2 Radio Channel Characterization in the Railway Environments

### 2.1 Introduction

Railway environments are very complex and harsh from a radio point of view. Various obstacles or scatterers such as the pylons supporting the catenary, as well as the rapid transitions between different scenarios (cutting/tunnel, cutting/viaduct) can create severe radio impairments. Due to speed, the train can rapidly go through diverse scenarios and a single-environment radio channel model is unable to accurately capture the channel variations. Thus, environment transition must be considered in the railway channel models. Doppler effects and possible interferences due to the proximity of high voltage in the vicinity of the antennas are additional factors that make the railway environments very specific compared to the urban or suburban environments generally considered in standardization groups (3GPP). In addition, to the challenges related to the nature of railway environments, it is important to insist on the fact that the organization of measurements in railway environments is a very challenging task.

In [1], the authors have classified several existing papers dealing with radio channel characterization mainly in HSL environments. The measurements are generally performed over 20 MHz in the LTE band. The measurement-based models proposed are mainly simple TDL (Tapped Delay Line) or CDL (Cluster Delay Line) models generally with no geometric information on angle of arrival or departure of the rays. The ambition of the 5GREMORA project is to build measurement-based 3D stochastic channel models inspired from 3GPP ones complemented by Ray tracing models. Three complementary channel sounders (CS) are considered in the project.

The CEA-LETI owns a unique 4 × 4 MIMO Channel Sounder System (CSS) [2] operating in the frequency band from 10 MHz to 40 GHz with a bandwidth up to 1 GHz and capable of measuring a mobility up to 300 km/h. The CEA CSS is composed of two subsystems, the receiver (Rx) part and the transmitter (Tx) part, each one synchronized with rubidium clocks. Comparing to VNA (Vectorial Network Analyser) method, the Tx and Rx subsystems can be separated at very large distance for propagation measurements and retrieve channel variations to address mobility (Doppler, stationarity, *etc.*). CSS maximum range variates with frequency, e.g. up to 3 km at 800 MHz and 500 m in the Ka band. To realize MIMO measurement, a switching array is implemented on the Tx side while on the Rx side, each antenna has its own RF chain allowing faster capture than switching arrays techniques (Switching @ Tx & Rx sides) and free of inter-symbol interference like in real arrays techniques (parallel @ Tx & Rx sides) [3] (Fig. 1).

Université Gustave Eiffel has recently developed a flexible sub-6 GHz 4 × 4 MIMO reconfigurable channel sounder based on SDR (Software Defined Radio) boards (USRP 2954R) and TDD LTE signal with 1200 pilots on 20 MHz (see Fig. 2). The system includes a base station and a mobile station that should be synchronized using clock distribution via GPS. The complex frequency response of the channel (CFR) is extracted continuously from the LTE signal at the estimation stage. The sampling rate is equal to

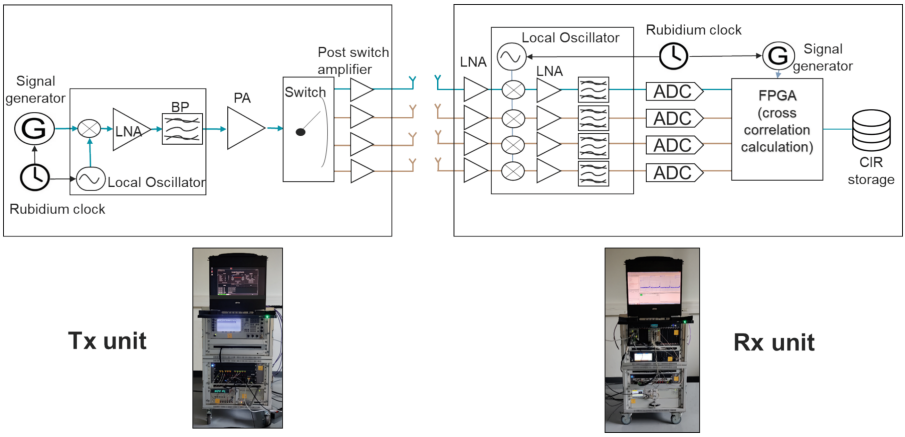



**Fig. 1.** CEA's channel sounder

30.72 MS/s. The sounder can record data during 1 h and it is designed to operate at high speed [4]. Amplifiers and pre-amplifiers are used both at transmitter and receiver sides. Specific railways antennas are used both on the ground and on the train roof.



**Fig. 2.** Sounding signal transmitter (left side) and receiver (right side)

IMT Atlantique has been developing a versatile measurement equipment to study wireless propagation channels [5]. In this project, this equipment is extended to perform passive propagation channel estimation using existing LTE signals. Many base stations from public operators are available along rail tracks, and their frequency bands are close to the FRMCS bands. For that, B8 and B20 LTE Band (10 MHz bandwidth) will be used to explore FRMCS 900 channel. B3 LTE (20 MHz bandwidth) band will be used for FRMCS 1900 band investigation. Main characteristics of these base stations (location, height, antenna orientation, etc.) are available in the public government database. This approach will provide a large amount of data in various and realistic scenarios without a complex setup (no need to deploy transmitters and request frequency allocation). Moreover, MIMO channel estimation will be performed with Cell-Specific Reference Signals, transmitted continuously regardless of the traffic load. The main drawback will be possible interference between base stations. The proposed channel sounder is composed of two USRPs (X310) with UBX daughterboard (Fc 0.01–6 GHz, BW 160 MHz),

a rubidium clock to ensure temporal and frequency synchronization, Huber and Suhner shark antennas located on train rooftop. To validate our system, test measurements have been performed with a car and an antenna array as shown in the figure below (Fig. 3).



**Fig.3.** IMT-Atlantique's Sounding system

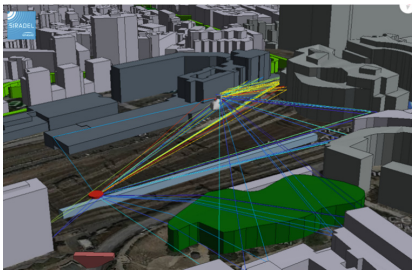


**Fig. 4.** Ray-tracing applied on an urban railway scenario.

## 3 Radio Channel Modeling for 5G-Based FRMCS

The development of radio channel models is an active field of research for 5G NR standard. The models generally give an analytical or stochastic expression of the channel impulse or frequency response obtained thanks to measurements, or may rely on deterministic ray tracing (RT) tools [6]. A complete state of the art on railway channel models is proposed in [7]. The lack of operational 5G MIMO (Multiple Input Multiple Output) radio channel models in RFB bands is highlighted. The ambition of 5G REMORA project is to fill this gap. That is why the wideband dual-polarization MIMO measurements presented in Sect. 2 will be exploited for the construction of new FRMCS statistical MIMO channel models.

Ray-tracing (RT) will complement the statistical modelling approach by emulating the train mobility and spatially-consistent MIMO radio channel variations in real environments. Several works over the last ten years have demonstrated the interest and applicability of RT for railway scenarios, either at sub-6 GHz or in the millimeter-wave band. RT gives the possibility for fast deterministic multi-path-predictions in diverse scenarios, including the urban, cutting and viaduct situations [8]. However, there are still several key challenges, which includes: validation from channel measurements; consideration of dual-polar MIMO; scalability; and capability to combine long-range propagation and strong interactions (by metallic objects) nearby the antenna. An enhanced version of the Volcano ray-tracer is developed to address those challenges. The initial Volcano solution [9] covers rural environments, urban areas, indoors and tunnel scenarios, in sub-6 GHz and millimeter-wave bands; multi-paths and polarized fields are computed to estimate realistic MIMO channels. In the 5G-Remora project, the tool is planned to be qualified and tuned by comparison to the measurements collected in real HST scenarios. Particular attention is brought to the modelling of scattered components e.g., due to poles or catenaries located close to the train antenna. The ultimate ambition is to predict accurate

train-to-infrastructure time-variant spatially-consistent MIMO channel traces, with fine time resolution (possibly 1 ms), based on the tuned RT model. That will be demonstrated in various complex scenarios, e.g., in urban areas (Fig. 4). Preliminary results will be presented at the conference (but without the tuning aspect) that shows the emulated channel variations when the train is travelling in the centre of a large city (Paris).

## 4 Advanced Scheduling Technique

As aforementioned in the introduction, the 5G REMORA project envisions enabling FRMCS evaluation in the railway frequency bands. When deploying FRMCS, it is crucial to pay attention to the requirements of the services to be proposed through FRMCS, e.g., the train virtual coupling or the control of automated train. These requirements are described according to several time-related metrics [10], one of which is the survival time defined as "the time that an application or service consuming a communication service may continue without an anticipated message". The management of multiple nearby trains that compete for the radio resources access is a major challenge to comply with the survival time requirements. Therefore, a scheduler responsible for allocating resources to the trains is essential in the evaluation. The 5G-REMORA project published in [11] a first version of a family of schedulers built on the survival time in a multi-train scenario based on the reinforcement learning approach. The current evaluation assumes a simple model of the radio propagation channel. As the results are promising, as observed in Fig. 5, it is planned to use the radio channel modeling for 5G-based FRMCS, see Sect. 3.

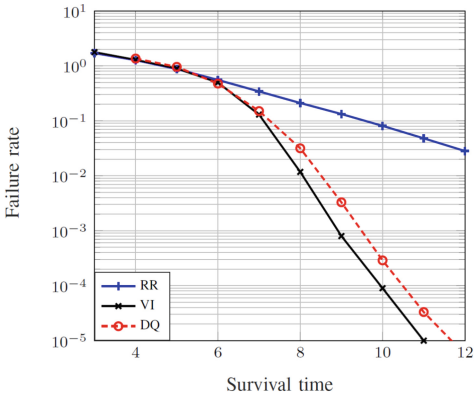



**Fig. 5.** Performance of the scheduling process.

In Fig. 5, the x-axis is the survival time in number of time slots, the y-axis is the number of survival time excesses per time unit. The Round-Robin (RR) is the baseline that allocates the resource to the trains following a buffer of all the trains index. The Value Iteration (VI) and Deep Q-learning (DQ) stem from a reinforcement learning approach.

## 5 Conclusion and Future Works

The efficient deployment of 5G-Based FRMCS along railway lines in the Railway frequency bands, will require the development of new 5G radio channel models. The paper has presented the main objectives and preliminary results of the French project 5GREMORA supported by ANR under Grant n° ANR-22-CE22-0015. The presentation will highlight the measurements results as the first trials is planned in October 2023.

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# Centimeter-Level GNSS Positioning Using C-ITS for Correction Data Delivery: An Experimental Study

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**Abstract.** High-accuracy GNSS (Global Navigation Satellite System) positioning requires the receiver to use correction data. This data is typically delivered via 4G mobile internet. In this paper, we present a novel method to deliver the data via C-ITS (Cooperative Intelligent Transport Systems and Service). We compare its performance against using 4G and analyze the impact on the accuracy during data gaps, all using data collected in test drives from a real deployment in a small segment of a motorway. The results show that with C-ITS, a comparable performance can be achieved. The observed 2D position errors in our tests were below 3.1 cm for 95% and below 10 cm for more than 99% of the time.

**Keywords:** GNSS RTK Positioning · C-ITS · RTCM · automotive · experiments

## 1 Introduction

Accurate and reliable positioning in all environments is important for highly automated driving. For reaching the required positioning accuracy and reliability in automated driving (cf. [1]), different sensor technologies are typically used (see e.g., [2–4]). In this context, Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) can provide valuable global position information with an accuracy that can reach the cm-level (cf. [5]). RTK positioning requires the rover to use different types of measurements and information (typically denoted

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as *corrections*) from a positioning service provider, and typically these *corrections* are sent via Internet/fourth-generation (4G) in the Radio Technical Commission for Maritime Services (RTCM) format. This implies that RTK is not available in regions and areas where 4G is not well deployed.

In the future, systems with an increased level of autonomy will intensively utilize infrastructure support to handle the requirements of the automated driving task. Cooperative Intelligent Transport Systems and Services (C-ITS) play a vital role in this regard for the exchange of information between the vehicles and the road infrastructure. C-ITS, in general, provides benefits in various areas, including improving road safety, reducing congestion, optimizing transport efficiency, enhancing mobility, increasing service reliability, reducing energy use and environmental impacts, and supporting economic development (cf. [6]). C-ITS could also improve the management of urban surface traffic and make it more efficient and safer (cf. [7]). Hence, due to the strong expected development of C-ITS (cf. [8]), it may be an attractive way for RTCM *correction* data delivery for GNSS, which could be used as an alternative or supplement to 4G to expand the RTK coverage. This would significantly increase the availability of high-accuracy localization. In this paper, we experimentally investigate the feasibility and performance of using C-ITS to deliver RTCM messages and compare it with 4G. Therefore, we collected data in a real scenario with a car traversing the highway A2 in Austria. The work has been done in the H2020-EUSPA funded project ESRIUM (cf. [9–11]).

## 2 Experimental Setting

Figure 1 shows a simplified scheme of the main components of the localization process in our experiments and the flow of information. The equipment installed in the vehicle is represented inside a light-orange square on the right-hand side of the figure. Two Septentrio Mosaic X5 GNSS receivers were connected to the same NavXperience 3G+C geodetic antenna via an active splitter and configured

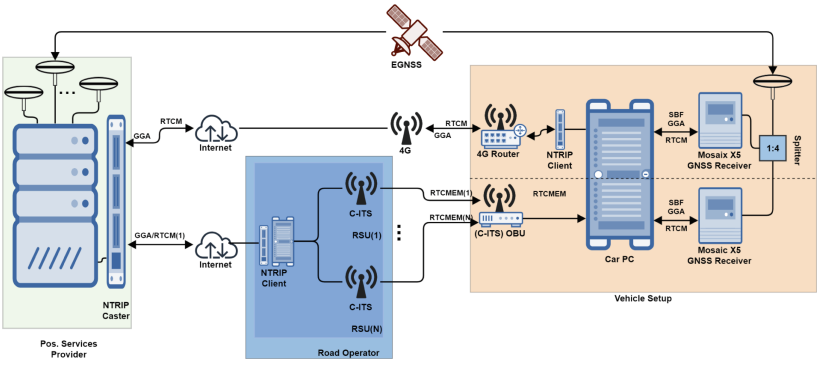
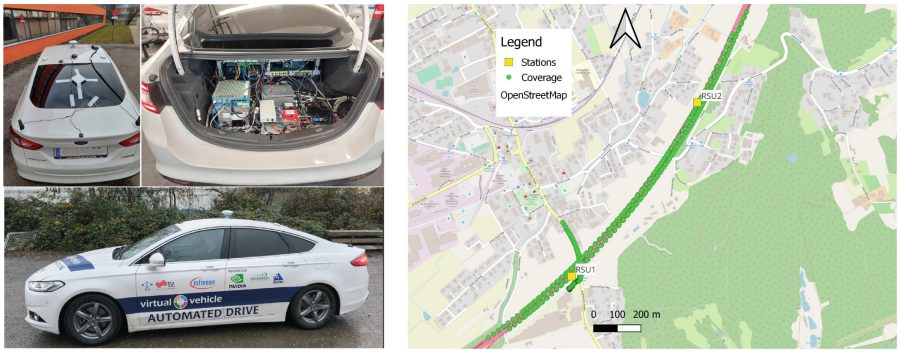



**Fig. 1.** Schematic representation of the information flow.

to compute RTK positions from GPS L1/L2 and Galileo E1/E5a satellite signals with fallback to so-called single point positioning (SPP) at 20 Hz. Thus, the receivers produced so-called fixed or floating positions when RTK was possible depending on whether they could or not solve for the cycle ambiguities (cf. [5]), and SPP when not, where only data from the satellites were used in the position, velocity and time (PVT) computation. Each receiver independently computed RTK positions using the incoming RTCM messages. The upper one received the messages via 4G, and the lower one via C-ITS. The position solutions from both receivers were stored together with additional relevant information for offline analysis. The RTCM messages were generated by the Austrian positioning service provider EPOSA using the virtual reference station (VRS) method (cf. [12]). When 4G was used, the GNSS receiver shared its approximate position with EPOSA using the networked transport of RTCM via Internet protocol (NTRIP). EPOSA then generated RTCM messages with observations corresponding to a hypothetical, not existing (and therefore virtual) receiver located near the user's receiver and sent these messages back to the user's receiver.




(a) Test vehicle setup.

(b) Test region along A2 near Graz. Base map: OpenStreetMap. Generated with QGIS.

**Fig. 2.** Setup.

When C-ITS was used to deliver the RTCM messages, an NTRIP client forwarded a mean position of the testing area to EPOSA's NTRIP caster. EPOSA again generated and sent dedicated RTCM messages to the NTRIP client. The received RTCM messages were forwarded to the road side units (RSUs). Once in the RSUs, the messages were encapsulated in RTCM extended messages (RTCMEMs) according to the C-ITS standard (cf. [13]) and broadcast, received by the on-board-unit (OBU)[1] of cars in the vicinity of the RSUs and then forwarded to the car personal computer (PC), where they were finally converted back to RTCM and handed over to the GNSS receiver. For our test drives, Yunex

[1] vehicleCAPTAIN toolbox, see https://github.com/virtual-vehicle/vehicle_captain.

Traffic prepared two RSUs for sending RTCM messages, which were separated by 900 m along the A2 motorway in Austria, (cf. Fig. 2b).

The motorway in the test region has noise barriers on both sides of the carriageway and in the middle, as well as hills and trees behind the noise barriers.

The used test vehicle is shown in Fig. 2a. In addition to the equipment represented in Fig. 1, a tactical-grade iMAR iNAT-FSLG-01 GNSS/IMU system was installed to generate the ground truth solution.

## 3 Performance Analysis

When comparing the RTCM message delivery via 4G and C-ITS, the mean message age for the C-ITS-based delivery method was around one second larger on average. The minimum observed RTCM data age for both methods was 0.55 s. For 4G, the typical age was 0.55 s rising to 1.5 s until the next RTCM message arrives (RTCM message rate is 1 Hz). For C-ITS, the typical age was 1.55 rising to 2.5 s until the next RTCM message arrives. The analyses showed that the architectural design of the C-ITS demonstrator was leading to this difference. This architecture can be easily optimized for deployment at the production stage.

Figure 3 shows the cumulative distribution function (CDF) of the horizontal (2D) position errors, Table 1a their 95 and 99.5% percentiles together with the availability of positions with errors below 10 and 20 cm, and Table 1b the percentages of position types obtained. From the tables and figures, we see that the percentage of RTK-fixed solutions is very high in both approaches (98.78% and 98.90% when using 4G and C-ITS, respectively) and that their accuracy is comparable, with errors below 10 cm for more than 99% of the time. This implies that the additional latency when using C-ITS did not significantly impact the accuracy. For PVT solutions with errors above 10 cm, the reliability of the receiver is very good always reporting a correct (overbounding) error estimate when applying a factor of 2.5 to the standard deviation.

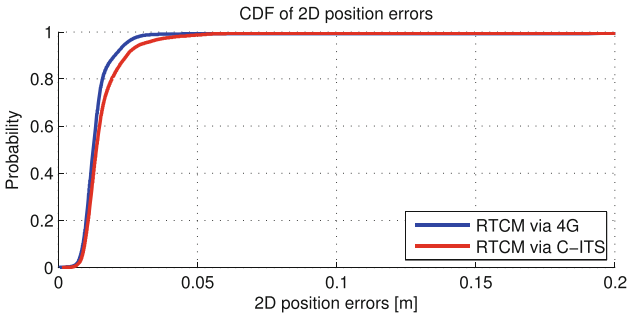



**Fig. 3.** CDF of 2D position errors for both solutions.

**Table 1.** Horizontal errors and occurrence frequency of position types.

(a) 2D position error statistics

| **Sol.** | **95%** | **99.5%** | **≤ 10 cm** | **≤ 20 cm** |
|---|---|---|---|---|
| 4G | 2.4 cm | 37.9 cm | 99.2% | 99.3% |
| C-ITS | 3.1 cm | 43.4 cm | 99.4% | 99.4% |

(b) Occurrence of position types

| **Sol.** | **No fix** | **SPP** | **RTK Float** | **RTK Fix** |
|---|---|---|---|---|
| 4G | 0.42% | 0.44% | 0.35% | 98.78% |
| C-ITS | 0.39% | 0.45% | 0.25% | 98.90% |

Some issues in our setup allowed us to investigate the impact of RTCM data gaps on the position accuracy. Such gaps typically occur in urban and suburban situations. In theory, a GNSS RTK solution requires continuous RTCM data and a little data delay for optimal performance. The test data shows that as long as an integer fix was possible, the Septentrio Mosaic X5 GNSS receiver was able to keep the 2D position errors below 20 cm up to 50 s. For float solutions, the errors stayed below 50 cm if the initial float solution was stable, otherwise, the errors can be as large as 22 m (maximum observed horizontal error of a float solution) (for details, cf. [11]).

This robustness against small coverage gaps increases the usability and suitability of RTK for high-accuracy positioning in automotive applications using both, 4G and C-ITS data links.

## 4 Conclusions

In summary, the observed horizontal position errors in our tests were below 10 cm for more than 99% of the time using either 4G or C-ITS as long as a data link was present and the transmission delays remained reasonably small. Gaps of a few seconds can be bridged by modern mass-market GNSS receivers like the used Septentrio Mosaic x5 while still maintaining a significant accuracy (better than 10 cm in our tests). For gaps of up to 50 s, the error could be kept ≤20 cm under specific circumstances. In addition to confirming the feasibility of using C-ITS for RTCM message delivery, this relatively large tolerance to communication delays enables the use of different and complementary data links for the delivery of the necessary RTCM *corrections*, and lowers the barrier to the spreading of RTK positioning for high accuracy in automotive applications.

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# Time Matters: Evaluating a Road Operator Event Management System Using Vehicle eCalls

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**Abstract.** This study investigates the potential integration of eCalls, mandated by the eCall Legislation for vehicles from March 31, 2018, into road operator Incident Management Systems (IMS). We utilize eCall data from the "SRTI Ecosystem" and match it with IMS incidents to verify the eCall data and enhance the IMS with the most accurate available timestamp for accident occurrence. To assess the potential temporal gains of eCall integration, we introduce a metric to quantify the time saved by incorporating eCalls into event management systems. The proposed metric was evaluated over a three-month period in 2023, and the results indicate that integrating eCalls into IMS is a viable step to expedite the incident management process.

**Keywords:** SRTI · Traffic & Incident management · eCall

## 1 Introduction

To enable the timeliest driver and emergency service alerts following vehicle crashes, the so-called eCall Legislation was introduced [1]. Consequently, vehicles with type approval from March 31st, 2018, onwards must be equipped with an eCall system, which utilizes onboard sensors and communication technology to detect a crash and send an automated signal that includes the vehicles position and the time of the accident to a predefined emergency response center.

This paper aims to use eCalls by matching each event to corresponding incidents in a road operator Incident Management System (IMS), to verify the eCalls and to subsequently evaluate the potential of an integration of eCalls into the IMS.

To achieve this the authors have used eCall data from the "SRTI Ecosystem" (SRTI – safety related traffic information, DFRS – Data for Road Safety [2]), an EU-initiated partnership of EU transport ministries, Service Providers of traffic data and the automotive industry to pool SRTI Data for common use and free of charge. Every eCall is matched to the corresponding entries in the incident management system of Austria's highway operator ASFINAG. Currently, certain key temporal parameters are either unknown or not available in the IMS, including the exact time when:

- an accident occurs or
- emergency vehicles are dispatched by the operator.

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However, one consistent piece of information at our disposal is the timestamp of insertion into the IMS. The transmission of eCalls allows us to benchmark the performance of the event management chain, by measuring the delay between the time of the actual accident and the event was reported to and verified by the road operator staff. Since every minute is crucial in post-crash-responses, the potential for speeding up the process using automatically or manually triggered eCalls is investigated in this survey. We consider data limited to the Austrian highway network in the period from June to September 2023.

## 2 Related Work

The Fatality Analysis Reporting System (FARS) [3] is a comprehensive database that collects and maintains data on fatal traffic accidents within the United States, dating back to 1975. FARS data is extensively used to study the relationship between emergency response times and traffic accident outcomes, such as mortality and severity of injuries.

In [4], they investigate the evolution of emergency response times for highway accidents from 1975 to 2017, utilizing data from FARS. Their findings suggest a significant 50% improvement in response times, highlighting the potential impact of reduced response times on highway accident outcomes.

Utilizing the 2015 version of the FARS dataset, the study [5], found that the relationship between emergency medical service (EMS) response time and fatality odds is non-monotonic, with two critical thresholds: 5.5 min, the fastest decline in the chance of survival, and 17 min, the "gold time" for operating rescues. This suggests that accurately assessing the urgency of different crash scenarios is important for understanding the impact of response times on survival.

Similarly, the European baseline report defines several key performance indicators (KPIs) for road operators, one of which is post-crash care (i.e., the time elapsed between the emergency call and the arrival of emergency services, to the 95$^{th}$ percentile (P95)). In 2019, the post-crash-care KPI for Austrian highways was 28 min and 54 s [6].

The critical time thresholds pose an ambitious but desirable temporal target for minimizing the death toll and increasing the effectiveness of post-crash care. Because the post-crash-care KPI is widely used to assess emergency service response times, we incorporate a variation of this metric in our analysis, with the long-term goal of benchmarking the entire event management chain from accident to arrival of road operator vehicles at the accident location. At this point in time only the part of the incident management chain is investigated between the accident and the first entry into the event management system of a road operator.

## 3 Methodology

The development of the matching script was guided by the datascience process. Understanding the data was not just a matter of exploratory data analysis but required a thorough investigation of the inner workings of the entire event management chain, achieved by frequent discussions with domain experts. This led to the following steps in the processing pipeline, summarized in Table 1 (Fig. 1).

**Table 1.** Data sources and preprocessing required for matching.

| | eCalls | Road operator events |
|---|---|---|
| Data Source | DFRS [2] | EVIS [8]<br>following DATEXII [9](requires parsing) |
| **Pre-Processing** | | |
| Event type filtering | Only keep eCalls | Only keep situations including accidents in their chronology |
| Duplicate elimination | Only keep first occurrence of event (reduction from 308 to 165 events) | Extract start and end of time and kilometer position on the road |

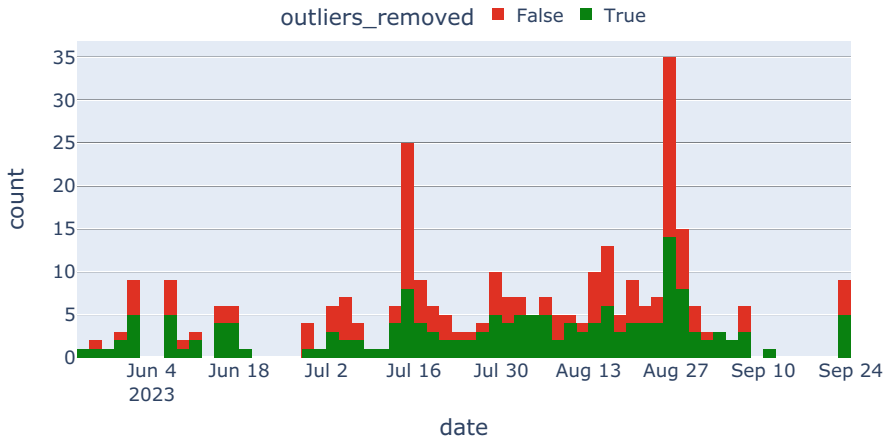



**Fig. 1.** eCall data availability overview (before and after duplicate elimination)

### 3.1 Matching

While the eCalls consist of event singular in location and datetime, the road operator events stretch over periods of time and road segments. A match occurs if the time and space of events from both sources overlap, with respect to a margin window (deltas).

The matching conditions are:

```
1. eCall.road == EVIS.road
2. eCall.time_stamp is in Interval(EVIS.start_time,
EVIS.end_time)
   +- time_delta
3. eCall.meter is in Interval(EVIS.start_meter,
EVIS.end_meter)
   +- meter_delta
```

Due to the inaccuracy in GPS positioning, the direction of the eCalls cannot be reliably map-matched to the graph representation of the highway network, prohibiting us from including the following matching rule:

```
4. eCall.direction == EVIS.direction
```

### 3.2 Metric

To assess potential temporal gain by incorporating eCalls into event management systems, we introduce the 'eCall-Gain' metric, which adjusts the post-crash KPI defined in [7] to align with our specific use case. We define it as:

'The time elapsed between the eCall following a collision and the timestamp of the first entry into the event management system of a road operator. The measurement unit is in minutes and seconds, calculated to the following percentiles: $25^{th}$, $50^{th}$, $75^{th}$, $85^{th}$ and $95^{th}$, over all matched events.'

The timestamp $t_{EVIS}$ is the timestamp of the insertion into the IMS, $t_{eCall}$ refers to the reported timestamp of the eCall. We denote the sorted data set of all temporal gains as $\Delta_t$ with N as the total number of matched events:

$$\Delta_t = \{t_1, t_2, \ldots, t_N\} where\, t_1 \leq t_2 \leq \cdots \leq t_N \tag{1}$$

$$t_i = \left| t_{EVIS,i} - t_{eCall,i} \right| for\, \forall i \ldots n \in \mathrm{N} \tag{2}$$

The Quantile Q(q) for a given percentile q is calculated finding the Index I and in case of non-integer value interpolating between adjacent datapoints. $m$ denotes the integer and $\alpha$ the fractional part. The following quartiles are calculated {0.25,0.50,0.75,0.85,0.95}:

$$0 \leq q \leq 1 \tag{3}$$

$$I = q\,N = m + \alpha \tag{4}$$

$$Q(q) = t_m + \alpha * (t_{m+1} - t_m) \tag{5}$$

## 4 Results and Discussion

The eCall-Gain for automatic (26 tuples) and manual eCalls (10 tuples) and an average of both was calculated for all proposed percentiles, using linear interpolation with the percentiles that lie between two data points. The results can be found in Table 2. It has to be noted that in our used dataset, the eCalls are only available from a single car manufacturer, and while higher sample sizes and longer observation intervals are required for strong statistics, it has to be reiterated, that behind each of the counts in Fig. 2. Gain in minutes of DFRS over IMS, duplicates and outliers eliminated in DFRS, separated into automatic and manual eCalls, is an eCall, for which we found a corresponding entry in the IMS. Thereby the accident was verified, which implies that knowledge about the accident could have been obtained minutes earlier, which is highly relevant in case of especially heavy accidents.

**Table 2.** Results for all eCalls (total average, manual and automatic)

| Percentile | 0.25 | 0.50 | 0.75 | 0.85 | 0.95 |
|---|---|---|---|---|---|
| eCall-Gain avg | 9 min36 s | 12 min 46 s | 16 min 49 s | 19 min01 s | 25 min 42 s |
| eCall-Gain automatic | 10 min 35 s | 13 min 54 s | 16 min 43 s | 17 min 5 s | 23 min 25 s |
| eCall-Gain manual | 7 min 23 s | 10 min 37 s | 18 min 40 s | 23 min 32 s | 26 min 17 s |

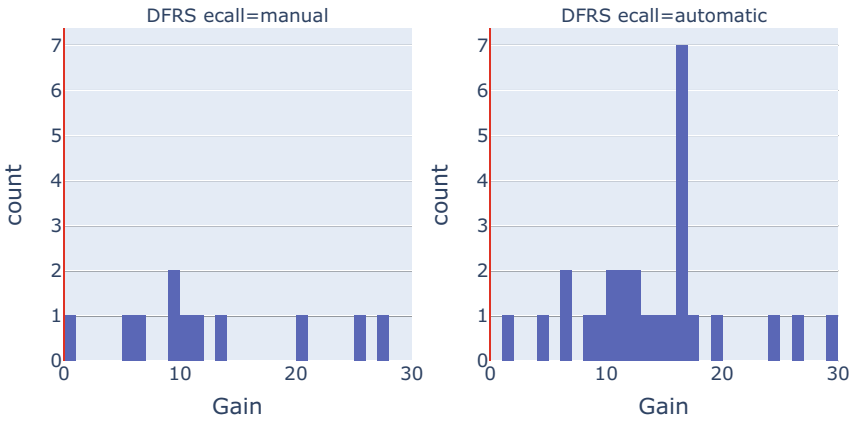



**Fig. 2.** Gain in minutes of DFRS over IMS, duplicates and outliers eliminated in DFRS, separated into automatic and manual eCalls, a Gain of 0 would refer to the two independent systems being synchronized.

Our understanding of the rest of the event management chain, namely the distribution of the differences of timestamps in the event management system and the timestamp of arrival at the accident location on the other hand is still lacking. Interviews with domain experts have raised several concerns. Frequently, emergency vehicles are dispatched or even arrive at the accident location before the entry is recorded in the road operator's database. To address this issue, an evaluation of the distribution or precise arrival times at accident scenes can be obtained using alternative data sources, which were not available at the time of the conduction of our investigation. Further refinement of the eCall gain metric will be explored by employing technologies such as C-ITS Communication to obtain precise timestamps for the arrival of road operator vehicles at accident locations. Preliminary exploratory analysis in this field has produced promising results, and we plan to conduct future research in this area, to better understand and then benchmark the ent+ire incident management chain.

## 5 Conclusion

In conclusion, our approach to matching eCalls with accident data in Incident Management Systems has allowed us to evaluate our proposed metric, known as eCall gain. We have also found that our verification and benchmarking processes are applicable.

Looking ahead, we plan to expand our analysis by considering longer time intervals, with our current results serving as a promising proof of concept. These findings are well-positioned to contribute to the integration of eCalls into the Incident Management Systems (IMS) more effectively. By bridging the gap between eCalls and accident data, our work has the potential to enhance eCalls by enriching it with informations about impacts of an accident that is available in an IMS such as lane closures, traffic jam sizes, influence on travel times, and to improve the event management chain by reducing response times in a digitally connected world, in order to enhance road safety.

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# Neuronal Networks to Analyze Accessibility and GPS Data: A Case Study of Santo Domingo

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**Abstract.** This paper analyzes the impact of Accessibility based on GPS data for both motorized and non-motorized modes on distance traveled by private and public transport users in developing countries. The data was collected from a mobile phone app called Inertia. A neural network model was developed for the dependent variable distance. The independent variables are the Level of Service (time, speed) measured via GPS data, public transport (e.g., distance to the nearest station, number of stops/stations within the catchment area) called PT Availability, and accessibility (off-peak and peak neighborhood and station accessibility). The results show that the type of station and neighborhood peak access promotes better modeling of the distance.

**Keywords:** Accessibility · Sustainable · Transport · Distance-travelled · Neural networks

## 1 Introduction

Several factors influence the use of public transport in developing countries. For example, distance to stations/stops can be a primary deterrent to using massive public transport modes (e.g., metro and train). At the same time, short-distance trips are more likely to be undertaken by informal public transport (PT) modes (e.g., public cars or shared taxis). Studies have shown that distance can have positive and negative effects on the choice of destination (Xue & Zhang, 2020); therefore, we have determined that distance is critical when making any trip, and its modeling is a priority. Distance as travel pattern recognition has been analyzed, considering its correlation with activity complexity (Joh et al., 2001). Although travel time and travel cost are essential representations of the level of service, distance is often used as a measure of friction. Access and egress to public transport stations are significant challenges for developing countries. In the Dominican Republic, gathering mobility data is a challenge for the transportation authorities; and monitoring daily volumes of trips is a pending task. Government significant invest on infrastructure. Therefore, it is important to develop data collection methods to analyze accessibility and monitor travel patterns, which will encourage more tailored services to the specific demand.

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This study examines how different levels of accessibility influence travel patterns, using traveled distance (per trip) as the dependent variable. The paper is based on GPS data collection in Santo Domingo using a smartphone app named Inertia. Four types of accessibility are developed in the present paper: off-peak and peak accessibility of public transport (station accessibility) and neighborhood off-peak and peak accessibility. The dependent variable is the trip distance retrieved from GPS data collected with the mobile phone application. Additionally, neural network models were created, and the peak hour and off-peak hour variables will be used for modeling.

## 2 Literature Review

Accessibility has been explained in the literature as a composition of spatial, temporal, transport, and individual components. Accessibility uses GPS data and measurements of access and egress. At the same time, GPS data represents substantial advantages for travel demand models that have not been present in accessibility models.

### 2.1 Transport Component, Spatial Component, and Station Class

There is a long discussion on accessibility measures and impedance functions, e.g., negative power, Gaussian, and log-logistic. Certain parts allow better behavioral representation, such as the S-shaped conventional logistic function (Geurs et al., 2016). The importance of having a distance decay function represents that shorter trips are more likely to be undertaken than more extended trips. Similarly, closer facilities are more likely to be chosen than farther ones. In the present paper, a distance decay function is estimated based on the observed trips.

Classification of public transport nodes or stations means specific nodes are better positioned in the transport network than others. This classification can infer the population, jobs, or other amenities reachable from specific nodes or zones. Similarly, to represent station class and spatial components of accessibility, the study by Luo et al. (2017) aims to combine stops at a micro-level and not aggregate stops at a zone level. In the present paper, we incorporate population as a spatial component, and we develop a cluster indicator of public transport station class.

### 2.2 Neural Networks

The concept of a "neural network" describes a collection of loosely related models that share common characteristics, including an ample parameter space and a flexible structure, which are inspired by studies on the brain's functioning (IBM, n.d.). In this study, we cover neural networks by modeling distance through variables such as speed, time, among others.

## 3 Data Description

In the Dominican Republic, public transport can be described as organized public and informal public transport. Organized public transport refers to the autobuses in the OMSA network and adjacent corridors with determined stops.

Our study used open street maps and road networks. We enriched this data by adjusting the speed per link to the collected speed values by the Inertia app. The travel times between OD pairs were calculated with the tool Network Analyst in ArcGIS.

We have worked with 743 trips, using neural networks for a total of 458 users, and more than 63 users undertaken more than ten trips. The dependent variable in the model is distance. For the selection of independent variables, consider the following:

- Time and Speed: retrieved from the Inertia app.
- Neighborhood peak and off-peak accessibilities: these variables are calculated to determine the connectivity between neighborhood centers during peak and off-peak hours.
- PT availability: variable showing which trips have public transport stop buffers nearby.
- Mode as motorized or non-motorized transport: this variable indicates whether motorized or non-motorized modes undertook the trip.
- Station peak and off-peak accessibilities: these variables are linked to the accessibilities of a station during peak and off-peak hours.
- Station type: a cluster analysis was developed to classify the PT stations. In this, the variables of public transport services (OMSA, Santo Domingo Metro, and Teleferic, known as cable car in English) and number of trips detected during peak hours were used.

We estimated the following models:

- Model 1: includes the explanatory variables neighborhood peak accessibility, time, and speed.
- Model 2: the model includes the explanatory variables neighborhood off-peak accessibility, time, and speed.
- Model 3: the model includes the explanatory variables neighborhood peak accessibility, time, PT Availability, motorized and non-motorized, and speed.
- Model 4: the model includes the explanatory variables neighborhood off-peak accessibility, time, PT Availability, motorized and non-motorized, and speed.
- Model 5: the model includes the explanatory variables neighborhood peak accessibility, time, PT Availability, motorized and non-motorized, speed, and Station type.

## 4 Analytical Framework

### 4.1 Modeling Accessibility

In this paper, we measure the accessibility of access/egress modes and main modes as a zone to zone and station zones, respectively.

Based on the literature review, we have selected the log-logistic function for this study. This function shows smoother change probabilities, similar to behavioral effects of increasing distances or travel times. The following function has been used to estimate the probabilities (F) based on the travel times ($t_{ij}$) from zone i to zone j in Eq. 1:

$$F\left(t_{ij}\right) = \frac{1}{1 + exp(a + b\, ln\, t_{ij})} \tag{1}$$

where a and b are parameters to be estimated with a log-logistic regression, the estimation has been done in the statistical software package SPSS. The values of the parameters a and b are used in the calculation of the Accessibility accumulated value as follows in Eq. 2:

$$A_i = \sum_j F\left(t_{ij}\right) * P_j \tag{2}$$

Neighborhood accessibility is the weighted sum of the population (($P_j$) reachable by the impedance (weighted by the probability) of travel times from origin i (neighborhood centroid) to destination j (neighborhood centroid). The speeds obtained from the GPS data are added to the accessibility to account for the area's real congestion levels and impedances. Additionally, peak-hour and off-peak-hour speed measurements were broken-down to calculate peak and off-peak accessibility, where the peak hours are from 6:00 a.m. to 9:00 a.m. and from 5:00 p.m. to 7:30 p.m.

In the station accessibility, the origin zones will be the stations, and the destination zones j will be the (remaining) zones of residential areas. The impedance curve is based on the measured travel times of the non-motorized modes and calculated per mode.

### 4.2 Modeling Neural Networks

For the neural models, we used three types of partitions based on previous works (IBM, n.d.):

- The training set: the training sample comprises the data records used to train the neural network. It must be greater than the test.
- The test sample: is an independent set of data records used to track errors during training to avoid excessive training.
- The holdout sample: provides a truthful estimate of the model's predictive ability.
- In our case, MLP was used, a powerful and flexible model that can learn complex non-linear relationships between input and output variables. The hyperbolic tangent was used in the network.

## 5 Results

We conducted a cluster analysis on public transport stations, categorizing them into two distinct groups:

- Group 1: This group shows higher average values for services (OMSA and Teleferico) and lower average values for number of trips detected during peak hours and Metro within the catchment area.
- Group 2: This group shows higher average values for service (Metro) and number of trips detected during peak hours and lower average values for services (OMSA and Teleferico) within the catchment area.

The catchment area is the radius covered by the buffer. These variables have been addressed by lines of the different modes of transport, not by stops, and the service options have been taken within the catchment area, which is a buffer of 1200 m around

the station. We can conclude that Group 2 contains the main public transportation and the greater flow of vehicles. This suggests that these stations are the busiest, with Group 2 having a more advantageous position than Group 1 due to higher vehicle traffic.

The north and northwest areas of Gran Santo Domingo (GSD) have the highest accessibility in the region. These areas are generally low-income, except for the northwest region, which boasts middle-to-high incomes. Most zones with higher accessibility tend to be significant commercial or industrial development areas with a nearby metro station. In contrast, areas with low accessibility are located in the southern part of GSD and are predominantly residential. The zones with the highest accessibility are located in the center and east of Gran Santo Domingo. In contrast, the least accessible stations are located in the north or nearly outside the GSD (Fig. 1).

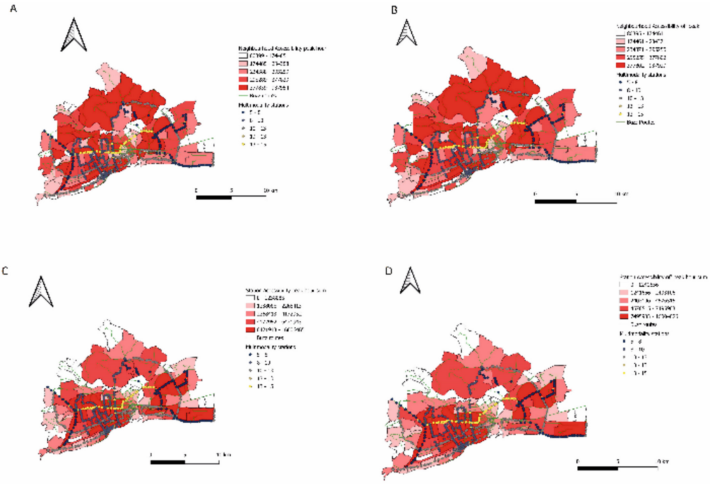



**Fig. 1.** Neighborhood and station accessibility. Source: own elaboration

We have worked with five models, and these are (Table 1):

**Table 1.** Neural networks.

| Relative error | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|---|---|---|---|---|---|
| Training | 0.059 | 0.059 | 0.059 | 0.059 | 0.013 |
| Test | 0.132 | 0.132 | 0.132 | 0.132 | 0.014 |
| Holdout | 0.068 | 0.130 | 0.016 | 0.195 | 0.011 |

Models 5, 3, and 1 have demonstrated lower relative errors for holdout partitions, which can be considered positive for modeling. Therefore, the "Station type" and "Neighborhood peak accessibility" variables significantly impact the distance traveled positively. Using Model 4 is not recommended because of its substantial relative errors; consequently, the use of "Neighborhood off-peak accessibility" is not advised.

## 6 Conclusions

This paper presented an innovative method by investigating accessibility within a developing country, notably the Dominican Republic, an aspect that had not been deeply studied in developing countries. The study highlighted the relationship between distance traveled, accessibility, and the transport infrastructure, such as the metro, which enhanced accessibility in some areas. Our analysis illustrated the interaction between distance, peak and off-peak accessibility, time, and speed. Models 5, 3, and 1 emerged as the best for modeling. A model that integrated peak-hour data provided more reliable results. Furthermore, Public Transport station type represents a key factor in the distance traveled by motorized modes.

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# Autonomous Heavy-Duty Vehicles in Logistics: Market Trends, Opportunities, and Barriers

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**Abstract.** This paper presents a comprehensive market research study focused on identifying opportunities and barriers for the adoption of autonomous heavy-duty vehicles (AHDVs) in the logistics industry. The methodology employs a qualitative approach, utilizing workshops, questionnaires, interviews, and social media polls to collect primary and secondary data. The empirical findings highlight both the current landscape and the future trends in AHDVs, fleet management, and logistics. The study reveals the importance of safety, technological readiness, regulatory challenges, and infrastructure development as key barriers, while also showcasing potential benefits like increased safety, reduced costs, and improved efficiency. Furthermore, a quadrant analysis prioritizes these opportunities and barriers for strategic decision-making. The article concludes by discussing the implications of the findings and the broader context of autonomous vehicles in logistics.

**Keywords:** Autonomous Heavy-Duty Vehicles (AHDVs) · Logistics · Barriers · and opportunities

## 1 Introduction

The integration of autonomous heavy-duty vehicles (AHDVs) represents a transformative shift within contemporary logistics and transportation. With the potential to enhance operational efficiencies in global delivery networks, AHDVs have emerged as catalysts for reshaping supply chain dynamics, logistics strategies, and material handling. Amid these advancements, navigating challenges becomes crucial.

AHDVs, endowed with autonomous capabilities, hold promise for streamlining material flow paradigms. Yet, their integration is impeded by multifaceted challenges, requiring an understanding of market dynamics, legal complexities, and technological advancements. This paper explores the landscape of AHDVs in logistics, shedding light on market dynamics and insights for integration. Rooted in a comprehensive three-year market analysis, it delves into AHDVs' interaction with logistics through literature reviews, workshops, interviews, and desk research.

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Research question: "**What are the significant market trends, barriers, and opportunities associated with the integration of autonomous heavy-duty vehicles within the logistics sector?**" By examining market trends, barriers, and opportunities, this study contributes to understanding AHDVs' role in logistics and aids stakeholders in navigating their integration.

## 2 Methodology

We adopted a qualitative approach to analyze the integration of AHDVs in the logistics sector. Creswell [1] suggests that this approach is well-suited for capturing the diverse perspectives, experiences, and insights of stakeholders, enabling a thorough exploration of the research problem. Our research process included several distinct phases: problem definition, research design, data collection, analysis, and reporting, as outlined by Sekaran [2]. The initial phase, Problem Definition and Objective Setting, focused on identifying market trends, barriers, and opportunities to aid decision-making at consortium and partner levels. The Research Design and Approach phase used a qualitative method due to its exploratory nature, which supports extensive data collection and analysis. This phase involved gathering both primary and secondary data for a comprehensive understanding, as recommended by Denzin and Lincoln [3].

Data Collection was critical, utilizing structured surveys, questionnaires, interviews, workshops, and social media polls to capture specific opinions and insights from industry professionals, experts, and practitioners. The variety of data collection methods, as detailed in Table 1, allowed us to gather a wide and deep range of perspectives. Neuman [4] notes that using multiple data collection methods enhances the data pool and the credibility of the findings. A thorough analysis of secondary data, including academic papers, reports, and business publications, helped establish a broad contextual framework that supported the authenticity of the primary data.

During the Data Analysis phase, we transcribed interviews and surveys to accurately capture key insights. We then used open-coding to identify initial themes and patterns, following grounded theory [5]. This process led to a thematic analysis, as Braun & Clarke [6] describe, where codes were grouped into broader themes that highlighted recurring relationships and insights. We maintained accuracy and consistency through the constant comparison method [7], comparing themes across different data sources. The final stage involved interpreting these themes in relation to our research objectives, offering a nuanced understanding of our findings.

In the Reporting and Communication phase, we aligned our presentation of findings with our research goals, incorporating relevant literature and direct quotations. The implications were discussed to encourage a detailed discussion on AHDVs in logistics, and the outcomes were shared with partners to improve the overall project results.

**Table 1.** Data Collection Methods.

| Data Collection Method | Focus | Participants | Method Description |
|---|---|---|---|
| Social Media Polls (LinkedIn) | Automation in logistics operations to AVs market readiness | 234 responses | Weekly polls to gather insights on different automation topics |
| Workshop | Drivers, barriers, and opportunities for AHDVs in logistics | Various consortium partners, around 36 (manufacturers, research institutes, consultancy firms, etc.) | Interactive survey using Mentimeter and collaborative session using Metroretro |
| Online Survey (Mentimeter) | Identification of barriers, opportunities, and drivers of automated HDVs in logistics | 16 partners | Survey to identify barriers, opportunities, and drivers |
| Interviews with Project Partners | Barriers and opportunities to connected and autonomous HDVs in real logistics operations | 11 key opinion leaders (ports, civil aviation, fleet management, automotive industry) | In-depth interviews for first-hand data on market dynamics |

## 3 Findings

### 3.1 Trend Analysis

Regarding trends, the authors did a preliminary analysis focusing on two main sources: (1) the DHL Logistics Trend Radar [8] and (2) the Trendmanager expert database [9]. The DHL Logistics Trend Radar is based on over 13,000 DHL customers, partners, and employees who visit the DHL Innovation Centers every year, providing DHL experts with invaluable feedback to develop the DHL Logistics Trend Radar. The Trendmanager tool helps companies and projects, as AWARD, to identify and systematically monitor the trends that are relevant for them. Furthermore, interviews with project partners of the EU H2020 project AWARD (All Weather Autonomous Real logistics operations and Demonstrations - https://award-h2020.eu/) regarding AHDVs were conducted. The trend radars revealed multiple relevant trends. For example, the Trendmanager tool identified 16 megatrends (see Fig. 1) related to "Autonomous vehicles in logistics" and 11 connected macrotrends. In general, both trend analysis tools provided similar aspects. Self-driving vehicles combined with intelligent infrastructure and (fleet) management components as well as sustainable logistics are core trends.

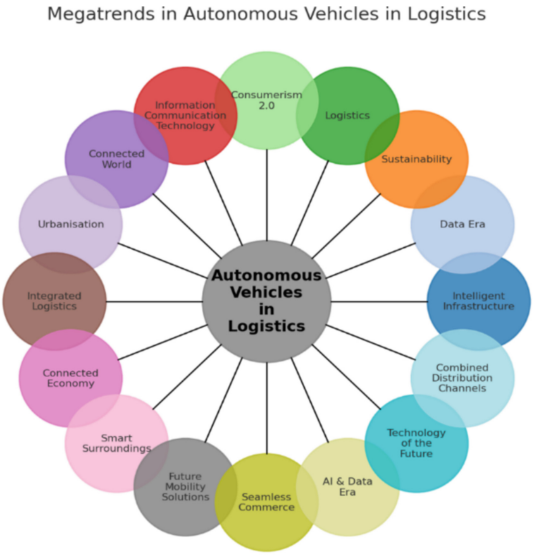



**Fig. 1.** A16 Megatrends identified related to autonomous vehicle in logistics.

Based on the four AWARD use cases (Hub-to-hub, Port, Airport, Forklift), the main outcomes for Porter's Five Forces [10] are as follows: Supplier Power is low due to products not being market-ready; Buyer Power is also low, driven by limited demand from innovators only; the Threat of New Entry ranges from medium to high due to numerous potential new tech entrants; the Threat of Substitution remains low, given the scarce availability of alternative products; finally, Competitive Rivalry is intense, fueled by competition among highly innovative companies and R&D projects.

### 3.2 Opportunities and Barriers Analysis

**Opportunities Analysis.** Some of the main opportunities identified are:

*Enhanced Safety:* A paramount opportunity arising from AHDVs lies in their potential to enhance safety within logistics operations. AHDVs, equipped with advanced sensors and real-time data processing capabilities, hold the promise of minimizing human errors and reducing the likelihood of accidents. This translates into a safer working environment, safeguarding human lives, and minimizing the risk of costly disruptions [11].

*Cost Reduction:* The integration of AHDVs carries the potential for substantial cost reduction in both transportation and labor. AHDVs' capacity for optimized route planning and efficient driving behavior can lead to decreased fuel consumption and operational expenses. Additionally, the elimination of the need for human drivers can result in significant labor cost savings, making logistics operations more financially viable.

*Resource Optimization:* AHDVs' continuous operation and ability to adhere to driving-hour regulations offer opportunities for enhanced resource utilization. This translates

to improved vehicle and driver utilization, thereby increasing the overall efficiency of logistics operations. The potential for extended driving hours and reduced downtime can lead to more streamlined and productive supply chain management [11].

*Customer-Centric Supply Chains:* AHDVs have the potential to reshape supply chains into customer-centric entities. By mitigating factors such as driver rest periods and human-caused accidents, AHDVs enable more streamlined material flow and efficient service delivery. This can lead to improved customer satisfaction, reduced delays, and enhanced overall supply chain performance [12].

**Barriers Analysis.** Some identified barriers are:

*Technological Barriers:* Technological immaturity poses a significant challenge to deploying AHDVs in non-protected environments, particularly when inadequate infrastructure is present. Challenges like GPS connectivity issues and the lack of reliable 5G networks hamper AHDV scalability. Integrating diverse sensors such as LiDAR, cameras, and radar, crucial for safe AHDV operations, presents another hurdle.

*Security and Safety:* Ensuring safety in AHDV operations encompasses preventing collisions with pedestrians and vehicles and implementing emergency stop systems. Robust cybersecurity measures are essential to safeguard AHDVs from cyber threats and unauthorized access. Ethical considerations also arise, with the challenge of defining AI decision-making in unavoidable accidents.

*Infrastructure and Regulatory Challenges:* The insufficiency of adequate infrastructure for mass commercialization of AHDVs without excessive investment remains a barrier. Regulatory frameworks lack uniformity, posing complexities across various jurisdictions. The EU's requirement for a driver's continuous responsibility on public roads hampers AHDV adoption. Establishing criteria to verify the safety of AHDV systems for licensing is also an unresolved concern.

*Liability and Ethical Concerns:* Liability attribution in case of accidents involving AHDVs remains unclear. As automation advances, liability is expected to shift from drivers to manufacturers. However, issues may arise during the transition phase when both human drivers and automation systems control vehicles. Ethical challenges arise from AHDVs' decision-making in inevitable accident scenarios.

*Employment and Organizational Changes:* The transition to AHDVs could disrupt employment structures, necessitating new skills and training for maintaining and operating autonomous systems. The restructuring of roles and responsibilities poses a potential barrier.

*Privacy and Economic Factors:* Privacy concerns linked to data collection and potential cyber-attacks on AHDV systems introduce additional complexities. High manufacturing costs, significant infrastructure investment, and the expenses associated with training qualified personnel are formidable economic barriers.

**Quadrant Analysis of Opportunities and Barriers**

The quadrant analysis of barriers and opportunities for AHDV integration in logistics

presents a detailed overview, highlighting the interaction between various challenges and potential gains in a dynamic logistics environment. Key barriers span technological, regulatory, safety, security, ethical, and economic areas, emphasizing the need for advanced technology, standardized regulations, improved safety protocols, and ethical frameworks. Some barriers may transform into opportunities with further technological progress and broader acceptance, but immediate actions are necessary to address safety, liability, infrastructure, and workforce changes. The opportunities for AHDVs promise to enhance operational efficiency, reduce costs, and boost sustainability. Advances in connectivity, sensors, and AI expand AHDV applications, while collaborative efforts and regulatory updates help establish AHDVs as safe and efficient logistics solutions. Additionally, shifting societal views on sustainability and automation support the adoption of AHDVs in supply chains (Fig. 2).

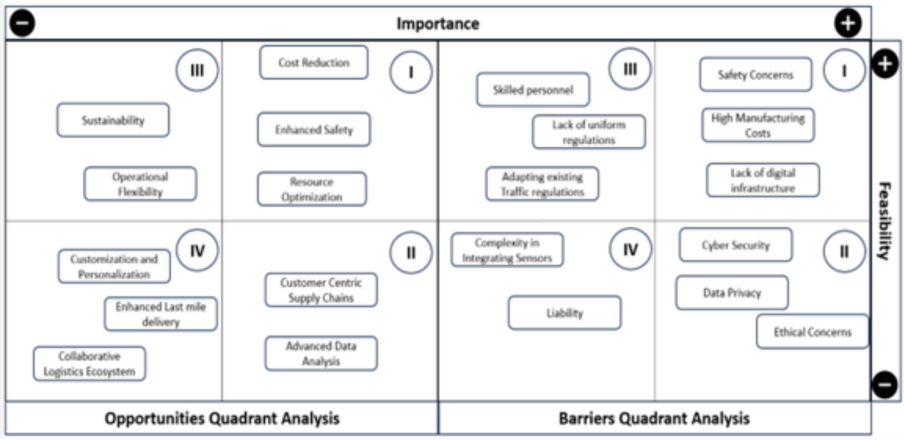



**Fig. 2.** Quadrant Analysis of Opportunities for Autonomous Heavy-Duty Vehicles in Logistics

## 4 Conclusion

This market research study clarifies how the logistics sector may evolve with the introduction of AHDVs, drawing on diverse methodologies like workshops and interviews to depict the current and future states of AHDVs in logistics. The thematic analysis highlighted specific challenges and opportunities, shaping our strategic recommendations for AHDV adoption. This aligns with the transformative potential seen in prior studies (Marsden et al. [13]; Kim et al. [14]) and the evolving landscape of Logistics 4.0, corroborated by shifts discussed by Clements & Kockelman [15] and Fritschy & Spinler [16]. Our findings also resonate with concerns about public perception and operational maneuverability (López-Lambas & Alonso [17]), emphasizing the importance of safety, technological readiness, legal frameworks, and infrastructure. The quadrant analysis conducted outlines the dynamic interplay of barriers and opportunities, emphasizing the need for collaborative, adaptive measures to harness AHDVs' full potential.

Our study contributes a detailed understanding of the dynamics shaping AHDVs' integration into logistics, highlighting the necessity for ongoing adaptation and proactive strategies among stakeholders.

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# Fleet and Traffic Management Systems for Conducting Future Cooperative Mobility

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**Abstract.** As urbanization continues to increase worldwide, cities face the challenge of accommodating growing populations while maintaining efficient and sustainable transportation systems. The advent of connected and autonomous vehicles promises transformative changes in urban mobility. This paper addresses developments and innovations aimed at seamlessly integrating CAVs into the complex urban mobility ecosystem. It presents assumptions related to a fleet of fully connected and autonomous vehicles coordinated by traffic management centers and focuses on optimizing route assignments based on various performance metrics, including travel time, energy consumption, congestion, and emissions. We are also exploring the integration of people and goods mobility by leveraging the cost efficiency and versatility of on-demand autonomous services.

**Keywords:** traffic management · fleet management · CCAM · load-balancing; demand-responsive transportation · multimodality · traffic simulation

## 1 Introduction

In the coming decades, the massive irruption of connected autonomous vehicles will lead to a profound transformation of the transportation sector and the mobility ecosystem. Cooperative connected autonomous mobility (CCAM) is one of the keys to achieving higher levels of road safety and greater environmental efficiency. However, transportation managers and service operators should be prepared to manage the demand and impact of these mobility services on the network to realize their full potential.

This paper describes how the Horizon Europe project CONDUCTOR [4] will improve traffic management and prepare for the entry of CCAM through the development and integration of advanced traffic and fleet management tools. These tools are based on machine learning, data fusion techniques, and traffic simulations. They will

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enhance the capabilities of authorities and operators, making them true conductors of future mobility networks. The solution portfolio will be demonstrated in complementary environments in different regions of Europe. Specifically, this paper describes the solutions developed for the management of traffic disruptive events and the integration of urban parcel distribution with on-demand passenger transport in the presence of CCAM services.

## 2 Introducing Connected Autonomous Vehicles into the Mobility Ecosystem

Various components are developed to demonstrate integration of Connected Autonomous Vehicles (CAVs) into urban transportation.

### 2.1 Traffic Management and Fleet Management Optimization Developments

In the context of the CONDUCTOR project, a relevant part of the developments relates to the use of the connectivity and automation possibilities offered by the entry of CCAM to improve traffic management and the integration of the movement of goods and people. Therefore, two components are being developed. The first one focuses on improving traffic management by leveraging the automatic rerouting capabilities of CAVs to balance the load on the traffic network during disruptive events in mixed traffic scenarios. In module development we made the following assumptions: There is a fleet of full-fledged CAVs connected to different traffic management sub-centers (TMC), which in turn are coordinated by the traffic management center (hierarchical control). The component also assumes that the origin and destination of each CAV are known to the TMC and that there are one or more predefined routes between each origin and destination. The component optimizes the route assignment for the entire CAV fleet (e.g., for each OD pair and route, the proportion of CAVs that take that route) and the traffic routing plan on specific arteries of the network under consideration given the following performance metrics: (i) travel time difference between CAVs and conventional vehicles, (ii) energy consumption of CAVs, (iii) total congestion levels in the system, and (iv) total emissions in the system.

The second component focuses on integrating the mobility of people and goods by leveraging the lower operating costs and greater versatility of autonomous on-demand services to provide sharing-a-ride services. On the one hand, autonomous on-demand services will be used to increase the use of public transportation in cities and solve the first/last mile problem, especially in areas that are not densely populated and/or where public transportation services are infrequent. On the other hand, these autonomous on-demand services are also used for parcel delivery. The objective of this component is to estimate the required CAV fleet and operating routes of autonomous on-demand services to serve both passenger requests and package deliveries. To this end, the component assumes that passengers specify in advance the origin and destination of their trips, with the preferred departure and arrival time windows. Similarly, it is assumed that the pickup and delivery locations of the packages are known, as well as their respective time windows, if requested by the customer. The performance indicators to be optimized by

the component are the following: (i) percentage of passenger trips requests served, (ii) percentage of packages picked up/delivered, (iii) operating cost of the autonomous on-demand fleet, (iv) total energy consumption of the autonomous on-demand fleet, and (v) average travel time of the passenger trip request served.

### 2.2 Demand Prediction and Classification

Planning and management of transport infrastructure and services require accurate, reliable, and up-to-date information about transportation demand. This applies to the characterization of general mobility and mobility by modes. The factors leading to the adoption of CCAM services and the substituted mode will depend on the characteristics of the services and different attributes of the passengers. Attitudes toward conventional public transport services may not change if they are served by CAV, but other services may affect demand for other modes of transportation. In particular, demand-responsive transportation (DRT) and car-sharing services are expected to be among the services boosted by the arrival of CAV [1]. The demand forecasting component aims to characterize and estimate travel demand from the fusion of anonymized mobile network data (MND) and other data sources. The goal is to create an origin-destination (OD) matrix segmented by mode, that distinguishes between professional trips related with delivery, and personal mobility performed by conventional public transportation, DRT with CCAM (DRT-CCAM), and private and non-motorized trips.

This component includes the integration of existing solutions and the development of new ones. Public transport trips are characterized using Nommon's Transit Insights [6], a solution that generates OD matrices for public transportation trips from anonymized intelligent fare collection systems. Private and non-motorized trips are identified using Nommon's Mobility Insights [7] solution, which generates 'activity travel diaries' [3] from MND.

New developments focus on achieving full characterization of demand. These developments are: Identification of delivery trips and DRT- CCAM estimation. Delivery trips are identified through longitudinal analysis of mobility patterns obtained from the fusion of MND, e-commerce surveys, land use information, and the location of points of interest (i.e., logistics and delivery centers).

Since there are currently no CCAM services in cities, the demand for DRT-CCAM trips is approximated by the demand for carsharing services, since these services are the best candidates to become DRT-CCAM when they become a reality [1]. Carsharing trips are estimated using Nommon's WiseRide solution [8]. WiseRide applies machine learning to analyze and predict the distribution of share mobility (SM) trips based on SM services, public transportation, general mobility matrices (from MND), weather and land use data. Based on the predicted carsharing demand, different DRT-CCAM penetration scenarios are created. These are created considering the travel and user characteristics observed in the predicted carsharing demand. The demand estimate is complemented by a mode substitution analysis that estimates what mode of transportation would have been used if the DRT-CCAM service had not been available. This information allows for the analysis and characterization of the impact of different CCAM penetration levels on each mode based on the socio-demographic characteristics of users.

To improve this characterization of demand, user profiles are further enriched with sociodemographic information about CCAM use that is not included in the MND. This is done by data fusion of MND and survey data based on machine learning techniques. The relevant identified features are household structure and car ownership.

### 2.3 Integration with Simulation Environment

The proposed demand traffic and fleet management models will be integrated into a state-of-the-art multi-resolution traffic simulation model Aimsun Next [2] to evaluate the network-wide impacts of the implemented strategies.

The integration will be done using the Aimsun Application Programming Interface (API) functions to transfer data from the simulated network to the external application. The external model then applies its own algorithm to evaluate the simulation results and responds dynamically with appropriate actions (e.g., changing the signal cycle) that are implemented in the next simulation step.

In addition, the Aimsun Ride simulation platform, which is a plug-in within Aimsun Next, simulates various on-demand service operations. The simulation results are then used to calculate actual operating costs and various fleet- and user-related KPIs. This tool is used in the UC to model and evaluate fleet operations for urban logistics with on-demand passenger transportation services in the simulation environment. Figure 1 summarizes the integration framework for modeling advanced functionalities for traffic management solutions in the presence of CAVs and shared mobility services.

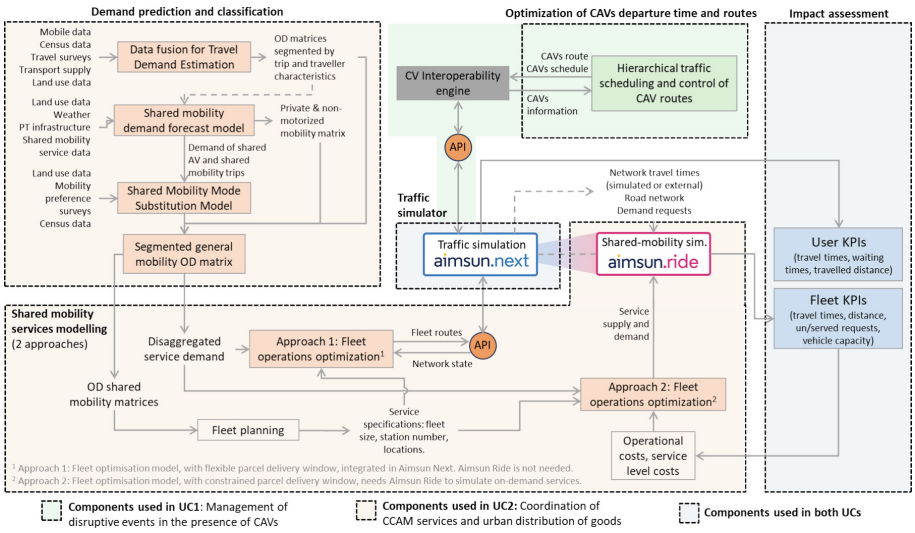



**Fig. 1.** Integration framework, outlining the workflow within both use cases

## 3 Application to the City of Madrid

The developed components and tools will be tested in the city of Madrid in two use cases (UCs) described below. More details on the UCs can be found in [5].

### 3.1 Management of Disruptive Events in the Presence of CAVs

This UC focuses on improving traffic management by using the automatic rerouting capabilities of CAVs to balance the load on the traffic network during disruptive events in mixed traffic scenarios. The study area is the Madrid M-30 ring road, a 32 km urban highway that surrounds the central neighborhoods of Madrid. The adjacent urban road network is also considered to account for possible detour options on these secondary roads. The UC is based on a simulated environment using the Aimsun traffic simulation software. The M-30 ring network is available with a microscopic resolution of traffic flow, so that vehicle behavior and interactions can be simulated in detail. However, to simulate rerouting decisions following disruptions on M-30, the surrounding urban network is modeled at a mesoscopic level to assess the impact on the broader network.

Planned events (e.g., roadworks) and unplanned events (e.g., accidents) are considered in different scenarios with varying penetration levels of CAVs. The vehicles in the simulation will communicate with the environment and receive personalized information, such as optimal departure times and routes, lane selection, and speed adaptation. An integrated optimization module will adjust the schedule and develop new CAV routes that will be transmitted to the simulator.

The expected benefits of this UC are the reduction in: (i) recovery time, (ii) average travel time and travel distance per connected vehicle, (iii) economic losses due to travel delays, and (iv) total vehicle emissions of CO2 and NOx.

### 3.2 Coordination of CCAM Services and Urban Distribution of Goods

Demand for urban delivery has increased over the past decade and is expected to further increase. The introduction of e-commerce, exacerbated by the COVID-19 crisis, is responsible for this shift and especially for traffic due to last mile delivery. To address the problem, this UC involves the combination of the components discussed in Sect. 2. It aims to develop and test coordination strategies for last mile delivery of parcels and DRT-CCAM services. The goal is to leverage the excess capacity of DRT-CCAM vehicles during periods of lower demand. In this way, we can effectively reduce the presence of delivery vehicles on the road, increase the occupancy of passenger cars and minimize the number of empty trips made by CAVs after their arrival. This addresses a common criticism of CAVs as an environmentally sustainable option that ultimately leads to less congestion and lower emissions.

The first step in implementation is to identify low-demand time windows for a particular DRT-CCAM service and predict delivery demand using the demand component described in Sect. 2. Based on this information, strategies are applied to coordinate and balance supply and demand. Although the goal is to prioritize passenger mobility, the potential negative impacts on delivery service must also be minimized. For this purpose, two levels of prioritization are considered: (i) optimization of the passenger route with

flexible time window for package delivery and (ii) optimization of the passenger route with preference-based categorization (high and low priority) of the time window for package delivery. Moreover, in this second scenario, passenger demand still remains the priority. Finally, the simulation tools Aimsun Next and Ride are used to simulate the new traffic scenarios and evaluate the impact of the proposed solutions.

The expected benefits of this UC are the reduction in: (i) average travel time for all vehicles, (ii) total distance traveled by delivery vehicles, (iii) the number of vehicles used to deliver goods, and (iv) overall transportation emissions.

## 4 Conclusions

This paper outlines the developments and innovations that are driving the integration of CAVs into urban mobility systems. Insights are provided, through two use cases, on managing disruptive events in the presence of CAVs and coordinating CCAM services with urban freight distribution. Ultimately, our research aims to illuminate the path towards a better connected, automated, and efficient urban mobility ecosystem.

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# SHINE-Fleet: Spanish Initiative for Sustainable Freight Transport Taking Advantage from Hydrogen and Automated Driving

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**Abstract.** In recent years, reducing emissions in Freight-Transport has become a top priority in mobility. This paper presents the methodology for the full control loop of a truck's powertrain, which has been transformed from a polluting GLP powered ICE to a zero-emission Hydrogen-powered electric powertrain within the SHINE-Fleet project. The adaptation has provided the ECU with increased flexibility to control the dynamics, enabling automated-driven missions like docking. The paper covers infrastructure-based localization for the vehicle, path planning to reach the setpoint, and control implementation with a Model Predictive Controller (MPC).

**Keywords:** Freight-Transport · Hydrogen · Autonomous · Decarbonization · Sustainable

## 1 Introduction

In Spain, the transport sector represents more than 40% of energy consumption and is responsible for 27% of direct greenhouse gas (GHG) emissions, which places it in the spotlight for regulatory compliance of the international [1] and national [2] regulatory framework for the reduction of emissions.

According to the Transport and Logistics Observatory (OTLE) [3] in Spain, regarding GHG emissions by road, it is the transport of goods that contributes the most to emissions ($< 10\%$ of the vehicle fleet but around 40% of carbon emissions), and their activity continues increasing.

In a European context of promoting measures for the decarbonization of transport, derived from the commitment to the "zero emissions" objective in

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2050 [4], trucks with hydrogen fuel cells aim to become the only possible replacement for petrol-powered trucks in long-haul freight transport.

Thus, the logistics sector has many potential applications for hydrogen propulsion technologies, but the most promising are long-haul trucks between 20 and 40 tons.

In this context, the SHINE-Fleet project -Technological solutions based on Hydrogen for the intelligent and sustainable mobility of autonomous Heavy-duty fleets- is based on research and the collaboration of technologies in a coordinated, structured, and interrelated way, to advance in overcoming the challenges that arise for hydrogen to replace fossil fuels in long-haul heavy transport distance, and take advantage of the electric powertrain to automate repetitive difficult maneuvers, such as docking.

The "SHINE-Fleet" Consortium comprises the synergy provided by 7 partners, joining efforts in human and material resources, generating the proper environment for achieving the objectives set in the Project.

With this preamble, the paper presents a non-invasive system for automating docking maneuvers without adding extra sensors to the vehicle within the SHINE-Fleet project. The system utilizes perception modules installed in the infrastructure to achieve this automation.

Throughout this paper, we will delve into the context of the project in Sect. 2. Then, a description of the system will be presented in Sect. 3, followed by an explanation of the localization and perception module in Sect. 4. The decision-making process for path planning to execute the mission will be explored in Sect. 5, while Sect. 6 will detail the control mechanisms used to follow the setpoint accurately. Finally, Sect. 7 will present the conclusions drawn from this study.

## 2 Context of the Solution

According to statistics, in Spain, there were 23,569 workplace accidents among drivers and mobile machinery operators in loading and warehouse areas during the first 6 months of 2023 [5].

Partner FMLogistic's information reveals that, apart from typical loading and unloading operations involving up to 200 trucks daily, there are additional activities like vehicle washing and repair, sometimes even at night or in low visibility conditions.

Hence, this paper aims to explore a cost-effective way to assist the docking maneuver by controlling the truck from infrastructure, improving safety and efficiency compared to only-human-driven operations and help reduce accidents.

## 3 Description of the Solution

In the project's development, four strategically placed LiDARs in the infrastructure, as seen in Fig. 1, calculate the head and load positions, as well as surrounding obstacles inside a map. Using this map, a continuous curvature trajectory is generated. The controller then determines accelerator, brake, and

steering signals, wirelessly transmitting them to the vehicle's onboard computer. After safety verification, the onboard computer sends the setpoint via the CAN line for the ECU to act upon the semi-trailer.

So, as in every manual driving loop, it is possible to identify three several modules inside the automated driving loop [6], but three modules are crucial inside this project, as can be seen in Fig. 2:

- **Localization & Perception**: this module is in charge of positioning the vehicle and the obstacles inside the map.
- **Path planning**: this module takes the position of the vehicle and the obstacles on the map and creates a plausible trajectory with speed to perform the docking maneuver.
- **Control**: this module tries to follow the setpoint trajectory by creating the throttle, brake, and steer signals that feed the vehicle system.




**Fig. 1.** Proposed architectural view.

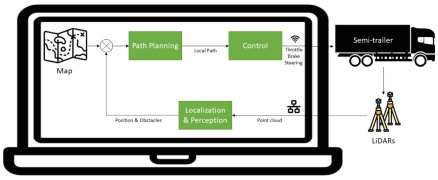



**Fig. 2.** Modular view of the solution.

## 4 Infrastructure-Based Perception

In order to know the position, orientation, and pitch angle of both load and head truck, a detection system is developed, using 4 Ouster OS1-32 LIDAR sensors for that purpose. We configure a setup shown in Fig. 1, maximizing the number of points that collide within the lateral parts of the trailer.

Our method, illustrated in Fig. 3, takes an octomap [7] that contains the environment representation, excluding the truck. A subtraction operation is performed between the merged point cloud of the LIDARs, concatenated, filtered, and aligned before this step, and the octomap, effectively isolating the points that define the truck. Then, the disseminated point cloud passes through a RANSAC [8] algorithm, used to exclude data not related to a plane of the trailer. Following this, we calculate the plane angle. The procedure also includes a clustering process to remove noise and identify the closest point to the wall. By leveraging this angle and the identified minimum point for load and head, their centers are accurately and stably determined.

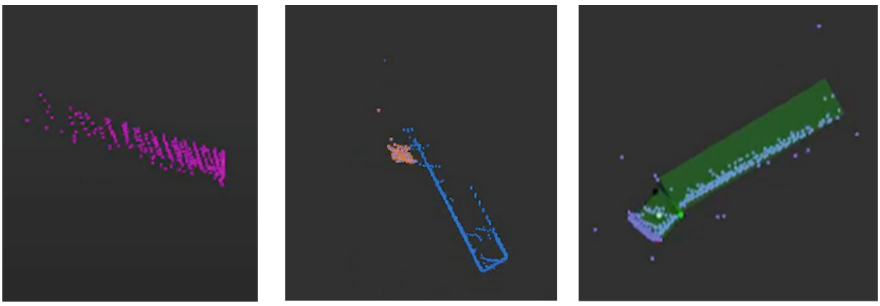


**Fig. 3.** Representation of each step of the algorithm: plane filtering, clustering and load-head marker from where position, orientation and pitch are detected.

## 5 Path Planning

After determining the vehicle's location, the next step is to establish the route, using a local trajectory connecting the semitrailer's control point (load's rear axle) to the destination. As the trajectory is exclusively in reverse for ensuring a smooth and unique parking operation, curvature continuity is crucial for defining feasible trajectories, given the vehicle's stability in reverse [9]. Then, the controller will optimize these smooth maneuvers to achieve the desired outcome.

To ensure continuity in curvature between the initial and final points, the simplest approach is to generate cubic Bézier curves [10] from the start to the end point, and projecting a straight line from the start or end with its orientation. The trajectory can be described as Eq. 1, depending on the percentage $p$ of the path:

$$B(p) = \sum_{k=0}^{3} \binom{3}{k} (1-p)^{3-k} p^k P_k$$
$$\begin{cases} P_0 = & (x_{now}, y_{now}) \\ P_1 = (x_{now}, y_{now}) & + a \cdot (\cos\psi_{now}, \sin\psi_{now}) \\ P_2 = (x_{end}, y_{end}) & - b \cdot (\cos\psi_{end}, \sin\psi_{end}) \\ P_3 = & (x_{end}, y_{end}) \end{cases} \tag{1}$$

Finally, $a$ and $b$ are parameters greater than 0, which will be adjusted to optimize the total distance of the generated trajectory while limiting the turning radius.

## 6 Control

The system will be controlled using a PID controller for longitudinal tracking and a Model Predictive Controller (MPC) with a cost function that minimizes the position and orientation of the load for lateral tracking.

### 6.1 Longitudinal Control

As the maneuver will start from a point that allows the entire trajectory to be covered exclusively in reverse, a velocity setpoint $v_k$ will be defined for each point of the trajectory $k$, given by the minimum absolute value between a limit value $v_{max}$ and a constant $c$ multiplied by the distance $d_{k,end}$ from point $k$ to the last point of the trajectory.

$$v_k = -min(|v_{max}|, |c \cdot d_{k,end}|) \tag{2}$$

Next, a PID controller will be responsible for obtaining a torque setpoint $\tau$ to reach the velocity setpoint. Finally, knowing the accelerator torque limits $\tau_{th\ max}$ and brake torque limits $\tau_{br\ max}$, the torque setpoint will be normalized to obtain the pedal signals.

### 6.2 Lateral Control

To define the MPC controller used for lateral tracking, a cascade bicycle model[12] is employed, where the front head acts as the front wheel. With this approach, using the variables described in Fig. 4, the discrete model equations in the spatial domain[11] can be obtained based on the steering angle $\delta$:

$$\begin{cases} x_{h,k+1} = x_{h,k} + \Delta s \cdot \cos(\psi_{h,k}) \\ y_{h,k+1} = y_{h,k} + \Delta s \cdot \sin(\psi_{h,k}) \\ \psi_{h,k+1} = \psi_{h,k} + \tan(\delta)/L_1 \\ x_{l,k+1} = x_{l,k} + (\Delta s \cdot \cos(\psi_{h,k} - \psi_{l,k})) \cdot \cos(\psi_{l,k}) \\ y_{l,k+1} = y_{l,k} + (\Delta s \cdot \cos(\psi_{h,k} - \psi_{l,k})) \cdot \sin(\psi_{l,k}) \\ \psi_{h,k+1} = \psi_{l,k} + \tan(\psi_{h,k} - \psi_{l,k})/L_2 \end{cases} \tag{3}$$

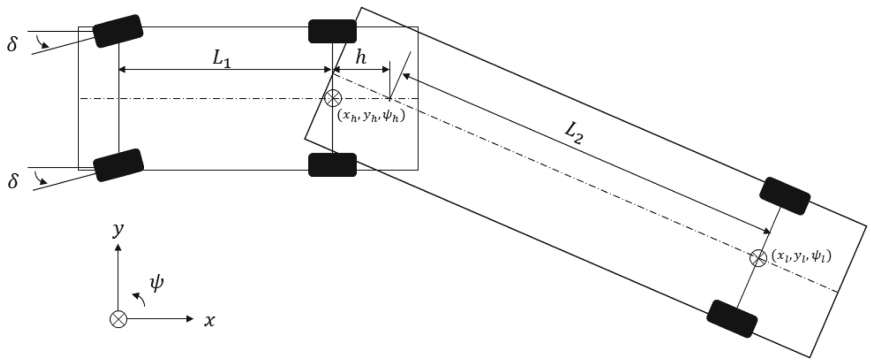



**Fig. 4.** Parameters and coordinates system used to describe the model

Once the system is defined, a cost function is created that takes into account the position and orientation of the load while minimizing the error in the rear

axle position $e_{pl}$ and orientation $e_{\psi l}$ tracking with associated weights $w$. Thus, the following system cost function is obtained:

$$J = \sum_{k=0}^{n_h} w_p \cdot e_{pl}^2 + w_o \cdot e_{\psi l}^2 \tag{4}$$

Finally, steering angle limits are defined as constraints on the control signal, as well as limits for the joint to avoid jackknifing. The optimization problem is then solved, returning the steering angle that should be applied at each moment.

## 7 Conclusions

Throughout this paper, we have elucidated the control strategy aimed at automating the docking maneuver of articulated vehicles in a minimally invasive manner. As a result, a single logistics center can compute trajectories for multiple trucks without necessitating expensive vehicle modifications. This approach holds the potential to mitigate workplace accidents during loading and unloading, while concurrently enhancing the overall maneuvering efficiency.

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# Enhancing Urban Convoying Safety by Mechanical Connection Among Automated Vehicles: Simulation Study on Controlled Trajectories

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**Abstract.** In this work, a control architecture is proposed for controlling a convoy of automated vehicles that are mechanically connected to each other. Connection allows them to circulate without specific permissions in any environment, even if a driver is present only in the leading vehicle. The connection in the real case is an elastic and compliant connection, a condition mediating the cases of rigid connection and absence of mechanical connection. To evaluate the capabilities of automation control algorithms in maintaining a prescribed path and estimate the required stiffness of the mechanical connection, simulations have been performed considering a geometric control algorithm (*Pure Pursuit* controller) for lateral control mixed with a *PID* controller for longitudinal control. Considering several trajectories of two convoyed vehicles, the control method has been analyzed based on the minimum value of errors (longitudinal and lateral) in vehicle trajectories. The ideal case is considered where all communication and environment scanning systems operate with maximum efficiency. While subsequent steps will be made to further decrease the trajectory error by modifying the vehicle control, the results enable an estimation of the required compliance of the mechanical connection expressed in terms of trajectory error.

**Keywords:** autonomous driving · mini-bus vehicle · pure pursuit · convoying

## Introduction

The aim of the work is to propose a control architecture for solving the *Trajectory Tracking* problem for a convoy of connected electric mini-buses by a geometric control technique (as the *Stanley* controller [1]); the technique is known in the literature as *Pure Pursuit* controller [2,3] for lateral control, supported by a

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*PID* controller for longitudinal control. In particular, the objective is to ensure that a following vehicle is capable of traveling a trajectory communicated by a moving leading vehicle [4] and maintaining a certain distance, minimizing the longitudinal position error and ensuring that this is stable in a certain error range; this enables to design the stiffness of the mechanical connection so that forces exchanged between the vehicles are reduced (e.g., using a shock absorber). Data transfer to the following vehicle is first simulated through the generation of timed information vectors (to simulate the release of values over time) and subsequently by using *GNSS* data from a real vehicle as input to the proposed control system. Here, it is proposed to contextualize these solutions for application to mini-buses available to the research team, previously customized and whose main specifications can be found in previous work [5].

# 1 Methods

## 1.1 Kinematic Model

As known in literature [6], a common approach to modeling the lateral motion of a vehicle is the so-called "*Bicycle Kinematic Model*". Taking Fig. 1 as a reference, the vehicle is approximated as a bicycle where the two left and right front wheels are represented by one single wheel and similarly for the rear wheels. In particular, we assume that only the front wheel can be steered; since the vehicle in question has a maximum speed of approximately 8 m/s, we can also assume that the wheel slip angles are negligible. Furthermore, let us consider that the vehicle has only planar motion, so that the coordinates required to describe the vehicle's motion are only three: $X$, $Y$ and $\vartheta$. Therefore, $(x_c, y_c)$ are the inertial coordinates of the Centre of Gravity (CG) while $\vartheta$ describes the orientation of the vehicle; all these parameters are defined with respect to a fixed reference system $(O; X, Y, Z)$. Finally, to account for the positioning of the *GNSS*, the CG was considered as a reference. Under these hypotheses, it is possible to write the following kinematic equations with respect to the fixed reference system (where the vehicle's CG speed is denoted by $V_c$ and defines an angle $\beta$ with respect to the longitudinal axis of the vehicle known as "slip angle"):

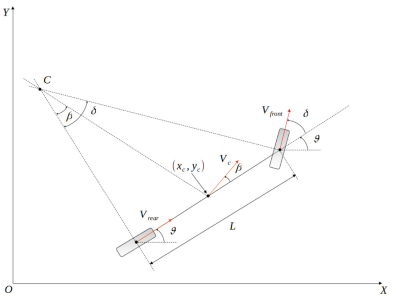



**Fig. 1.** Kinematic Bicycle Model

$$\begin{aligned}
\beta(t) &= tan^{-1}(\frac{tan(\delta(t))}{2}) \\
\dot{x_c}(t) &= V_c(t) \cdot cos(\theta(t) + \beta(t)) \\
\dot{y_c}(t) &= V_c(t) \cdot sin(\theta(t) + \beta(t)) \\
\dot{\theta_c}(t) &= \frac{V_c(t) \cdot tan(\delta(t)) \cdot cos(\beta(t))}{L}
\end{aligned} \tag{1}$$

### 1.2 Pure Pursuit Controller

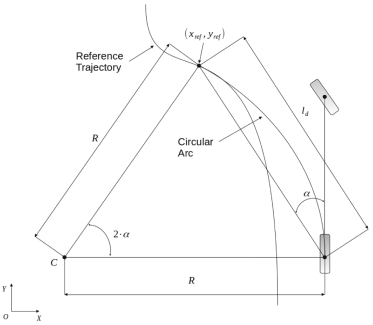



**Fig. 2.** Pure Pursuit Model and Control Architecture

Regarding the vehicle's lateral control, a *Pure Pursuit* controller has been implemented. Taking Fig. 2 as a reference, the main idea of the *Pure Pursuit* controller is to compute the steering angle $\delta$ of the front wheel based on the concepts of look-ahead distance $l_d$ and look-ahead angle $\alpha$, so that the vehicle can steer towards the reference coordinate $(x_{ref}, y_{ref})$ following a circular arc trajectory with its rear wheel. Based on the wide literature on the subject, there are different versions of the *Pure Pursuit* controller; specifically, the version is considered in which the look-ahead distance $l_d$ is proportional to the longitudinal speed of the vehicle [7], i.e. $(l_d = K_p \cdot V_{long})$ ($V_{long}$ can be obtained by projecting the speed of the CG of the vehicle $V_c$ on its longitudinal axis via the slip angle $\beta$). As regards the look-ahead angle $\alpha$, this can be easily obtained through the following equation:

$$\alpha(t) = tan^{-1}(\frac{y_{ref}(t) - y_{rear}(t)}{x_{ref}(t) - x_{rear}(t)}) - \vartheta(t) \tag{2}$$

Finally, under the hypotheses previously considered, it is possible to write the nonlinear feedback control law that controls the steering angle $\delta(t)$ (For implementation purposes, the equation was subsequently modified as follows $\delta(t) = atan2(2 \cdot L \cdot sin(\alpha(t)), K_p \cdot V_{long}(t) + c)$.):

$$\delta(t) = tan^{-1}(\frac{2 \cdot L \cdot sin(\alpha(t))}{K_p \cdot V_{long}(t))}) \tag{3}$$

To account for the physical limitations of the steering system of the real vehicle under consideration, $\delta(t)$ was saturated between the values $[-22.5°, 22.5°]$. The architecture of the used control system is depicted in Fig. 3 through a block diagram. This diagram shows the flow of the control logic highlighting the inputs and outputs of each block. After some experiments, it was decided to modify the

reference speed value using a feedforward term proportional to the longitudinal error $E_{long}$ (i.e. $V_{ref,ff} = V_{ref} + K_{ff} \cdot E_{long}$), at the input to the *Speed Error Computation* block, to allow the system to accelerate if it was too far from the reference position. Lastly, as regards the tuning phase, all controller gains were tuned empirically.

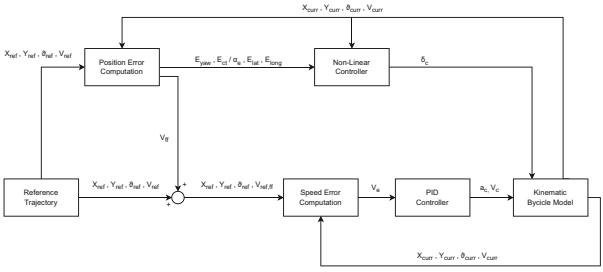



**Fig. 3.** Control System Architecture

### 1.3 Simulation Environment and Hardware

All simulations were carried out in the *MATLAB/Simulink*® environment. The ideal reference trajectories were generated through scripts in *MATLAB*. Timed arrays were generated to simulate the sampling of the input data over time. As regards the real trajectories, however, these were acquired through a *GNSS* device placed near the CG of the moving vehicle. The device had a maximum frequency of 25 Hz, but to guarantee a certain stability in the data acquisition it was decided to limit it to 20 Hz. The data thus obtained were then filtered through a moving average filter and used as input to the control system. Acquisition and filtering were carried out through a *MATLAB* script. In all *Simulink* simulations we used a fixed step of 0.01 s and *ode14x* as solver. The value of 0.01 s was coherent with the one for the hardware onboard the vehicle.

## 2 Results and Discussion

For brevity, only the results will be shown and discussed regarding the simulation of a real trajectory, i.e., acquired through the use of the previously introduced *GNSS* device. Therefore, from Fig. 4 it can be seen how the implemented control system guarantees close tracking of the trajectory despite the disturbances (partially filtered) present in the measurements with a maximum speed of approximately 36 km/h. Furthermore, as can be seen from Fig. 4, the trajectory is reproduced smoothly, without cutting corners or rapid changes in orientation thanks to the mixed control architecture used (*Pure Pursuit* + *PID*). Cutting corners and rapid changes in orientation are typical problems in *Pure Pursuit* applications, partly because *Pure Pursuit* ignores trajectory/path curvature [7].

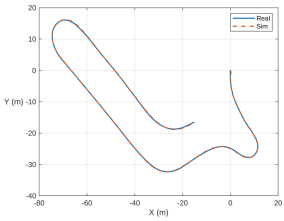



**Fig. 4.** *GNSS* Trajectory Simulation

The trend over time of the error values, relating to the simulated trajectory, is shown in Fig. 5 where it is possible to observe how the implemented controller manages to obtain relatively low error values, especially in the case of lateral error ($0.02 \pm 0.01$ m). As regards the longitudinal error ($0.09 \pm 0.07$ m), however, this tends to have higher values than the lateral error, probably because the dynamics of the vehicle was not considered at this stage.

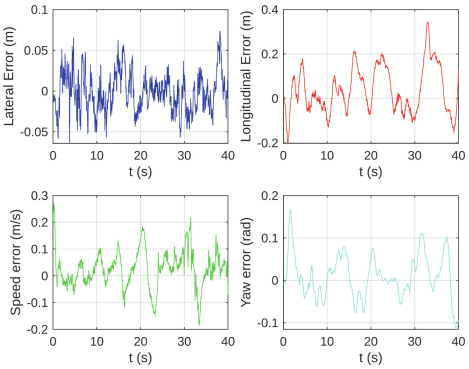



**Fig. 5.** Error trends over time

## Conclusion

The proposed and implemented control architecture demonstrated good performance in terms of error minimization (particularly in the case of lateral error, with an average absolute value of $0.02 \pm 0.01$ m) even when using real acquisitions as a reference. Conversely, an average absolute value of $0.09 \pm 0.07$ m was achieved in longitudinal error, which requires special attention and might be reduced also considering vehicle dynamics. Further steps will be moved to improve the control algorithm already implemented (e.g., modelling the dynamics and the connection between the two vehicles at a kinematic and/or dynamic

level) and implementing new algorithms to perform comparisons between different control architectures. The findings highlight that a compliant connection allowing a displacement of 0.2 m can be sufficient to prevent the discharge of significant forces between vehicles; this information will guide the proposal of a new mobility scheme where vehicles at a different level of automation will be able to merge, forming a tram-like transportation alternative that needs only one active driver at a time and does not follow a prescribed path (as railway lines).

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**Author contributions.** Conceptualization: M.S.G., M.F., L.P.; methodology: L.P., A.A.; software: M.F., L.P.; formal analysis: M.S.G., L.B., M.F., A.A.; investigation: M.F., L.P.; writing—original draft preparation: M.S.G., M.F.; writing—review and editing: M.S.G., L.B., D.V., A.A.; visualization: M.B.; supervision: D.V., A.A.

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**Availability of Data.** Data may be provided on request by the authors.

**Competing Interests.** Not applicable.

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# From Concept to Reality: Augmented PDI Solutions Supporting Connected, Cooperative and Automated Mobility in Madrid

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**Abstract.** The work described in this paper provides valuable insight into the novel PDI solutions to be developed for CCAM support within the Horizon Europe-funded AUGMENTED CCAM project. To this aim, two different test sites are being prepared in Madrid, Spain, for the implementation and demonstration of four cutting-edge solutions: Equipped Vulnerable Road Users (VRU) protection; Traffic Management Optimization based on Probe Vehicle Data (PVD) from CCAM; Emergency Vehicle approaching; and Ad-hoc on-demand unmanned aerial vehicle (UAV) based VRU protection for closed environments. This document unveils how the proposed services underline the vast potential of CCAM when synergized with advanced Infrastructure support, which is not only limited to the extension of the Operational Design Domain of Connected and Automated Vehicles. This approach also demonstrates PDI's capacity to significantly enhance road safety, traffic efficiency and sustainability. Additionally, the importance of the Digital Twin is highlighted as an indispensable element for advanced traffic management and comprehensive infrastructure monitoring.

**Keywords:** Connected Mobility · Cooperative Mobility · Automated Mobility · Physical and Digital Infrastructure · Digital Twin · Madrid

## 1 Introduction

In recent years, Europe has seen remarkable progress in the advancement of Connected, Cooperative and Automated Mobility (CCAM) in Europe. The European Commission has taken decisive actions to enhance its growth and adoption, such as the creation of the CCAM Single Platform (2019) and the CCAM Partnership (2020) [1]. Despite these steps, CCAM still faces great challenges, such as the technological complexity of its solutions or the great investments needed in Physical and Digital Infrastructure (PDI).

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The AUGMENTED CCAM project aims to enhance the implementation of CCAM by developing and evaluating 11 new PDI support solutions to extend the Connected and Automated Vehicles (CAV) Operational Design Domains (ODD) and the intelligence and functionalities of CVs. This paper presents the work conducted for the implementation of the four PDI solutions to be deployed in Madrid: Equipped VRUs protection (**PDI 1**); Traffic Management Optimization based on Probe Vehicle Data from CCAM (**PDI 2**); Emergency Vehicle approaching (**PDI 3**); Ad-hoc on-demand UAV-based VRU protection for closed environments (**PDI 4).**

## 2 Madrid Test Site and PDI Solutions

Madrid disposes of two different test sites: an urban open-traffic area (Fig. 1a) and a semi-controlled private environment in the inside and surroundings of an EMT bus depot (Fig. 1b). Villaverde neighborhood will host the open-traffic scenario, where a 3.5 km circuit has been designed so that vehicles can circulate in real traffic conditions. The Traffic Management Optimization service **(PDI 2)** will be deployed here.

The depot test scenario is split into two zones: inside the depot and its surroundings, Carabanchel neighbourhood. Here, CAVs can interact with VRUs and other vehicles in semi-controlled conditions and UAV-based VRU protection **(PDI 4)** solutions is showcased inside the depot. Equipped VRUs protection **(PDI 1)** will be deployed at its gate. On the other hand, the depot surroundings extend along Carabanchel neighbourhood, where a route has been designed for the Emergency Vehicle approaching service **(PDI 3)**.

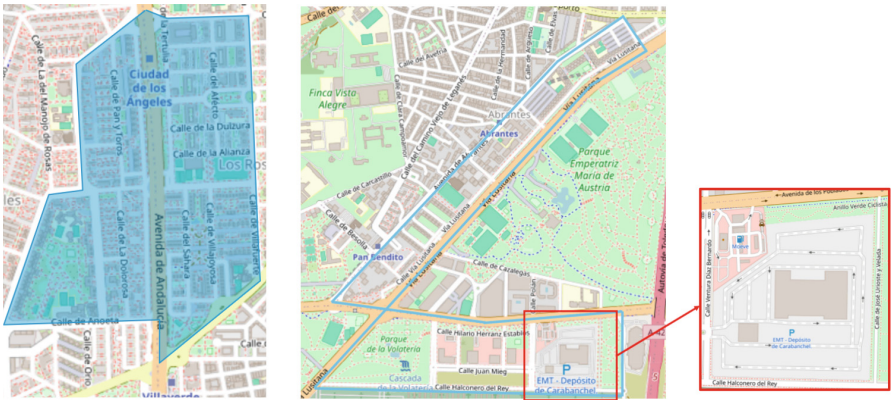



**Fig. 1.** Open-urban traffic site in Villaverde (left) and Carabanchel depot (right) aerial view. Maps based on OpenStreetMap data, © OpenStreetMap contributors, ODbL license. Routes added manually.

### 2.1 PDI 1: Equipped VRUs Protection

This service's objective is to enhance VRUs' safety by notifying CAVs and CVs of the presence of VRUs in the vicinity. Simultaneously, connected VRUs will also receive a

warning when a CAV approaches. The solution will be deployed at EMT depot's gate, where risk situations arise during the exit manoeuvres of buses. Here, the CAV's sensors are unable to detect if a VRU is approaching the gate, as the walls obstruct their visibility. The vehicle selected for this demonstration is a SAE L4 microbus (Gulliver Tecnobus model) and one manual driven connected Renault ZOE.

VRUs will be detected thanks to AI-based cameras. Infrastructure will monitor VRUs whereas the Collision Risk Estimator (CRE) evaluates potential risks, sending out warnings to CAVs about the detection of VRUs as they exit the depot. Connected VRUs will also receive warnings about the presence of CAVs through an app. Whenever the cameras detect a VRU near the gate, they send its position and speed to the CRE, which will also receive the speed and position of the CAV and calculate the possible trajectories and risks. Then a warning is sent to both the CAV and the connected VRUs, allowing them to take the required avoidance actions.

Two modules have been developed for the deployment of the service: the VRU Manager (VRUM) and the Connected Vehicle Manager (CVM), which handle the information related to VRUs and CAVs, respectively. The Digital Twin (DT) and the CRE are part of MISTRAL, ETRA's Smart Mobility platform, which unifies urban mobility management systems for real-time management and monitoring (Fig. 2).

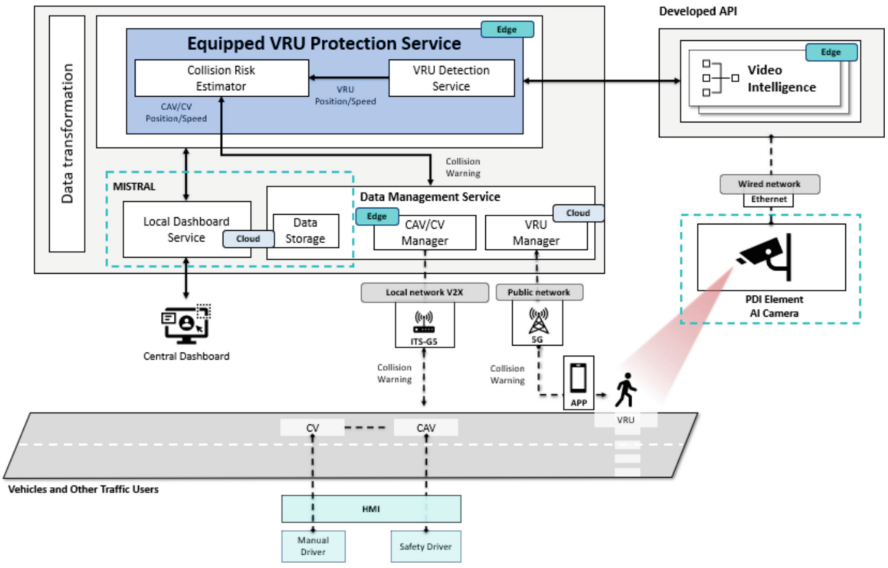



**Fig. 2.** Data flow of the Equipped VRUs Protection service. Figure produced using Microsoft PowerPoint.

## 2.2 PDI 2: Traffic Management Optimization Based on PVD from CCAM

This service aims to boost traffic network efficiency through the information CVs can provide to the Traffic Management System (TMS). To do so, CVs will share their location and speed in real-time, along with their origin and destination. Thus, the TMS will be able to adapt to the reported traffic conditions and offer CVs real-time route recommendations.

The solution will be implemented in the open-traffic urban scenario in Villaverde, where a circuit has been designed for CVs to perform several routes that will allow the generation of O-D matrices and route recommendations. The vehicles selected for the demonstration will run as CVs (SAE L0): two Renault Twizy and one Renault ZOE.

This service will need the CVM to receive the information shared by the CVs and forward it to the DT. With this information, the DT shall generate traffic metrics about the status of the road network and the O-D matrices that represent the traffic demands, so MISTRAL is able to adapt the traffic plans to the current situation and send route recommendations to the CVs in the area (Fig. 3).

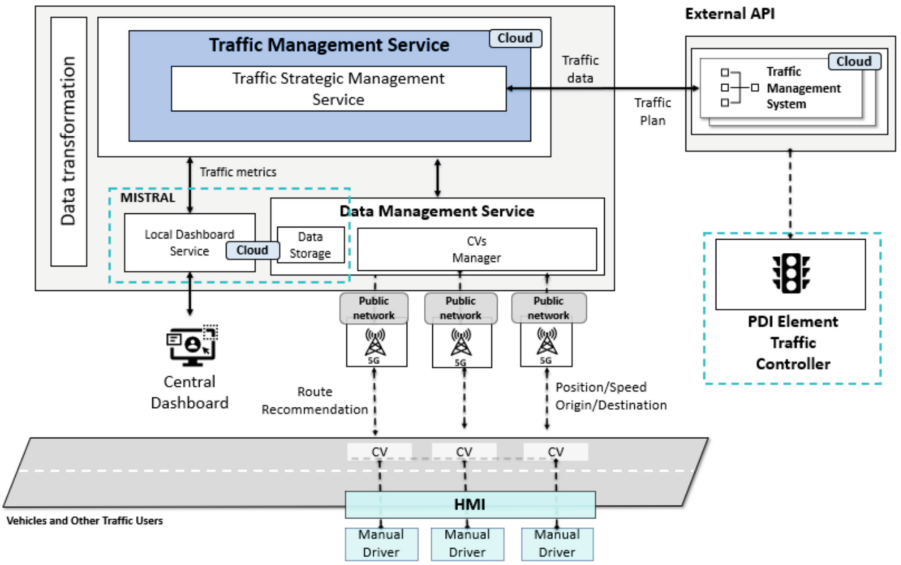



**Fig. 3.** Data flow of the Traffic Management Optimization service. Figure produced using Microsoft PowerPoint.

### 2.3 PDI 3: Emergency Vehicle Approaching

This solution focuses on the management and prioritization of connected emergency vehicles (CEV) during emergency events, reducing CEVs' travel time through optimal route recommendations, signal priority and diffusion of warnings to other CVs nearby.

The service will be deployed in the surroundings of Carabanchel depot, where the CEV will perform a meshed route of nearly 7 km to reach the location of the emergency, while also providing advance notification to other CVs and CAVs about its presence for them to perform cooperative manoeuvres to clear the way. The vehicles to be used in the demonstration are two Renault Twizys SAE L4, a Gulliver Tecnobus SAE L4 and a connected Renault ZOE (SAE L0), apart from the CEV, which will be SAE L0.

An Emergency Vehicle Manager (EVM) has been designed for this service. It will receive the notification and location of the emergency and request optimal routes from MISTRAL. Once the route is selected, the EVM will ask MISTRAL for signal priority. Simultaneously, the EVM and the CVM will send MISTRAL the positions, speeds,

origin and destination of the CEV and the CVs/CAVs involved. With this data, the DT estimates the possible trajectories and risks and sends the required warnings to CAVs and CVs, so they can form the emergency corridor. On the other hand, MISTRAL will perform the priority requests to the traffic controllers to ensure the CEV finds green light at crossings. Once the CEV reaches the emergency site, MISTRAL is informed and normal operations resume for the TMS (Fig. 4).

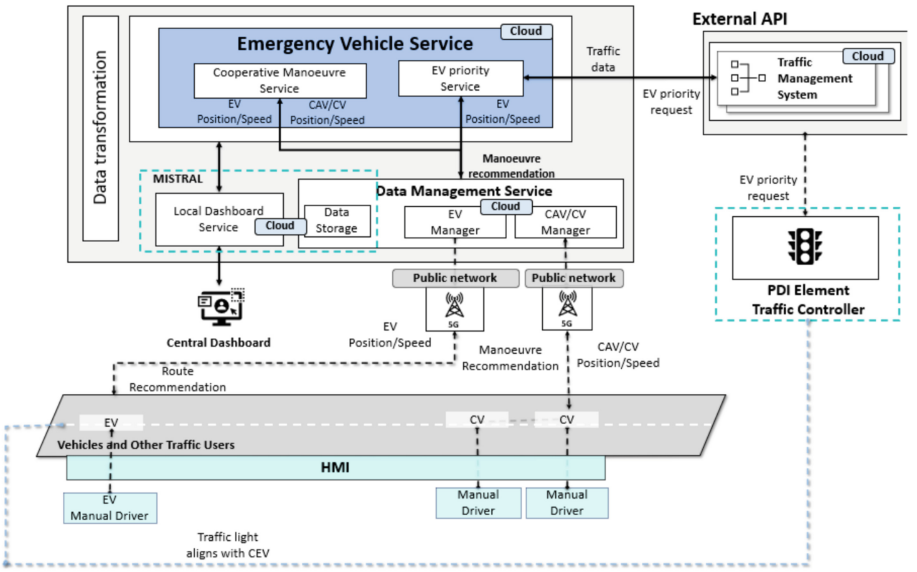



**Fig. 4.** Data flow of the Emergency Vehicle approaching solution. Figure produced using Microsoft PowerPoint.

### 2.4 PDI 4: Ad-Hoc On-Demand UAV Based VRU Protection for Closed Environments

This PDI service is designed to enhance the safety of VRUs navigating within enclosed environments frequently traversed by CAVs and CVs.

The service's deployment takes place within Carabanchel EMT bus depot, distinguished by numerous crosswalks that create occluded pedestrian areas, primarily due to parked buses, resulting in potentially hazardous zones. The vehicles to be used in the demonstration are one Renault Twizy SAE L4, a microbus (Gulliver Tecnobus model) SAE L4 ~~a~~ and a connected Renault ZOE (SAE L0).

VRUs will be detected by a camera mounted on a UAV that will fly over the area with a favorable field of view of the crosswalk. The camera's video feed will be transmitted to an edge processing computer, which will employ AI perception algorithms to identify the position, speed, and motion predictions of VRUs.

The detection results will be communicated to CAVs/CVs via standard V2X (Vehicle-to-Everything) messages, enhancing the vehicle's decision-making system. The goal is to improve the vehicle's response time when encountering pedestrians, thereby reducing

the risk of accidents, allowing more comfortable stopping maneuvers, and avoiding an unnecessary conservative driving style (always assuming the presence of pedestrians). The VRU protection service will receive the data from both the VRUs and the CAV/CV and sends to the vehicle the VRUs related to the zone of interest (Fig. 5).

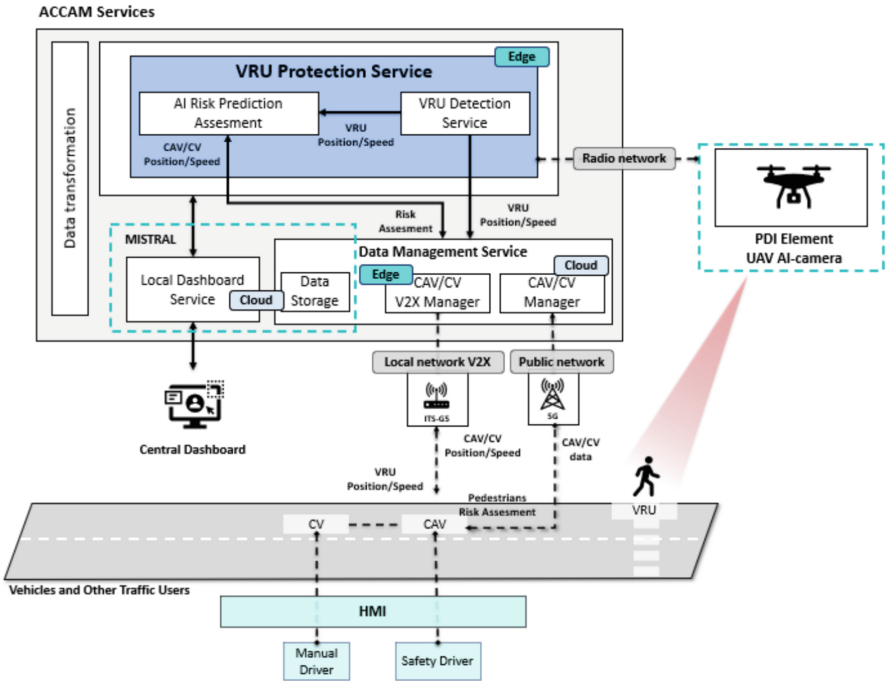



**Fig. 5.** Data flow for the Ad-hoc UAV based VRU protection for closed environments solution. Figure produced using Microsoft PowerPoint.

## 3 Conclusions and Future Work

This paper discusses the PDI solutions to be deployed in Madrid within the AUGMENTED CCAM project. All services show the benefits that CCAM can obtain from PDI support, not only to extend the vehicles' ODD but also to improve traffic management and enhance road safety. In addition, the Digital Twin is highlighted as a crucial element for real-time infrastructure monitoring and advanced management.

As of writing this paper, the project is in its 16$^{th}$ month and the services are still being developed. In Madrid, test scenarios are beginning to upgrade their PDI and initiate the permit and equipment acquisition processes. First demonstrations are scheduled in month 22, with small-scale tests in the field and on virtual demonstration platforms.

**Acknowledgements.** This document is based on the developments within the Horizon Europe-funded project "AUGMENTED CCAM – Augmenting and Evaluating the Physical and Digital Infrastructure for CCAM deployment" (Grant Agreement; 101069717).

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# Exclusive and Controlled 5G Network for Development of Connected and Automated Vehicle Technologies

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**Abstract.** The sensors and cameras in a car are limited to the information that the vehicle receives and processes in its immediate environment and line-of-sight applications. To further extend these data collection capabilities (with the intention of increasing traffic efficiency and safety), Cooperative Intelligent Transportation Systems (C-ITS) technologies are based on the exchange of information between vehicles through wireless communication systems and networks. This paper shows how IDIADA addresses this reality and proposes a pioneering and innovative solution for wireless networks. IDIADA has built a Connected Vehicle Hub, equipped with the latest mobile communication technologies and in compliance with the ETSI ITS G5 standard, to facilitate the construction of increasingly reliable systems, offering its facilities and adapting the platform to the needs of specific test scenarios, in order to repeat tests and evaluations that are difficult or even impossible to perform on the public road due to the constant changes in the road environment and in the networks themselves.

**Keywords:** CVH · 5G · C-ITS

## 1 State of Art

Testing of cooperative systems increases complexity compared to testing of traditional automotive systems, this is because cooperative systems interact with other ITS systems (vehicle, pedestrian, or road infrastructure).

Most vehicles today are connected in some way to external application servers, networks and the Internet through embedded communication modules, tethered solutions that rely on the driver's smartphone or integrated solutions where applications are deployed directly on the driver's smartphone or in the car's infotainment system.

With the development of new standards, such as Cellular Vehicle-to-Everything (C-V2X) included in 3GPP Release 14, which in its first version extends the LTE platform to offer direct Vehicle-to-Vehicle (V2V) communication capabilities [2], cellular networks are likely to become increasingly important as major technology enablers for the deployment of C-ITS technologies and higher levels of automation deployment. On the other hand, 802.11p has already established itself as a proven standard specifically

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designed to meet all V2X application requirements and performance specifications [4, 5].

The progressive introduction of these wireless technologies in vehicles will bring a wide variety of new cooperative and connected services and applications to be implemented over lower-layer standards, and their importance will grow rapidly towards the future introduction of fully autonomous vehicles [3]. The development of such services and applications requires an extensive and costly testing effort, revealing the need for new test suites and tools that facilitate the execution of these tests while ensuring safety.

Traditional test tracks are fine for traditional cars, but cooperative, connected, and automated vehicles require new test environments that can provide a fully configurable and controlled network spanning both physical and digital infrastructure to replicate and recreate test scenarios safely.

For specific scenarios, it is often necessary to travel many kilometers to achieve specific challenging conditions, which is resource intensive. In some countries, it is not even possible to conduct certain tests on public roads, as this is prohibited by current regulations. In addition, commercial cellular networks are not suitable for this type of testing, as their operating conditions are not controlled: the available capacity varies according to the number of connected users and their use of network resources, coverage conditions cannot be modified, and network availability can be affected by their operation and maintenance activities. For test results and subsequent conclusions to be reliable, it is necessary to control network parameters to reproduce specific scenarios [1].

On the other hand, commercial networks are not easily adapted to the latest features and solutions needed to enable efficiency and security applications, as their implementation depends on the mobile network operator's interest in offering these features and requires a deployment plan that must consider the size of the network and the number of network elements affected. Finally, privacy issues can be avoided by keeping sensitive data in-house, which is another advantage of a private environment.

## 2 Connected Vehicle Hub

With the goal of replicating any possible network condition that a vehicle might face on the road, the ability to cover test tracks with the full suite of access technologies that enable the development and deployment of C-ITS applications is an important requirement from a network design standpoint. This includes both DSRC devices that meet IEEE 1609 and ITS G5 standards, as well as a cellular network that spans all generations from 2G to 5G.

### 2.1 C-ITS Platform

As part of its wireless communication infrastructure, IDIADA has designed and deployed a C-ITS platform. IDIADA's proving ground is fully covered with ETSI ITS G5 and WiFi technologies. It also has High Definition (HD) mapping information with 2 cm accuracy and D-GPS/RTK coverage.

A new C-V2X network with the latest technologies on the market is expected to be deployed by the middle of Q3, 2023 (Fig. 1).



**Fig. 1.** Planned C-V2X Network Coverage Map

### 2.2 Exclusive and Controlled Cellular Network

The other key asset of the IDIADA Connected Vehicle Hub is the cellular network deployed with all available cellular technologies: 2G, 3G, 4G and 5G-NSA (currently under design, 5G-SA deployment). Full coverage of the proving ground is provided by 4 multi-standard radio base stations, which complement the C-ITS infrastructure by jointly building a complete connectivity test platform.

The cellular network can be separated into three main functional domains: Radio Access Network (RAN), Transport Network and Core Network (CN), all of which must be considered if a complete operational solution is to be deployed. Security applications demand high performance networks in terms of bandwidth, latency, reliability, and availability, which require target values that are difficult or even impossible to achieve with current standards, requiring that all network elements and the interconnections between them be carefully designed and implemented. The solution adopted at IDIADA shows the following coverage map (Fig. 2):

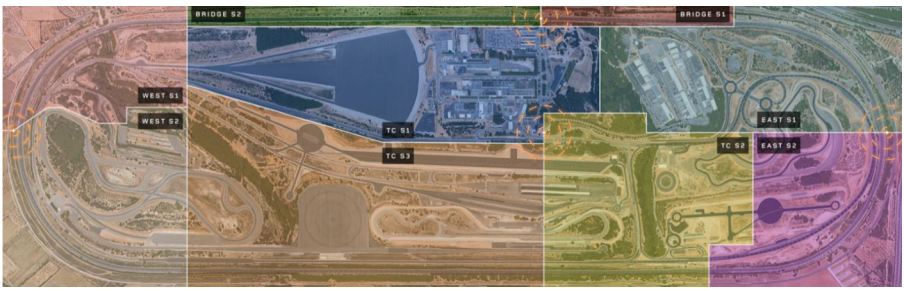



**Fig. 2.** Cellular Network Coverage Map

The transport network connecting the base stations to the Base Station Controller (BSC), Radio Network Controller (RNC) and Evolved Packet Core (EPC) is based on IP over fiber optic links, ensuring high reliability, high-speed performance, and minimal latency. External Application Servers (AS) can be connected directly to the internal network or remotely via broadband connections, depending on the scope of the tests to be performed.

The core network performs the switching functions and provides connection to other external networks, such as the Public Switched Telephone Network (PSTN), Public Data Network (PDN) or private data networks, among other messaging, authentication or charging functions. In 2G and 3G networks the core is divided into Circuit Switched (CS) and Packet Switched (PS) network elements, the former carrying voice services and the latter carrying data, while 4G is a fully integrated PS network. The 5G-NSA uses the 4G core. The Packet-Switched network core elements that carry network user traffic in the data plane are deployed locally in a dedicated server room.

The radio access network connects the User Equipment (UE) through the air interface by implementing one or more radio technologies. The Connected Vehicle Hub includes four base stations implementing 2G, 3G, 4G and 5G-NSA (in 5G-SA design) radio access technologies, configured with the latest available software versions and network features. In terms of frequency spectrum usage, the collaboration with Orange Spain grants permission to radiate in all its common frequency bands, allowing the configuration of specific network scenarios in which the coverage of a combination of these radio access technologies and frequency bands can be adjusted as desired. This agreement between Orange and IDIADA allows the use of commercial and licensed bands for all access technologies.

Its extension to new frequency bands will be studied once new frequency bands are auctioned by the Spanish government according to its 5G deployment plan (such as the 700 MHz already auctioned or the 26 Ghz mm for a future tender).

The 4 base stations are composed of 9 sectors in total, with the following technologies:

- 2G in 1800 MHz (BW = 1TRX per sector).
- 3G in 900 MHz (BW 5 MHz)
- 4G on 1800 MHz (BW 20 MHz) and 2100 MHz (BW 10 MHz)
- 5G NSA on 3500 MHz (BW 60 MHz)

As mentioned above, 5G SA technology is in the design phase for a short-term deployment, with which we will be able to exploit all the features and virtues associated with 5G, such as latencies between 1 and 4 ms or DL throughputs of up to 20 Gbps and UL up to 200 Mbps.

The services offered with the IDIADA cellular network include the possibility of configuring 4G + 5G Carrier Aggregation (CA) using only the two 4G carriers or disabling it completely to only have traffic with a single carrier. In addition, the MIMO configuration can be modified from the standard $4 \times 4$ to a $4 \times 2$ or $2 \times 2$ configuration.

This is achieved by modifying the network characteristics so that a customer can test the performance of their systems in non-optimal situations.

In parallel, power reductions can be applied to all radio technologies (together or separately) to emulate adverse coverage level conditions.

If a customer wants to evaluate the performance of its systems and services when moving from one technology to another, HandOvers (HO) can be forced between the different Radio Access Technologies (RATs), so that it can move, for example, from being in a cell with 5G coverage to another with 2G. In this way, the user has the possibility to test mobility by making HO between cells of different technologies.

In short, the IDIADA network can be adapted to recreate different scenarios in which users can test their systems and services in a private and confidential environment, emulating features and issues of a public network.

To ensure that developments in the field of testing can be deployed commercially, it is essential that the cellular network used in IDIADA approximates that available in public networks, as all standalone developments will need to use standard public providers without significant network modifications.

To this end, IDIADA's cellular network is built on high quality commercial equipment that guarantees relevant results. The current 5G deployment is NSA with a roadmap already defined for the introduction of 5G SA.

### 2.3 5G Ecosystem Validation

The Connected Vehicle Hub is the pure connectivity tool testbed with which IDIADA studies, develops and implements the multiple use cases required by European Commission projects.

C-MOBILE was one of the most important projects for the development of C-ITS tools, services and applications, similar to TARGET X or 6G TWINROAD today, promoting innovations such as Digital Twin creation services for the pre-validation and testing of automotive systems, services to enhance the Cooperative Perception of vehicles, not only using current V2X standards but also taking advantage of commercial cellular networks introducing NR-V2X technologies, services to improve the Vulnerable Road Users safety in the CCAM environment and, finally, services to identify strategies with which the infrastructure can improve the Quality of Service for road users using prevention algorithms.

Furthermore, through TARGET X, IDIADA will add an edge node to enhance the aforementioned services using edge computing technology, with the aim of finding a balance between the advantages of cloud services and those of on-premises services.

## 3 Conclusions and Next Steps

The continuous evolution of network capabilities, including hardware, software, and new features to be implemented, allows the Connected Vehicle Hub to match the characteristics of the commercial network with the aim of offering a real driving experience to allow the development and testing of Cooperative, Connected, and Automated Mobility (CCAM) solutions. Specifically, the evolution of the network towards 5G-SA will have the highest priority, given the impact it is expected to have on the development of a whole new set of applications for connected vehicles and communications in general, while allowing an improvement in performance and smoothing the way for the introduction of full driving automation.

On the other hand, the progressive introduction of wireless communication modules in the vehicle will encourage the development of new cooperative, connected and automated mobility applications and services. This will require existing and new test facilities to adapt their physical infrastructure to support the development of this type of application, adopting wireless technologies to provide them with the necessary communication capabilities. IDIADA's Connected Vehicle Hub implements both DSRC and cellular networks, offering a complete development and test environment that enables system-level and vehicle-level validation of C-ITS applications and connected and autonomous vehicle functionalities.

As a next steps IDIADA has planned at short and middle term to deploy a new C-V2X network and a new 5G SA Core.

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# Results from CEDR-Work Done Around Intelligent Access

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**Abstract.** The working group Road Freight Transport in CEDR (Conference of European Directors of Roads) performs different tasks. One is about Intelligent Access, later only referred to as IA. The used definition of IA is to ensure "the right vehicle on the right road at the right time with the right weight".

The goal for the work is to collect best practice of IA and recommendations for implementation. IA is a rather new concept in Europe but has been used in Australia for more than 15 years (TCA 2018).

Conclusions from the work so far are. A survey and in-depth interviews show that National Road Authorities sees the concept of IA as something with many possibilities. Using IA as an enforcement tool is the most obvious interpretation of the concept and when scaling up also other opportunities become visible, such as better coordination of traffic and logistics, better use of infrastructure, control of emission zones, monitoring of abnormal transport and transport of dangerous goods.

This gives possibilities for almost all stakeholders and therefore also for society. In this way, can also NRAs improve the quality of their services. The example from Italy, there you use IA for abnormal transports, shows a use case that give benefits to all involved and showing benefits and/or incentives for all involved will be important for the implementation of IA.

**Keywords:** Connected vehicles · Telematics · Enforcement · Weight control · Decarbonization · Digitization

## 1 Background

Most road vehicles are today connected and that gives many possibilities to send information both to and from these vehicles. This has enabled many location-based services and applications, for example by geofencing, which can be defined as an application that triggers a response when the vehicle passes a virtual boundary. Australia pioneered using this technology for assuring that school buses comply with regulations and time schedules and was the first country to introduce IAP (Intelligent Access Program). Now is the main area of use to on dedicated roads allow larger trucks than allowed for general access, so called High Capacity Vehicles (HCV).

IA could be defined in different ways but our definition of IA is as follows:

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*A regulatory framework using vehicle technology (where the vehicle reports its position and other relevant parameters) to ensure the right vehicle with the right cargo/freight, operates on the right road, at the right time to secure minimum impact on environment, infrastructure, human health & safety, and society.*

Intelligent Access can be used in a lot of areas:

- Better use of existing infrastructure with traffic management based on time and place
- Less degradation of road infrastructure through improved management of weight, speed and routing of heavy vehicles
- Realizing climate objectives by reducing congestion and prioritizing climate-friendly vehicles
- Increasing road safety through, for example, less overloading or insight into safety events in relation to location
- Create a level playing field between carriers, as the risk of truck overloading is reduced
- Improved control of the transport of abnormal loads and dangerous goods;
- Controlled introduction of High Capacity Vehicles
- Faster and more controlled processing of transport documents in cross-border transport through digitalization

This was the reason to why the CEDR (Conference of European Directors of Roads) working group of Road Freight Transport started a task group about IA.

This work started in the first half of 2021 and was in the beginning focused on a report (Asp, et al., 2022). The main goal for the work with the report was to collect best practices about IA and recommendations for implementation. Another goal was to see in which areas NRAs (National road authorities) could see potential in using IA.

This paper will present results from the work with the report and but also results from a webinar and a GDPR-workshop but not the work with a just started CEDR-Call.

## 2 Completed Activities

Following activities has been undertaken to collect information from different stakeholders, mainly NRAs:

1. A survey were conducted in CEDR with a response from 12 countries
2. Based on the results of the survey, in-depth interviews were held with 5 countries
3. In collaboration with PIARC, a webinar was organized on January 27, 2022 with the participation from Australia, the Americas and Europe.
4. In collaboration with PIARC, a GDPR-workshop was organized on October 19, 2022 with the participation of stakeholders from different areas in Europe

Results from these activities has been summarized and analyzed and will be presented in upcoming chapters.

### 2.1 Results from Survey/Questionnaire

In June 2021, CEDR's WG 3.11 Road Freight transport launched a survey on the topic of intelligent access.

The purpose of the survey was to collect knowledge and best practices about how NRAs can use IA and how IA can be implemented. Twelve countries participated in the survey.

Conclusions from questionnaire:

- Five of twelve answering countries has implemented IA or plan to do it. This means that seven countries doesn´t do it but all countries could see possibilities in IA. Estonia (mostly timber transports) is in the lead but also Italy (abnormal transports) has IA in real use. Austria, Netherlands and Sweden have planned different form of pilots. It is clear that we have a growing interest for this subject.
- Possible use of IA was to monitor transport of dangerous goods together with control of abnormal transports. To manage the entry of vehicles whose weight exceeds a predefined threshold for example on certain bridges and to be able to introduce HCV in a controlled manner had also a "yes" from more than half of the respondents.
- Data they wanted to collect was position, weight (total and on axle), volume of heavy traffic and vehicle type. What sort of data you want to collect depend a lot on the purpose of collecting the data and/or the planned use of data.
- The level of reliability on data should be so good that it can be used for preselection of vehicles for control and for statistical use. Having so good reliability so that you can use data for direct enforcement will probably be interesting in the future.
- Most important stakeholders are road and vehicle authorities but all stakeholder (OEMs, Logistic service providers, drivers and their unions, shippers, policy makers) needs to be involved.
- It is obvious that there are obstacles that need to be solved and there are solutions for most of them. Obstacles are widely spread all the way from personal integrity like GDPR to lack of political willingness but there are also EU-regulations like eFTI and eCMR that can help introduction.

### 2.2 Results from in Depth Interviews

**Italy.** Through an integrated telematics monitoring system Ulisse (Unified Logistic Infrastructure for Safety and Security) allows for the tracking of vehicles carrying dangerous goods and waste in the Campania Region. The information recorded by the system facilitates an organized and rational management of flows through the planning of itineraries or the "booking" of spaces at the nodes. In this way, it is possible to plan the activities of loading/unloading and boarding of vehicles and goods. This results in a significant reduction in operating times and costs and speeds up the bureaucratic activities and the movement of goods in the ports.

The Teweb APP is similar to Ulisse but is designed to monitor abnormal loads. Special Transport: TEWeb | Anas S.p.A. (stradeanas.it).

**Netherlands.** A pilot on intelligent access started in the Netherlands September 2021. This involves two consortia providing monthly reports with road authorities that will provide insight into the performance of heavy-duty vehicles. The pilot was running until May 2022. The aim of this pilot is to learn by doing and is part of a larger project investigating the feasibility and scalability of intelligent access.

This pilot is driven by the need to better understand the use of the road network by heavy-duty vehicles and transports of abnormal goods. The pilot will help track the

routes of these approved abnormal loads. The management of network assets can also be smarter if there is more data on the actual use of the road by heavy vehicles and freight traffic.

In this pilot is it especially important to show policymakers and the market how IA can work and what possibilities it offers. Results from pilots will be presented at the conference.

**Sweden.** In Sweden, an IA-system has been developed but it is not yet implemented. It uses in the vehicles already installed fleet management systems. The on-board computer registers GPS position, axel loads, and the ID of the prime mover and all vehicle modules, which is saved in the cloud or directly reported to a telematics service provider (Asp 2016 och Asp 2018).

There are now two ongoing projects on IA in Sweden. One for digitalization of the process for abnormal loads and one for allowing higher weight then the roads are frozen. The main scope in the ongoing pilots there are to control speed when the trucks pass bridges that not are strong enough for the ordinary speed. This has worked well and the main obstacle has been to set right coordinates for the trucks geofencing system.

**Estonia.** Since 2010 Estonian Transport Agency (ETA) has been developing IA. In the beginning, it was meant only for the wintertime 52t timber transport, if the pavements were frozen. At the same time, the strong infra corridors were analyzed and mapped. Together was this used in the VELUB system, there it was possible to apply for a special vehicle permit. The VELUB principle is also shown in the figure below (Fig. 1).

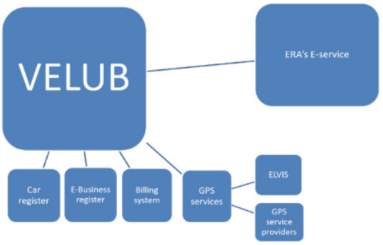



**Fig. 1.** The VELUB system in Estonia

Estonia has tested new cloud-based logistic systems in the logistics digitalization area, some are now in pilot face: eCMR | Real-time economy (realtimeeconomy-bsr.eu). Possible future use is, if the heavy vehicle is in the wrong road corridor or has a total mass over the limited value.

### 2.3 Results from CEDR-PIARC Webinar

**Introduction.** CEDR and PIARC jointly organized a webinar to share knowledge and experiences on Intelligent Access Policies for road freight transport with experts from all over the world. Below are the main takeaways from presentations and panel discussion summarized.

**The Main Takeaways**

*Taking Advantage of Opportunities*

We need to understand the importance of creating incentives that make it interesting for parties in the logistics chain to share data. There is a strong link with sustainability. With the help of Intelligent Access, the emissions become transparent, so that the shipper can also demonstrate their ecological footprint for the transport and formulate ambitions for it.

*The Promises of Intelligent Access*

IA technology can bring useful information for drivers and vehicle. This will help traffic management and therefore road authorities. There are various expectations and statements regarding the relationship between IA and harmonization. Stakeholders who are currently dealing with a patchwork of regulations in different countries hope that IA will lead to harmonization in regulations but that is not obvious. This is an important incentive for certain stakeholders to participate in IA and it is important to further explore this relationship.

*Are We Ready for IA?* Various domains play a role in technology and we need to understand that better. Authorities could/should play a role in promoting technological readiness. This can range from making telematics devices in the vehicle mandatory to promoting the eCMR. Authorities also have to analyse more what their needs are and what they want to achieve. We need collaboration between stakeholders who are normally more likely to oppose each other.

### 2.4 Results from GDPR-Workshop

Main takeaways from the workshop were.

- Legislation about GDPR is not just a barrier there are also possibilities in the six legal grounds that could and should be used when you process personal data. One example is if the data subject has a contract with the data controller.
- There is a distinction between the rules and the interpretation of those rules
- The underlying principle should by default be to share as little data as possible. The question should therefore not be how could we circumvent the GDPR, the question should be. “Why do I need which data and are there perhaps alternatives that require fewer personal data.”
- There is a distinction between data and information and usually you don´t need all the data you only need the information you can get from all the data

## 3 Topics for Further Exploration

1. *Rewarding desirable behaviour instead of punishing undesirable behaviour.*
   How can we get all stakeholders on board? How do we build in efficient incentives? Show the benefits of transparency for all stakeholders involved.
2. *IA as catalyst for harmonization of regulations.*
   How can IA promote harmonisation of regulations? If it doesn´t promote harmonisation, what other incentives are there for the transport sector to participate in an IA system on a voluntary basis?

3. *Transformation of the relationship between transport sector and government.* What change in the attitude of the transport sector on the one side and the government on the other side do we need?
4. *The organization of trust.* Third party / authority vs block chain? How can we secure the reliability of self-declaration system? How do we create information with minimum of data processing?

## 4 Discussion and Conclusions

The survey and the in-depth interviews show that many National Road Authorities (NRAs) sees the concept of IA as something with a lot of possibilities.

Using IA for enforcement is the most obvious interpretation of the IA concept but there are also many other opportunities such as better coordination of traffic and logistics, better use of infrastructure, control of emission zones, monitoring of abnormal transport and transport of dangerous goods.

This gives possibilities for almost all stakeholders like transport companies and shippers, therefore also for society. In this way, can also NRAs improve the quality of their services. The example from Italy, there you use IA for abnormal transports, shows a use case that give benefits to all involved and showing benefits or incentives for all involved will be important for implementation of IA.

At the heart of the IA concept lies the legislation for the protection of personal data. Also, during the panel discussions of the webinar, organizing of trust and legal basis of data collection appeared to be important issues. To be able to implement many of the use cases of IA so will we need to find adequate solution for these issues.

In Europe, the protection of personal data is regulated in the General Data Protection Regulation (GDPR). It is an advantage that the same law binds all European countries. This was the reason to the GDPR-workshop that were organized in October 2022. At the GDPR workshop, we got insights not just about barriers with GDPR but also about possibilities that could and should be used. Again, the importance about saving and sharing as little data as possible was shown.

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# Trustworthy AI on the Road

## A Legal Perspective

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**Abstract.** The proposed AI Act lays down requirements for so-called high-risk AI-systems that need to be met by the high-risk AI-system and its provider. These requirements contain core elements for trustworthy AI such as transparency, technical robustness, and human oversight. Automated vehicles are considered to be high-risk AI-systems, but nevertheless these requirements do not (fully and directly) apply to these vehicles. Automated vehicles are excluded from the scope of the proposed AI Act, as the functioning, safety and security of cars driving on EU public roads are governed by existing acts specifically applicable to vehicles. This causes a gap between the findings of two ethics expert groups (EC High-Level Expert Group on AI and the Horizon 2020 Commission Expert Group to advice on specific ethical issues raised by driverless mobility) and the EU legislation for AI-systems of automated vehicles. This contribution will therefore explore two questions: what current legislation is in place that contributes to achieving the core elements or principles of trustworthy AI in automated vehicles and how can a (future) legislative framework for automated vehicles realize these core elements for trustworthy AI?

**Keywords:** AI · Automated Driving · Responsible · Regulation · Liability · Policy

## 1 Introduction

Transportation systems are becoming increasingly more digitised and reliant on the use of Artificial Intelligence (AI). In road transport, the use of AI can bring automated driving closer to reality. The use of AI, however, also poses risks. These risks are related to the very nature of AI systems: complexity and opacity as well as unpredictability can present danger.

The European Commission has recognised these risks of AI systems and acted by way of proposing the so-called AI Act. At the moment of writing, the AI Act is being negotiated, so amendments will be made. For reasons of brevity, this contribution only refers to the European Commissions proposal of 2021.

This proposed AI Act lays down requirements for high-risk AI systems in Chapter 2 of Title III. This includes, for instance, requirements on: data governance (art. 10); record-keeping and technical documentation (art. 12, art. 11); transparency (art. 13); robustness

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and cybersecurity (art. 15); and human oversight (art. 14). These requirements reflect ongoing ethical discussions on trustworthy AI.

Automated vehicles are considered to be high-risk AI systems (art. 3, 6). However, art. 2 of the AI Act limits the scope of the AI Act, thereby leaving (safety components of) products or systems falling within the scope of the EU Type-approval Regulation or the EU General Safety Regulation outside of the scope of the AI Act. Only when adopting implementing acts relating to the General Safety Regulation, do the requirements of Title III, Chapter 2 of the proposed AI Act have to be taken into account (art. 82). Consequently, a high-risk AI system (the automated vehicle) with which the public might see itself confronted with on a daily basis, would not have to be in conformity with the proposed AI Act and its requirements on transparency, robustness, and so on. This appears to be in conflict with the recommendations of the High-Level Expert Group on AI (AI HLEG), as well as the findings of the Horizon 2020 Expert Group to advice on specific ethical issues raised by driverless mobility (Horizon 2020 Expert Group 2020). This contribution will therefore explore two questions:

- What current legislation is in place that contributes to achieving the core elements of trustworthy AI in automated vehicles?
- How can a (future) legislative framework for automated vehicles realise these core elements for trustworthy AI?

Thereby, how these elements and requirements for trustworthy AI are and can be respected in the regulatory framework is explored. This study adds to the existing literature by bridging the gap between the outcomes of ethics research and legal developments.

## 2 Ethics Expert Groups on Trustworthy AI

### 2.1 AI HLEG

The AI HLEG states that 'Trustworthiness is a prerequisite for people and societies to develop, deploy and use AI systems' (AI HLEG 2019, 4). When not worthy of trust, unwanted consequences could develop and the uptake of AI systems might be hindered (AI HLEG 2019, 4). The experts list three requirements that should be met throughout the lifetime of an AI-system: it should be lawful, ethical and robust (AI HLEG 2019, 5). The AI HLEG develops principles that contribute to the requirements of robust and ethical AI, as they 'proceed on the assumption that all legal rights and obligations that apply to the processes and activities involved in developing, deploying and using AI systems remain mandatory and must be duly observed' (AI HLEG 2019, 6). Four ethical principles are formulated: (1) respect for human autonomy, (2) prevention of harm, (3) fairness, (4) explicability (AI HLEG 2019, 12). The AI HLEG expert group derives 7 requirements from these principles (though this list is not exhaustive) (AI HLEG 2019, 14): (1) Human agency and oversight; (2) Technical robustness and safety; (3) Privacy and data governance; (4) Transparency; (5) Diversity, non-discrimination and fairness; (6) Societal and environmental wellbeing; (7) Accountability. Compliance with these principles should ensure the trustworthiness of AI, thereby facilitating the safe and responsible development of AI systems.

### 2.2 Horizon 2020 Expert Group

Whereas the principles of the AI HLEG are designed for trustworthy AI in general, the Horizon 2020 Expert Group focuses specifically on connected and automated vehicles (CAVs). The Horizon 2020 Expert Group has drawn up 20 recommendations that can be divided into three broader topics/themes: (1) road safety, risk dilemmas, (2) Data and algorithm ethics: privacy, fairness and explainability, (3) responsibility (Horizon 2020 Expert Group 2020, 4–5). The recommendations range from reducing physical harm (recommendation 1) to safeguarding informational privacy (recommendation 5) to creating fair and effective mechanisms for granting compensation to victims of crashes or other accidents involving CAVs (recommendation 20). It goes beyond the scope of this contribution to discuss the recommendations more in-depth, but it is already clear that several recommendations of the Horizon 2020 Expert Group show similarities to the 7 requirements formulated by the AI HLEG.

## 3 Ethics and the AI Act

The findings of both the AI HLEG and the Horizon 2020 Commission Expert Group show some similarities or overlap. Most notably, the following elements seem to be recurring in both reports of the expert groups as well as the AI Act (in no particular order):

- Ensuring technical robustness and safety (AI HLEG requirement 2; Horizon 2020 Expert Group recommendations 1, 2, 3, 4; art. 15 AI Act)
- Privacy or data governance (AI HLEG requirement 3, Horizon 2020 Expert group recommendations 7, 9, 10, 13, 15; art. 10 AI Act)
- Transparency (AI HLEG requirement 4; Horizon 2020 Expert Group recommendations 10, 12, 13, 14, 18; art. 13 AI Act)
- Human oversight (AI HLEG requirement 1; art. 14 AI Act)

As automated vehicles fall outside of the scope of the AI Act, the question arises what current legislation is in place that contributes to achieving these four core elements of trustworthy AI in automated vehicles. Simply because the AI Act does not (directly) apply, does not mean that the above identified principles or requirements are not supported by other legislation. Therefore, each of the four principles will be discussed in light of the current legal framework to identify how this framework is already catering to these principles.

## 4 Ethics Principles in the Current Legal Framework

### 4.1 Technical Robustness and Safety

Ensuring the technical robustness and safety of automated vehicles can be achieved via different routes, including the EU type-approval framework as laid down in the EU Type-approval Regulation. The EU General Safety Regulation already sets requirements for (fully) automated vehicles in art. 11. In addition, requirements from the UN Regulations (can) contribute to the automated vehicle's safety and technical robustness. UN R155 on cybersecurity, for instance, is an important instrument in ensuring vehicles' digital security and thereby fostering the safety of vehicles.

### 4.2 Privacy and Data Governance

Privacy and data governance are not just important in relation to the automotive field, they are topics that are of great importance in all sectors. Regardless of the sector, when it comes to processing personal data ("personal data' means any information relating to an identified or identifiable natural person ('data subject'); an identifiable natural person is one who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person') the General Data Protection Regulation (GDPR, art. 1, 4) applies. In addition, the EU Data Governance Act sets requirements for the re-use, within the EU, of certain categories of data held by public sector bodies (art. 1) and the proposed Data Act lays down harmonised rules on making data generated by the use of a product (like an automated vehicle) 'available to the user of that product or service, on the making data available by data holders to data recipients, and on the making data available by data holders to public sector bodies or Union institutions, agencies or bodies, where there is an exceptional need, for the performance of a task carried out in the public interest' (art. 1(1)). Legislation specifically for (automated) vehicles also lays down some rules on the recording of data: the General Safety Regulation provides some provisions on data recording (e.g. art. 6(4)), as work is being done on a data storage system for automated driving (DSSAD) at a UN level.

### 4.3 Transparency

Other than with robustness and safety as well as privacy and data governance, transparency seems to be lacking in the current legal framework for automated vehicles. There are elements of transparency in UN regulations and the type-approval process, but these requirements do not seem to achieve the level of transparency strived for in the proposed AI Act: 'High-risk AI systems shall be designed and developed in such a way to ensure that their operation is sufficiently transparent to enable users to interpret the system's output and use it appropriately' (art. 13(1)). Especially when it comes to transparency towards users, legal lacunas seem to exist. Domestic legislation could fill this gap, setting requirements in this. In addition, the EU Product Liability Directive might provide an incentive for manufacturers of automated vehicles to inform the vehicles' users of its possibilities and limitations: if not or incorrectly informed, the manufacturer might be found liable for resulting damage (art. 6(1)).

### 4.4 Human Oversight

The proposed AI Act requires that 'High-risk AI systems shall be designed and developed in such a way, including with appropriate human-machine interface tools, that they can be effectively overseen by natural persons during the period in which the AI system is in use' (art. 14(1)). Human oversight, according to the AI HLEG, can help in ensuring human autonomy by for instance enabling human intervention in every decision cycle of the system (AI HLEG, 16). This gives rise to the question of whether human oversight is contradicting the idea of automated vehicles, in which a human is taken 'out-of-the-loop'

and does not take part in the decision making concerning the execution of the driving task. This could explain why the Horizon 2020 Expert Group does not refer to human oversight in this meaning. Regarding human oversight, this expert group does however explain that algorithmic decisions require adequate explaination (which is closely tied to the requirement of transparency) because 'Without adequate means of access, the role of human agency and oversight is severely weakened or hindered and risks undermining the principles of human dignity and autonomy, with the consequence of critically eroding public trust in these fastdeveloping technologies' (Horizon 2020 Expert Group, 50). The AI HLEG adds to this that 'the less oversight a human can exercise over an AI system, the more extensive testing and stricter governance is required' (AI HLEG, 16). This could mean that establishing human oversight in the development phase might be sufficient. The UN regulations and EU Type-approval Regulation could ensure this.

## 5 Future Law-Making and Ethical Principles

From the analysis above, it is clear that mainly transparency and human oversight are not covered sufficiently by the current legislative legal framework. This means that automated vehicles can be held to a different standard than other high-risk AI systems that do fall within the scope of the AI Act. Given the findings of the AI HLEG and the Horizon 2020 Expert Group, this would be undesirable. As the Horizon 2020 Expert Group points out that 'The timely and systematic integration of broader ethical and societal considerations is also essential to achieve alignment between technology and societal values and for the public to gain trust and acceptance of CAVs [connected and automated vehicles; *NEV*]' (16) it is important that a legal baseline is also estabished for the principles on transparency and human oversight. A harmonised approach, as in other AI and vehicle matters, would be adviseable. However, if this is deemed not feasable, the domestic legislator can step in. For instance, the German legislator requires 'Technisches Aufsicht' when operating an automated vehicle, which seems in line with the human oversight principle (§1d, §1f Abs. 2 Straßenverkehrsgesetz). So even though the proposed AI Act will not be directly applicable to automated vehicles, the key principles and requirements from Title III Chapter 2 can still be ensured.

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## Legislation and Legislative Proposals

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Council Directive 85/374/EEC of 25 July 1985 on the approximation of the laws, regulations and administrative provisions of the Member States concerning liability for defective products

Proposal for a Regulation of the European Parliament and of the Council laying down harmonised rules on artificial intelligence (artificial intelligence act) and amending certain union legislative acts. COM/2021/206 final (2021)

Proposal for a Regulation of the European Parliament and of the Council on harmonised rules on fair access to and use of data. COM/2022/68 final (2022)

Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC

Regulation (EU) 2018/858 of the European Parliament and of the Council of 30 May 2018 on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending Regulations (EC) No 715/2007 and (EC) No 595/2009 and repealing Directive 2007/46/EC

Regulation (EU) 2019/2144 of the European Parliament and of the Council of 27 November 2019 on type-approval requirements for motor vehicles and their trailers, and systems, components and separate technical units intended for such vehicles, as regards their general safety and the protection of vehicle occupants and vulnerable road users, (...)

Regulation (EU) 2022/868 of the European Parliament and of the Council of 30 May 2022 on European data governance and amending Regulation (EU) 2018/1724

Straßenverkehrsgesetz in der Fassung der Bekanntmachung vom 5. März 2003 (BGBl. I S. 310, 919), das zuletzt durch Artikel 16 des Gesetzes vom 2. März 2023 (BGBl. 2023 I Nr. 56) geändert worden ist

UN Regulation No. 155 Uniform provisions concerning the approval of vehicles with regards to cyber security and cyber security management system

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# Simulation Platform to Analyse Future Traffic Regulations for Automated Vehicles in a Mixed Traffic Environment

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**Abstract.** The gradual introduction of automated vehicles (AVs) rises a variety of challenges. Besides technical issues, legal aspects need to be considered, as nowadays driving regulations are orientated towards human drivers. Policy makers will have to define a legal framework for AVs, which will also effect an AVs' driving behaviour and therefore also impacts traffic flow characteristics. To investigate possible legal adjustments for AVs and their consequences, traffic flow simulation (TFS) is an established tool. However, applying TFS requires much simulation and modelling expertise. Hence, we present a newly developed simulation platform, which allows to intuitively define, simulate and analyse a simulation scenario for different generic multi-lane highway segments without extensive TFS expertise. In addition, five exemplary simulation scenarios are investigated, focusing on the effect of temporarily increasing the desired time headway of AVs on the main road in order to assist merging vehicles at the on-ramp. The results showed rather negative effects, as congestion was increased in space and time due to temporarily increasing the time headway of AVs.

**Keywords:** Driving regulations · automated driving · mixed traffic · simulation platform · traffic flow simulation · policy making

## 1 Introduction

The share of automated vehicles (AVs) on European roads is expected to rise, posing major operational and legal challenges for traffic operators and policy makers. There will be a gradual and long-lasting transition phase with mixed traffic, which is widely agreed on among the research community, the industry and road operators. Many studies investigated the effects regarding traffic efficiency and traffic safety for varying AV penetration rates. The results suggest, that traffic efficiency is highly dependent on the future AV driving behaviour and

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their capabilities. If AVs have improved reaction characteristics and are able to keep shorter time headways and reduce traffic oscillations, traffic efficiency will increase, especially with rising penetration rates. However, these characteristics are not guaranteed. Postigo et al. [1] investigated the range of potential impacts on traffic performance in terms of throughput. Three different types of AVs (cautious, normal, aggressive) were analysed. Cautious AVs were modeled with a desired time headway of 1.5 s, which resulted in a lower throughput. Besides technical aspects, legal circumstances need to be considered too. Todays' driving regulations are orientated towards human driven vehicles and are hardly transferable to automated driving systems. Within the proposed amendments for UN regulation 157 [2] specifications with clear thresholds for AV lane changing are defined. Whether such standards will also be integrated into national regulations is not known yet. Since potential effects on traffic need to be analysed carefully beforehand, this will be a difficult task for policy makers.

To investigate such future AV driving regulations traffic flow simulation (TFS) is a proper tool and it is often used to analyse the effects of mixed traffic. However, applying TFS is complex and requires a lot of traffic simulation and modeling expertise. Therefore, we developed a simulation platform, which enables traffic operators and policy makers to easily perform simulation-based analyses of mixed traffic on typical multi-lane highway segments. Within the platform a user can define a simulation scenario intuitively and start a simulation without being a TFS expert. After the simulation is finished, all result files are processed automatically and result tables as well as figures are displayed within the simulation platform. In course of this contribution, we focus on the scope, the structure and the capabilities of the developed simulation platform. The calibration process and the automated driving functions, which are used within the simulation are shown too. The platform allows to simulate a huge variety of scenarios. Hence, we show some exemplary results of five scenarios considering two different AV penetration rates and one specific use-case of temporarily adapting regulations for AV driving behaviour.

## 2 Simulation Platform

The aim of the developed simulation platform is to enable traffic operators and policy makers to easily perform simulation-based analyses. The web-based graphical user interface (GUI) allows to configure a simulation scenario, to run a simulation and to display the simulation results, which guarantees intuitive usage without simulation expertise. The GUI was developed in python utilising the streamlit library [3]. While PTV Vissim [4] is used to simulate on- and off-ramp segments, SUMO [5] serves as back-end for construction site and tunnel segments. Integrating two varying traffic flow simulation tools should ensure openness for any further developments. The network files are automatically generated based on the input values defined via the simulation platform. Additionally, we utilise the DLL-Driver Model provided by PTV Vissim, which allows to replace existing driver behaviour models by newly developed AV driving functions. In

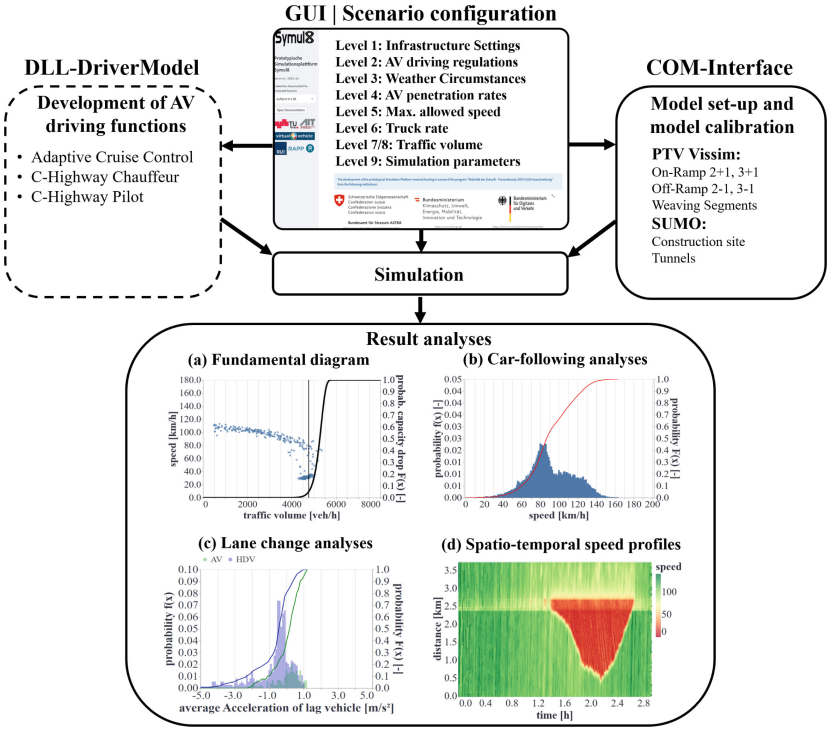



**Fig. 1.** Concept overview of simulation platform. Simulation platform was developed using *streamlit* [3] package (License: Apache 2.0)

the following subsections, we shortly describe the parameters to be defined in the scenario configuration, the developed AV driving functions, the model set-up and the model calibration as well as the automatically processed results, which are shown in the platform after all simulation runs were simulated successfully. A schematic overview of the simulation platform can be seen in Fig. 1.

### 2.1 Scenario Configuration

When starting the simulation platform, the user has the possibility to show the results of already simulated scenarios or to define a new simulation scenario. Based on the defined parameters a unique hash-code is created and allocated to each scenario, which allows to re-open already simulated scenarios and hinders users from simulating the same scenario twice. The scenario configuration is done in a level-based manner (see Fig. 1), where a user can adjust the simulation parameters. First, the user has to define, which highway segment (e.g. on-ramp, off-ramp, weaving segment, construction site, tunnel) to investigate. Depending on the chosen segment, varying infrastructure related parameters can be defined in the first level. For on-ramp segments this includes the length of the acceleration lane and the location of loop detectors. In a next step, the

user may defines different AV driving regulations in the second level. These possible future AV driving regulations were elaborated based on an international workshop focusing on legal aspects from the perspective of increasing vehicle automation. The third level allows to parameterise weather circumstances (e.g. sunny, rainy, cloudy weather with bad visibility). In the forth level, the AV penetration rates can be set, the maximum allowed speeds needs to be selected in level five and the truck rate can be defined in level six. For on-ramp segments, the share between vehicles entering via the on-ramp and vehicles entering via the main carriageway can be chosen in level seven. Next, in level eight the traffic volume can be defined for every 5-min interval. As default, traffic volume is getting increased in a 5-min cycle. After 2/3 of the simulation time, traffic volume reaches the maximum level and is decreased again, which allows to investigate varying traffic states including the dissolution of congested traffic. In the last level simulation parameters, like the number of simulation runs and the simulation duration can be selected. All parameters are adjusted automatically within the simulation environment.

### 2.2 Automated Driving Functions

Three different levels of AV driving functions were developed and integrated into the simulation platform. A connected environment is assumed, which means that the AV driver models receive vehicle state information (speed, acceleration, etc.) of all surrounding vehicles, including obstructed vehicles. For AVs with Adaptive Cruise Control (ACC) only the longitudinal behaviour is executed by the AV driving function, lane changing behaviour is controlled by Vissims' internal lane change model, which reflects human driver behaviour. Additionally, we introduce a Connected Highway Chauffeur (C-HC) and a Connected Highway Pilot (C-HP), for which both the longitudinal and lateral control is done by the AV driving function. However, the lateral control of the C-HC driving function is only active on the main road. Therefore, a C-HC equipped AV is not capable of performing mandatory lane changes (e.g. merging at on-ramp). The C-HP is active in all areas and is also able to plan and execute merging and diverging lane changes in on-ramp and off-ramp areas, respectively. For longitudinal control, an ACC-controller was implemented. For lane changing we developed a rule-based gap acceptance framework, which is shown in Hofinger et al. [6].

### 2.3 Model Calibration

Since reliable results are crucial, human driver behaviour was calibrated extensively utilising varying data sources. Based on single vehicle data from multiple highway cross-sections we computed various desired speed distributions and time headway distributions to calibrate car-following behaviour. To also calibrate lane changing behaviour, trajectory data from aerial videos of drones was investigated. We developed a 3-step calibration process, that is described in detail in Hofinger et al. [7]. Any adaptions in human driver behaviour due to the existence of AVs were neglected, since there is only little data available.

### 2.4 Processing Simulation Results

After each simulation, the results files are processed automatically. Besides single vehicle cross-sectional data, all simulated vehicle trajectories are investigated. In the result section of the simulation platform, we first included overall simulation statistics with the most relevant indicators (e.g. travel time, delay, number of simulated vehicles, etc.). Next, the user can choose a cross-section for which the fundamental diagram will be displayed as shown in Fig. 1a. Given that the capacity was reached, a stochastic capacity estimation is computed based on the work from Geistefeldt et al. [8]. To investigate car-following properties (see Fig. 1b) speed distributions and time headway distributions are presented for a selected cross-section within the platform. Regarding lane changing, a gap acceptance distribution is computed and the reaction of approaching vehicles on the target lane due to lane changing vehicles can be investigated (see Fig. 1c). Last, the spatio-temporal speed profiles (see Fig. 1d) are displayed within the simulation platform. There, the user can select the simulation run for which the results should be shown. The spatio-temporal speed profiles allow the user to assess the overall impact on traffic flow and to investigate the spatio-temporal occurrence of congestion.

## 3 Simulation Experiment and Results

In this section, we show the results of 5 simulation scenarios for which the described simulation platform was utilised. A 2+1 on-ramp (OR) scenario, with 2 lanes on the main road (MR) and one acceleration lane with a length of 250 m is focused on. The desired time headway (DTH) for AVs was parameterised with 1.0 s. Within two scenarios (S2, S4), we assumed that AVs on the main carriageway need to increase their following time headway in the on-ramp area to 1.5 s, which is intended to ease the merging lane change of AVs at the on-ramp. In addition, two varying penetrations rates (PR) are investigated. We assumed, all AVs being equipped with a C-HP driving function.

In Table 1 the maximal congestion length and the total duration of congested traffic are displayed for all scenarios. This indicators were derived from

**Table 1.** Overview simulation results of maximal spatiotemporal propagation of congestion on the main road (MR) and on the on-ramp (OR)

| Scenario | AV PR [%] | AV DTH [s] | | congestion length [km] | | congestion duration [h] | |
|---|---|---|---|---|---|---|---|
| | | MR | OR | MR | OR | MR | OR |
| S0 | 0 | – | – | 2.53 | 1.02 | 1.25 | 0.80 |
| S1 | 25 | 1.0 | 1.0 | 2.58 | 1.75 | 1.70 | 0.99 |
| S2 | 25 | 1.0 | 1.5 | 2.92 | 1.82 | 2.19 | 0.99 |
| S3 | 50 | 1.0 | 1.0 | 2.10 | 1.52 | 1.62 | 0.97 |
| S4 | 50 | 1.0 | 1.5 | 2.80 | 1.48 | 2.03 | 1.05 |

the spatio-temporal speed profiles. Compared to the base case with only human driven vehicles, the spatiotemporal propagation of congestion increased with an AV penetration of 25%. With an AV penetration rate of 50%, congested traffic could be reduced on the main road, while an increase could be observed at the on-ramp. The temporal increase of the desired time headway for AVs on the main road, which should ease the merging lane change of vehicles at the on-ramp caused rather negative effects. Traffic flow characteristics deteriorated on the main road and on the on-ramp. Further analyses revealed that increasing the time headway for AVs on the main road supports merging AVs at the on-ramp. However, due to the increased time headway, traffic capacity on the main road was reduced. Therefore, congested traffic could be observed already in an earlier stage on the main carriageway, which also effected the on-ramp traffic flow.

## 4 Conclusion and Outlook

In course of this work, we presented a simulation platform, which was developed to investigate AV driving regulations without extensive TFS expertise. In addition, some exemplary simulations were conducted. The results showed that traffic throughput is slightly decreasing if AVs on the main carriageway increase their desired time headway in merging areas. Traffic safety aspects were not addressed in our current work. This will be part of our future research, since we plan to integrate a traffic safety evaluation module into the simulation platform.

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# Decision-Making Process for (National) Road Authorities to Invest in Information Support for Automated Driving Systems

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**Abstract.** Current Automated Driving Systems (ADS) immaturity causes a lot of uncertainty for road authorities as they cannot decide with confidence what is the best way to anticipate ADS development and deployment to preserve operational safety and efficiency on their road network. Typically, the actual competencies of ADS in the operating environment are not entirely known and ADS capabilities are regularly overestimated or underestimated based on assumptions that are derived from the scarce information that is publicly available. At the same time, many different situations can occur on open roads and in variable traffic and weather conditions, in particular when these roads are dynamically managed by the road operator (e.g. lane, speed and tunnel management). It is natural that National Road Authorities (NRAs) are concerned about the introduction of ADS that execute the complete dynamic driving task. The most constructive and perhaps only way forward is to create a dialogue between road authorities, automation system developers and regulators. The decision making process presented in this paper aims to support NRAs in this conversation.

**Keywords:** Automated Driving Systems · Operational Design Domain · Infrastructure support · Traffic Management · Decision-making · Road Authorities

## 1 Introduction

A basic principle of Operational Design Domains (ODD) is that an Automated Driving System (ADS) continuously evaluates if it can operate in the local conditions based on the situational awareness it has. The Distributed ODD attribute Value Awareness (DOVA) framework as defined in [1] enables the ADS to benefit from off-board sensing infrastructure and data sources to become aware of ODD attribute values which it may not be able to measure or sense by itself. Typically, the earlier the information is available,

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the more options are possible for the ADS to respond (operational, tactical, strategic). The objective for making off-board information available is to enable timely transfer of the dynamic driving task (DDT) to the driver in case of Level 3 ADS (and thereby decrease the risk of minimal risk maneuver in case the driver does not respond) or avoid the need for a transfer of control entirely. Whereas in case of Level 4 ADS the aim is to avoid the minimal risk maneuver or to achieve a safer minimal risk condition.

An important understanding related to the operation of ADS with the DOVA concept is that (only) the ADS decides if it is capable to handle the current local conditions based on its situational awareness. This has three implications for national road authorities (NRAs) that are regularly misunderstood:

1. Traffic management systems will not actively manage the tactical or operational decision making of ADS, i.e. activate and de-activate automation, instead its added value to ADS and thereby traffic safety lies in improving the situational awareness of ADS and providing strategic guidance.
2. The driving rules and expected driving behaviour must be defined in regulations such as the Vehicle General Safety Regulation and UN Regulations. ADS developers will define the ODD of their systems in line with the boundaries as defined by these regulations.
3. Information beyond the line-of-sight of vehicle sensors is relevant for timely anticipation of the downstream conditions. This is how NRAs can support ADS the most today, by providing information in advance. Currently there is no indication that ADS will comply with tactical and/or strategic guidance provided by e.g. a TMC. It could decide to follow strategic guidance regarding for example identifying the fastest route to take to reach a particular destination.

With these implications in mind it seems pivotal that the concerns and experiences of road operators are considered upfront and that ADS technology developers and road operators jointly interpret ADS regulations [2] to assess if known edge cases and known safety critical situations in day-to-day operations are sufficiently covered. In addition, regulations could provide a framework for ‘expected drivership’, which lets the ADS to decide if it can operate under a particular local conditions. Such a framework could specify the minimum driving skills and acceptable driving behaviour of ADS in a particular situation. In other words, it describes the rules of the road an ADS must adhere to as well as the driving behaviour the ADS is supposed to reveal. This principle is discussed in [3] whereas this paper focusses on the role of NRAs.

## 2 Decision-Making Process for NRA Role

Current ADS immaturity causes a lot of uncertainty for road authorities as they cannot decide with confidence what is the best way to anticipate ADS development and deployment to preserve operational safety and efficiency on their road network. How should they act? What investments to make? What information is most important to ADS and NRA core business? To support NRAs in creating a dialogue with automation system developers and regulators, the flow diagram below was developed [4] and aims to break down the assessment of any use case into smaller elements (Fig. 1).

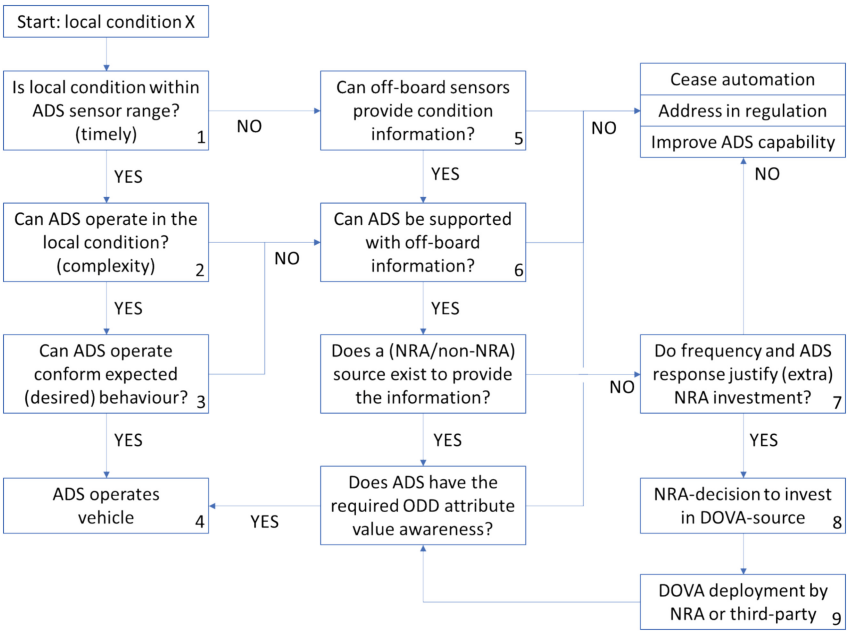



**Fig. 1.** Decision-making process for NRA role.

For any given use case (i.e. the combination of a local condition of concern and an ADS), the first question to ask is (1) whether the local condition is within the ADS sensor range so that the ADS can respond to the condition in time. For example, a downstream traffic jam or weather condition is typically not within the sensor range of ADS. If the local condition is within the ADS sensor range, the next question (2) to ask is whether the ADS can operate in the local condition or not. In other words, is the local condition within the ODD of the ADS and when the ADS detects it, is the ADS able to handle the complexity of the situation? If the answer is positive, the third question (3) to consider is whether the ADS can operate the vehicle to conform with expected or desired driving behavior. Perhaps the ADS decides it can operate in the local conditions, but the resulting driving performance is poor, for example a (too) low driving speed and/or a (too) long response time. Clearly, the assessment of driving performance requires a benchmark to determine what is 'correct' and acceptable behavior as stated above (and the ADS should not try to perform the DDT if it cannot do this according to the rules of the road). If all three questions are answered 'YES', the ADS can operate the vehicle also from the point of view of the NRA.

However, the answer 'NO' to any of the first three questions leads to another flow which is more NRA-oriented. The first consideration (5) is whether off-board sensors can provide information about the local condition of concern. If so, it is worthwhile to assess (6) if the ADS will actually benefit from off-board information in the particular local condition. If the situational awareness and/or decision making modules of ADS are not able to process and act on the information or it will not improve the driving behavior of the ADS, there is no point in making it available. Though, when both questions are

answered positively and no (non-NRA) source exists that can provide the information, the NRA has to weigh (7) if the frequency of the local condition occurring and the impact of the ADS response to the local condition justify and require investment by the NRA. This is a policy and planning decision.

For this deliberation it is important that NRAs are well informed about ADS competencies, capabilities and driving behavior, as well as differences between high-end and low-end vehicles, current and future vehicle capabilities, and different brands of vehicles. With regards to the driving behavior of ADS more precise information about the minimal risk maneuver is needed, in particular what the minimal risk condition (MRC) is. The MRC is entirely situation dependent and represents the lowest risk action that can be taken under the current combination of vehicle and ADS failures, ambient conditions, current traffic density surrounding the ADS vehicle, whether a hard shoulder exists nearby and whether that shoulder is open or obstructed by other vehicle(s) or debris. From the NRA and traffic safety viewpoint it matters greatly if minimal risk condition means a full stop in the driving lane, or if it means to stop the vehicle on the hard shoulder or to continue driving the vehicle at 60 km/h. Finally, even when the frequency of occurrence and impact of the ADS response to the local condition justify exploring counter measures of some sort, it does not necessarily mean that NRAs are required to act. For some local conditions the sensible outcome may be that the ADS is inadequate and the logical solution is appeal to the vehicle manufacturer to improve the ADS capability. In case the questions 5–7 are answered 'YES' it means that the outcome is in favor of (8) a Distributed ODD attribute Value Awareness solution. There are several governance options for NRAs to move forward at this point, ranging from the NRA doing the information collection, processing and distribution to mandating a (trusted) third-party to fulfil this job. Either way, when the DOVA solution is present (9) and information about the local condition is available to the ADS, the ADS can operate the vehicle (3).

Lastly, the answer 'NO' to any of the NRA-related questions (5–7) leads to the outcome that the ADS must not operate in the case of this particular local condition. This means that the necessary situation awareness cannot be obtained by ADS due to the absence of information, ADS are not designed to operate in the local condition or ADS adhere to the expected driving behavior standards. Depending on the observations made throughout the flow diagram, it may be appropriate to address the local condition in ADS regulation, for example because the situation is a special circumstance, safety critical, occurs frequently and/or has a high probability of causing undesirable behavior. As a consequence and as also stated above, in some cases there is a task for vehicle manufacturers to improve the capability of ADS.

## 3 Towards Implementation: Actor Landscape

When it comes to the implementation of DOVA there are likely to be multiple stakeholders involved who each take one or more roles. To get a better understanding of these roles and how they interact, the actor landscape was studied [4]. Figure 2 shows the actor landscape and the actor relationships in a schematic and simplified way.

The role of the ADS is to perform the DDT and uses on-board and off-board sensors to create situational awareness. It can request the vehicle driver to take over the driving

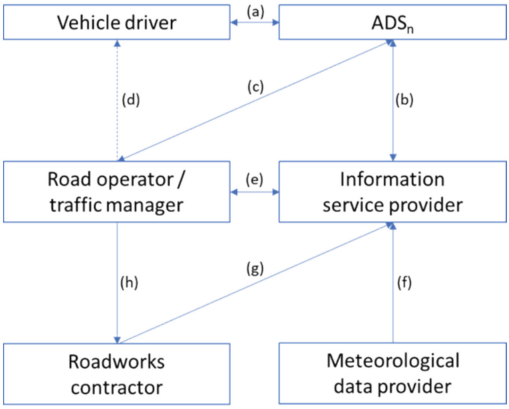



**Fig. 2.** Actor landscape of DOVA use cases.

task (a) and the vehicle driver can activate and deactivate the ADS (a). The primary sources of off-board information are assumed to be the road operator / traffic manager (c) and the information service provider (b). Road operators/traffic managers can have different communication channels to publish information ranging from roadside signaling equipment to digital cloud-based solutions. They can provide information to vehicle drivers and ADS directly (c/d) and/or via information service providers (e). An information service provider can be a third-party information broker or vehicle fleet operator that facilitates the exchange of information between road authorities and fleets of vehicles, which are operated by either vehicle drivers or ADS. Information service providers can aggregate information coming from other specialist actors, such as roadworks contractors (g) and meteorological data providers (f). Roadworks contractors manage the road works site and can provide real-time information about of the location and topology of the site. Its contract with the road operator (h) specifies the obligatory actions that it needs to carry out. Meteorological data providers can provide real-time information about the location, type and severity of weather conditions (f). Another source of information for information service providers can be ADS (b), which can sense local conditions with on-board sensors and collect and provide probe vehicle data. Similarly, the road operator / traffic manager can benefit from this probe vehicle information once it is aggregated to obtain a better understanding of the local conditions on the road network (e). In fact, this information can enable the road operator/traffic manager to provide local condition information to other actors. Naturally, also other information flows likely exist such as information service providers providing information directly to the drivers via e.g. nomadic devices or meteorological data providers to road operators or traffic managers.

## 4 Conclusion

Exchange of information between automated vehicles and the infrastructure requires NRA investment. This paper provided a decision-making process for NRAs to help determine if they should act on a given local condition. The paper also discussed the

actors involved in the implementation of DOVA. These results can be the starting point of a constructive dialogue between NRAs and ADS technology developers to establish a common vision and ambition. For example, in the short term the interested parties can express to work together on objectives such as avoiding unsafe driving of ADS and any disorder of traffic flow. For the medium term the interested parties might agree to collaborate on ADS overcoming limitations associated with DOVA. For the longer term perspective, the involved parties may aim for their mutual interests in the better management of traffic volumes and traffic flow dynamics, enabled by vehicle automation in case the penetration rate of ADS becomes sufficiently high.

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# User-Centred Design for CCAM: A Holistic Approach Combining Stakeholders' and Users' Needs with Regulatory Requirements

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**Abstract.** Building on the insights provided by the EU CCAM Partnership SRIA, this paper introduces a new double-funnel methodology for eliciting stakeholders' and users' needs and requirements, developed and tested within the CONDUCTOR EU research project (GA 101077049). This methodology aligns with the EU's holistic approach by integrating formal inputs from institutional stakeholders with specific, service-oriented inputs from users and other stakeholders, such as industry and service operators. The approach relies on three components. A top-down analysis maps mobility policy principles and outlines social and regulatory requirements for design, encompassing safety, environmental protection, inclusion, accessibility and social well-being. Complementary, a bottom-up perspective captures user and stakeholder needs related to specific use cases. The integration of these results maps CCAM-specific needs into the broader social and regulatory framework. Applied to three use cases in the CONDUCTOR project, this approach contributes to methodological research by testing an integrated, user-centred framework for designing and evaluating CCAM solutions.

**Keywords:** CCAM · stakeholders' and users' needs and requirements · user-centred design · sustainability · acceptability · greener-mobility

## 1 Introduction

The challenge for the successful design and implementation of Connected and Cooperative Automated Mobility (CCAM) services lies in finding a way to intercept the multiple needs and interests of a wide range of stakeholders and users and bring them together in a holistic design process.

CCAM solutions aim to innovate local mobility by addressing specific user needs and existing features of each scenario. However, transport and mobility policies operate across various territorial levels, not inherently localised. While mobility services are fundamental for societal integration and workforce participation, they also constitute a substantial portion of household expenses. Mobility plays a critical role in social inclusion, particularly for disadvantaged groups, impacting overall human well-being.

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Additionally, transport policies significantly influence economic needs related to mobility, considering the economic and social dynamics of territories and communities, along with the broader impact of these solutions at national and supranational levels.

Many of the ongoing multiannual research frameworks funded by the European Union (EU) stress the importance of a holistic approach to innovative mobility solutions. One of the main open issues approaching innovative sectors is precisely the correct and fair alignment of technological innovation and individual and social expectations about these pioneering solutions.

This paper introduces a novel user-centred design methodology for identifying stakeholder and user needs and requirements. Developed and tested within the EU research project CONDUCTOR (GA no. 101077049), the method integrates formalized requirements from institutional stakeholders with service-specific inputs derived from user needs and the interests of other stakeholders. Combining a broad perspective with specific context considerations, this approach leverages insights from diverse scenarios to systematically enhance understanding and application.

## 2 Methodology

### 2.1 Why CCAM Needs a Holistic Approach to User-Centred Design

The successful deployment of CCAM services hinges on their ability to generate societal benefits and gain individual user acceptance. Considering both user and societal aspects is crucial for ensuring that CCAM offerings are acceptable, appreciated, and aligned with social, economic, and environmental needs and objectives.

Understanding the specific needs, impacts, and costs of CCAM solutions may currently demand more effort than usual. CCAM is intricately linked with diverse policy ambitions extending beyond mobility, prompting the integration of social and human-based approaches in transport innovation. However, society still lacks clear knowledge of the potential benefits of CCAM-enabled mobility, making it challenging to comprehend its advantages, limitations, and rebound effects. Additionally, while public policy sets broad goals, researchers and developers must address specific use cases (UCs) based on distinct contextual needs and requirements.

Research projects thus are spurred to dare something more than the mere technological research on CCAM, promoting a holistic understanding of innovation and testing in practice the acceptability of the solutions that the EU aims to promote on a larger scale. Funded research is aimed at assessing the feasibility of policy ambitions in practice, and collecting evidence about the consistency and adaptability of general principles and requirements in practice.

CONDUCTOR provided an opportunity to develop an innovative methodology aimed at reconciling the perspectives of institutional stakeholders, such as regulators and public authorities, with the diverse needs of users and other stakeholders, including industry and service providers. This comprehensive methodology also resonates with factors influencing the acceptance of CCAM services by users and other stakeholders involved in the deployment and management of these solutions, according to multiple and related to both sociodemographic aspects and lifestyles and mobility needs [1–6].

The workflow behind this methodology can be represented by a dual-funnel framework [Fig. 1]. The top-down analysis gathers formalised and overarching inputs from regulatory bodies and public authorities, while the bottom-up approach facilitates the collection of use case-specific inputs derived from user needs and stakeholder interests.

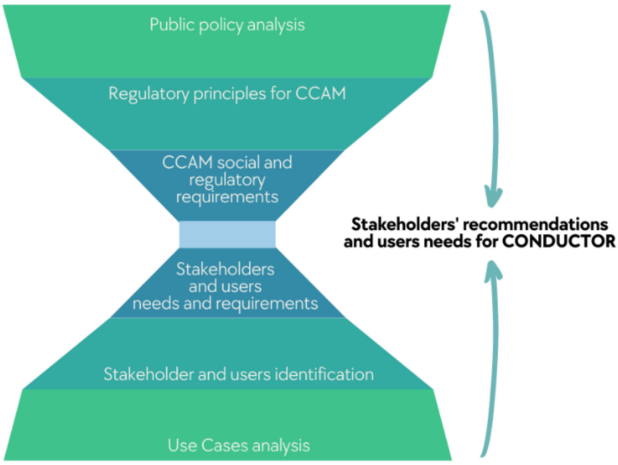



**Fig. 1.** The double funnel methodology

The use of this methodology from the early stages of CCAM design has two expected benefits. This combined reading aims to facilitate the design process of the UCs, including the analysis of the social requirements that could better ensure the acceptability of the CCAM in the medium and long term. This approach also aims to test if and how the practical experience provided by the UC owners and their stakeholders can improve the specification of the social requirements.

### 2.2 CONDUCTOR, in a Nutshell

CONDUCTOR aims to design, integrate and demonstrate advanced high-level traffic and fleet management within the CCAM ecosystem, using innovative dynamic balancing and priority-based vehicle management to develop next-generation simulation models and tools enabled by machine learning (ML) and data fusion. The CONDUCTOR innovations, integrated in a common open platform, will be validated in three UCs, anchored in five local pilots, to test the interoperability of traffic management systems and the integration of different modes of transport for people and goods.

The following sections present the logical steps that led to the development of the methodology, how it was applied to the project and how it can be reused in other different contexts.

# 3 Top-Down Approach: Framing CCAM Policy Objectives and Requirements

## 3.1 Objectives and Process

The top-down analysis aims to place the UCs in the context of a wider picture, considering CCAM solutions not only according to local needs but also according to wider societal objectives as outlined in the reference policy framework.

The analysis scheme can be tailored to the needs of each project, adapting the criteria and scope of the analysis to the specificities of the reference framework. In particular, the mapping of relevant policy principles and applicable regulatory requirements may include different policy levels (local, national and supranational). In addition, the analysis should cover different policy areas, including all aspects that may have a significant impact on the assessment of the solutions under consideration.

In general, the top-down analysis process for CCAM unfolds in three successive phases. It begins with a careful examination of public policies generally relevant to mobility, which serves as a basis for identifying the broad policy issues and key societal objectives related to mobility and transport, and for contextualising CCAM innovations within a broader scenario. The second sub-step explores the rationale behind these policy objectives in their respective contexts, identifying the specific regulatory principles that guide ongoing CCAM research. Finally, the third sub-step culminates in the identification of regulatory requirements that should inform the design and development of these innovative solutions.

## 3.2 Scope of the Analysis

The first step is to define the scope and level of the analysis, in light of the characteristic of the project and solutions considered. In this regard, CONDUCTOR aims at exploiting local based experience to develop a scalable solutions and policy outputs valid beyond the national dimension of the UCs considered. Therefore, the attention was focused on the public policy framework for CCAM that now drives EU action in this area.

The EU, as a sui generis regional system, offers interesting insights. Its programs aim to link national and local needs with common supranational objectives, systematically addressing specific needs in a way that can be scaled to other contexts. Transport is a shared competence of the EU and mobility involves many other policy areas related to CCAM. Since detailed analysis of the contextual regulatory requirements at an early stage of solution design could lead to an uncertain and fragmented scenario, the project opted for a high-level analysis to obtain appropriate and ready-to-use regulatory requirements for pilots development.

In light of the above, the top-down analysis began with an overview of the policy and regulatory framework for CCAM from a broad perspective, analysing not only from a mobility and transport perspective, but also from a wider viewpoint.

The topic was considered in light of the Sustainable Development Goals of the UN Agenda 2030 [7], as well as the EU Priorities Plan towards 2030 [8]. The attention converged on the EU policy principles and requirements for CCAM, encompassing the

policy programs directly and indirectly dedicated to this issue. It starts outlining the specific recommendations offered by the CINEA and DG-MOVE for more sustainable urban mobility [9]. The study also took into account the guidance provided by the EU Green Deal [10], Digital Decade [11], and EESC [12]. Since mobility directly and indirectly affects policy areas, like climate, environment, economic growth and social inclusion and cohesion, the inquiry considers the corollary policy inputs coming from the DGs for Climate Action [13, 14], Environment [15], Internal Market, Industry, Entrepreneurship and SME [16] and Employment, Social Affairs and Inclusion [17].

### 3.3 Outlining CCAM Regulatory Requirements

The analysis of the policy framework in CONDUCTOR identified five key principles: Safety, Environment, Well-being, Accessibility, and Inclusion. The study outlined the scope of these principles and provided a preliminary mapping of relevant requirements. These requirements were then elaborated to generate practical design suggestions for the UCs' proposed CCAM solutions.

From a safety perspective, the analysis focused on technical requirements ensuring societal expectations for CCAM safety, covering trustworthiness, transparency, awareness, and fairness. Trustworthiness involves the safe activation/deactivation of automated driving, considering user needs. Transparency ensures fair interactions between users, vehicles, and CCAM and traditional solutions. Awareness proposals aim to provide information on automated driving operations and limitations. Fairness conditions explore promoting CCAM compatible with the safe circulation of non-automated vehicles, considering the needs of vulnerable users, and emergency services, and addressing dangerous behaviour by both CCAM and non-CCAM users.

Considering the environmental impact of mobility, a key concern on the EU agenda, especially with the EU Green Deal, relevant requirements focus on emission reduction, infrastructure and vehicle capacity optimisation, and fleet operations and management impacts. Notably, positive impacts of CCAM include limiting emissions, supporting sustainable mobility, reducing congestion and pollution, optimising traffic flows, and encouraging diverse transport modes to minimise unnecessary journeys. The analysis emphasises that CCAM solutions should adopt combined approaches, such as load optimisation, consolidation, asset sharing, and improved management of logistics centres, warehouses, and transport infrastructure.

Addressing the social relevance of transport and mobility, according to the European Pillar of Social Rights [18] and the New EU Urban Mobility Framework [19], the research also includes requirements for inclusivity, exploring requirements related to travel purposes, individual conditions (i.e., gender, age, income, literacy) and territorial coverage. The analysis emphasised the need for affordable, inclusive mobility to foster social cohesion and local economic development. CCAM could contribute to the spread of shared and on-demand mobility within public transport, considering the need for efficient, inclusive connectivity and sustainable mobility across rural, peri-urban, and urban areas.

Drawing by the EU Accessibility Act [20], the analysis highlighted requirements for service and vehicle/infrastructure accessibility. Considering services, accessibility

needs primarily focus on the requirement for CCAM solutions to include a comprehensive strategy for easy multimodal journey planning. Specific recommendations cover ticket planning and purchase, smart ticketing information, and additional service details. Regarding vehicles and infrastructure, the attention focuses on effective access, surrounding infrastructure, assistance for people with disabilities, availability of sensory channels, and the introduction of elements and functions facilitating access, perception, operation, understanding, and control for individuals with disabilities.

Finally, the analysis took into account the collective expectations of society in relation to innovation in transport and mobility. The requirements related to the well-being of people and communities addressed the challenges of more sustainable urban hubs with a higher quality of life and better connectivity, affordability and accessibility of mobility services for urban and surrounding rural areas. Achieving the major shift in urban mobility will require rapid and significant action and investment at EU, national, regional and especially local levels. The requirements therefore cover all possible issues related to the objectives of just transitions and social and economic sustainability, identifying as essential the requirements to promote participation and a preliminary assessment of the economic and social impacts.

### 3.4 Regulatory Requirements for CCAM Design Purposes

The requirements were summarised in a report and a visual template [Fig. 2], which were provided to the UC owners. Dedicated workshops were then used to conduct a multidisciplinary analysis of CCAM user-centred design and regulatory issues. These workshops prioritised contextual aspects within this framework and identified detailed sub-requirements and acceptability conditions for designing their solutions.

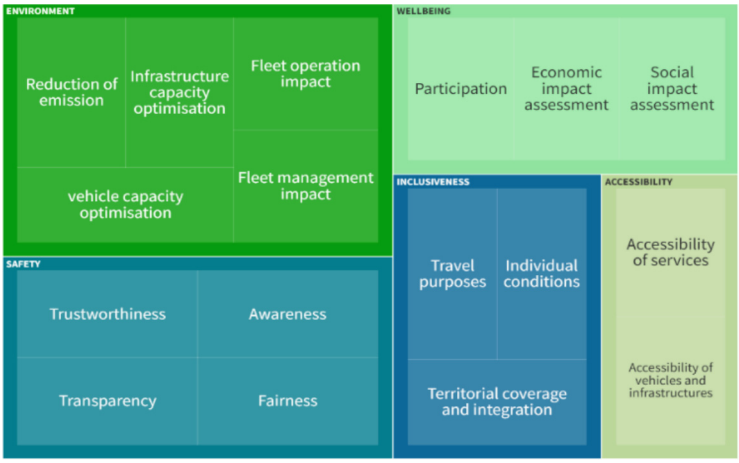



**Fig. 2.** CCAM regulatory principles and requirements

# 4 Bottom-up Approach: CCAM Stakeholders and Users' Needs and Requirements

## 4.1 Objectives and Process

The bottom-up analysis provides a complementary perspective to the top-down approach by focusing on the specific requirements for CCAM solutions based on local scenarios. This involves identifying the stakeholders and users who will interact with the new mobility systems, as well as setting out the main needs and requirements of each category of actors, case by case. The approach is divided into three sub-steps: Frist, analysing local CCAM cases to understand their specific characteristics. Second, mapping the intricate network of stakeholders and user categories through a comprehensive matrix. Third, collecting and prioritising stakeholders' and users' needs and requirements via a dedicated survey to understand their needs and prioritise them based on significance and feasibility.

## 4.2 The Rationale and the Use Cases in CONDUCTOR

The bottom-up examination of stakeholders' and users' needs begins with evaluating how different actors interact with the proposed CCAM solutions. This phase aims to gather insights for implementing these solutions, using UCs to identify and analyse their functional requirements. UCs are a proven tool for identifying and analysing the functional requirements of a system under development or evaluation [21–24]. In fact, they help assess the quality of user-system interactions and facilitate stakeholder discussions, supporting subsequent modelling and development stages.

In this context, CONDUCTOR aims to design, integrate, and demonstrate advanced traffic and fleet management. For that, in order to understand the contextual and operational factors, the first step involved gaining an overview of the context in which UCs would be used. A participatory approach was promoted using concept maps to represent different scenarios, leading to the identification of three UCs:

**UC1** involves integrated traffic management with intermodality, focusing on CCAM solutions for balancing demand and supply, optimising overall network performance, and aiding recovery from incidents within a transport network.

**UC2** refers to demand-response transport, exploring CCAM applications for planning and implementing cooperative routing strategies and customised travel services under Mobility as a Service (MaaS).

**UC3** refers to urban logistics, proposing solutions for last-mile delivery by integrating urban goods distribution with existing on-demand passenger transport services.

These findings provided a foundation for a survey to collect user and stakeholder needs, facilitating discussions on the specificities of each solution and an understanding of their benefits and limitations.

## 4.3 Stakeholders and Users Identification

The second step of the bottom-up approach involves identifying the users and stakeholders linked to each UC, guided by the taxonomies from the CCAM Partnership and

SRIA [25]. Thus, leading the matrix to include six categories: (1) industry, (2) public authorities & and road operators, (3) mobility & and logistics services, (4) representative bodies, (5) research institutions and (6) users.

Regulators were excluded, as their requirements were expected to be covered by the top-down approach. The matrix was created to catalogue all relevant actors, with input from all project partners to ensure accuracy. This matrix provided a comprehensive overview of stakeholders' needs and requirements for each UC.

In CONDUCTOR, 58 stakeholders were identified [Fig. 3], reflecting the complexity of the CCAM network. The most represented groups were mobility & logistics services (N = 19) and public authorities & road operators (N = 17). The survey within each UC highlighted that the size and consistency of each category varied depending on governance and network structure, deepening the understanding of each actor's role in the solutions implemented.

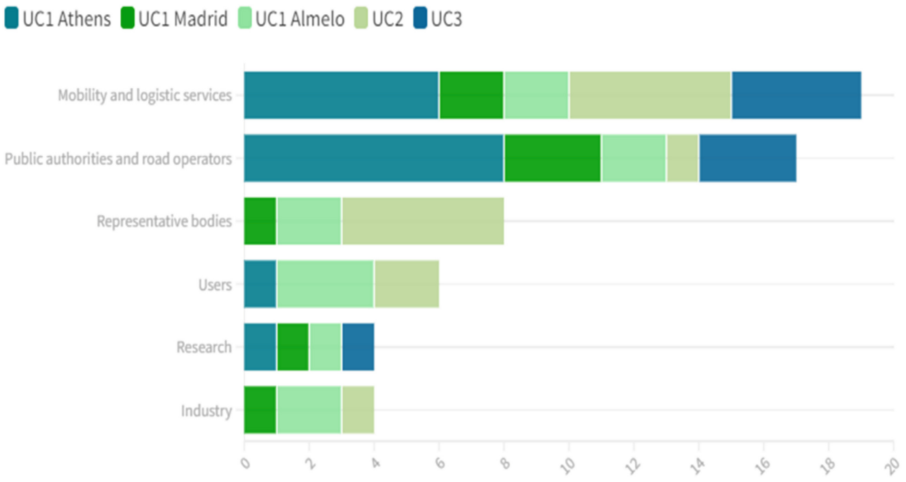



**Fig. 3.** Analysis of needs and requirements

### 4.4 Analysis of Needs and Requirements

The third step involved gathering stakeholders' and users' needs and requirements through an ad-hoc designed survey focused on CCAM expectations. The survey was based on prior research in personalized digital transport systems, using their frameworks as a reference while making necessary adjustments to align with CONDUCTOR's objectives. The survey was refined to capture detailed information on regulatory needs, stakeholders, end users, benefits, and challenges associated with each UC. It was thoroughly tested, reviewed and administered to the identified stakeholders and users, ensuring their input was accurately documented. The findings from this process were carefully integrated into the design and development of the project, ensuring alignment with the needs and requirements of all stakeholders and users.

The survey key topics included:

- Perceived goal and purposes of the proposed service;

- Needs and impact to develop location-specific solutions;
- Requirements for scalable, adaptable, and interoperable solutions;
- Skills and capabilities to identify knowledge and skill gaps to operate/use the solutions and eventual training and educational programs;
- Trust, privacy, and security concerns and expectations of citizens and stakeholders regarding the use of CCAM solutions;
- Individual and social benefits & risks of the proposed solutions;
- Attitudes toward socially and culturally acceptable solutions;
- Regulatory framework and necessary positive actions to ensure that solutions are implemented in a responsible and sustainable way; and
- Sociodemographic factors.

The results revealed that safety (m = 5.78), lower emissions (m = 5.39), and accessibility (m = 5.35) were the most important needs, with safety emphasised through accident reduction (n = 14) and increased safety awareness (N = 3). Emission reduction focused on cutting greenhouse gases (N = 13) and shortening travel distances (N = 6). Accessibility improvements were suggested for passengers with disabilities (N = 3), practical solutions (N = 3), and more frequent routes (N = 3). Competitiveness was the least prioritised need (m = 4.13).

This systematic approach provided a scalable understanding of diverse needs and integrated these insights into the broader project framework, enhancing result interpretation and fostering discussions with other related projects.

## 5 A Holistic Approach to CCAM User-Centred Design. Results and Discussion

### 5.1 Objectives and Process

The results of the top-down and bottom-up analysis were finally merged using a participatory approach. The proposed methodology promoted a collaborative analysis, bringing together insights from the policy analysis and survey with inputs from workshops attended by project partners.

This approach aims to foster a shared understanding of on-desk research results and facilitate collaboration with UC owners and partners in policy development. By merging top-down and bottom-up analyses, it enables the mapping of CCAM service needs within the broader societal and regulatory framework derived from the top-down approach, guided by feedback from stakeholders.

For each UC, a set of user cards has been produced showing the stakeholders and users identified, their purposes for the proposed solutions, and the advantages and disadvantages in terms of social and regulatory requirements [Fig. 4]. This presentation of the results makes it possible to address the specificities of each UC within a systematic framework, able to keep together the relevant regulatory requirements and the priority needs and requirements of each category of users and stakeholders.

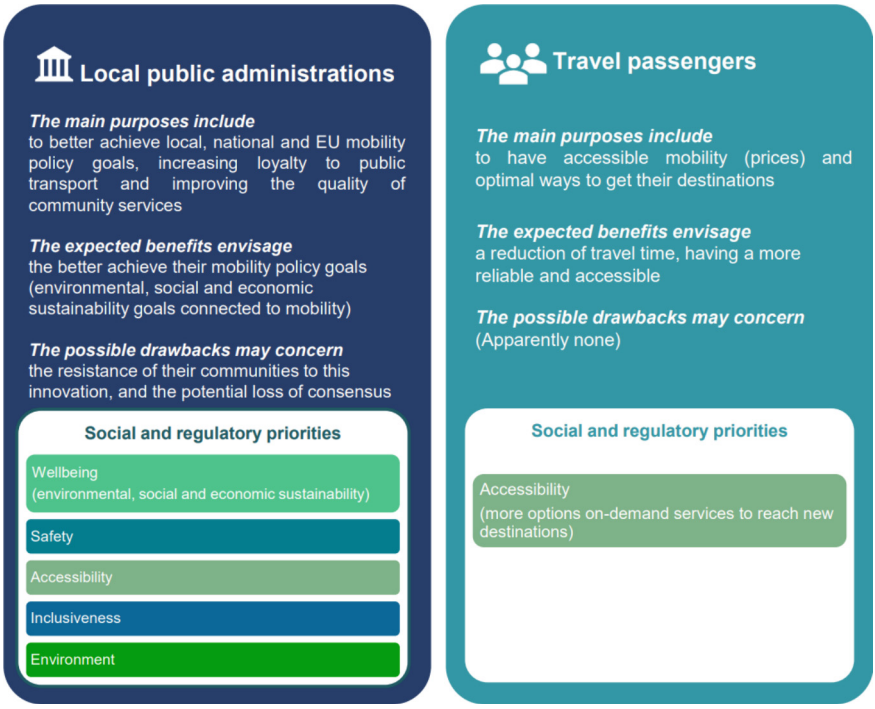



**Fig. 4.** Example of User cards

The consolidated findings were employed to enhance the design process for UCs, integrating socially based requirements to ensure the acceptability of CCAM in the medium and long term. Furthermore, this approach seeks to evaluate how real-world experiences shared by UC owners and their stakeholders can contribute to refining the specification of identified social requirements.

### 5.2 Results and Discussion

The data collected during the workshop facilitated a realistic reading of the results of the top-down and bottom-up analysis. The user journey maps allow for a better contextualisation of user and stakeholder needs and requirements, including categories of actors that had not emerged clearly before. The mapping of these needs to the respective social and regulatory priorities promoted a reasoned assessment of the general principles and requirements, highlighting the key compliance issues for a better acceptance of CCAM in CONDUCTOR.

The use of the CONDUCTOR methodology first of all highlights the real categories of actors mainly considered in the implementation of CCAM within the project, highlighting the critical role of mobility and logistics services, public authorities and road operators. It is particularly interesting to note how the contextual analysis of the different clusters allows the position of indirect beneficiaries to emerge more clearly. This is a special category of subjects that includes all those who are not directly involved in the

implementation of CCAM but who are affected in some way by the implementation of these innovations. This cluster could take into account the interests of local residents as well as the mobility experience of all users not directly involved in CCAM solutions.

Secondly, the analysis of the data allows a reasonable assessment of the regulatory requirements in light of the specific needs of the stakeholders considered. In particular, we were able to take a broader view of the relevance of the various needs and requirements collected for each stakeholder, combining the results relating to a single actor with those relating to the respective categories. In addition, the involvement of the project partners allowed us to take into account additional elements that had not previously emerged clearly, such as the needs and requirements of indirect beneficiaries and local communities.

In line with more intuitive expectations, the more representative categories include direct beneficiaries and public stakeholders. The two clusters obviously give a genuine voice to the most recognisable policy objectives of the CCAM: improving the safety and accessibility of urban mobility and mitigating the negative impacts on the climate and the environment. On the other hand, the requirements and needs of private stakeholders and indirect beneficiaries cannot be overlooked. If we look at the main concerns of these two categories, we see that social well-being and environmental impact are the top priorities, in line with the results obtained for the other two groups of actors.

Against this background, private and public stakeholders - as well as direct beneficiaries - highlight the benefits of CCAM solutions in terms of improved user experience. In particular, they highlight the expected benefits in terms of travel time reduction, congestion, fuel consumption, maintenance operations and (where relevant) social responsibility of Connected and Autonomous Vehicles (CAVs).

The lessons learnt from the user journeys, involving public stakeholders as well as direct and indirect beneficiaries, highlighted the overriding importance of having a comprehensive and networked understanding of the specific solutions being implemented. The possible frictions experienced by users and stakeholders in the transition phase could in fact have a negative impact on the consolidation of these innovations and discourage upstream investments.

Finally, a combined reading of the results obtained allowed a better understanding of the weight of the different requirements for the purposes of CONDUCTOR. If they have the same weight and value from a qualitative point of view, the scenarios specifically considered in the pilots highlighted the priority of some of them for a better acceptance of CCAM in the short and medium term.

This reading of societal needs and requirements for ‘smart mobility’ solutions has led to the following considerations. Firstly, the acceptability of these solutions depends on their contribution to improving environmental sustainability. This is especially true if we consider the immediate benefits in terms of reduced emissions and consumption, which should be a key driver in the design and implementation of CCAM. Secondly, there are needs related to the complementary fulfilment of accessibility and social well-being requirements. The impacts of CCAM should be addressed in advance, modulating and mitigating negative impacts from the early stages of projects. The data shows that the specific concerns related to accessibility of services, vehicles and infrastructure and minimising negative impacts on residents and local communities are the core needs

in this regard. These should therefore be the priorities for social acceptance of these innovations in the medium to long term. Finally, safety – understood as a holistic and gradual awareness of the direct and indirect effects of CCAM on urban mobility in general – should be the cornerstone of any CCAM solution. In fact, this principle embeds, to a greater or lesser extent, the expectations of all the actors involved and promotes an accessible and inclusive approach to the development of these solutions, without leaving anyone behind.

## 6 Conclusions

In the CCAM domain, the innovation process affects not only the direct beneficiaries (e.g., passengers, drivers, operators, mobility and logistics services), but also the wider communities and territories. These two dimensions are interdependent and complementary. Consequently, a proactive and holistic approach from the early stages of design can significantly improve the development, deployment and sustainable integration of these solutions over time. Drawing on lessons learned from the CONDUCTOR project, the methodology here presented aims to address the needs and requirements of users and stakeholders from a comprehensive perspective, reconciling overarching policy requirements with context-specific nuances.

Based on this premise, the methodology considers the principles and requirements identified through top-down assessments and the results of bottom-up analyses of user and stakeholder needs within a unified research framework. This approach ensures due consideration of the specificities and innovations introduced by these integrated solutions and fills the methodological gaps identified in the state-of-the-art literature. This methodology aims not only to reconcile different working methods but also to promote a common understanding of the societal issues and challenges associated with CCAM. It maps and addresses context-specific needs and requirements onto the broader principles and standards outlined by public policies at higher levels of governance. The experience of CONDUCTOR highlights the importance of incorporating human and social science desk research into the definition of technical and organisational requirements for CCAM, using collaborative and participatory methods. CCAM poses challenges that are rooted in traditional transport and mobility issues and require a more comprehensive and interdisciplinary perspective.

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# A New Generation Cable-Driven Dynamic Driving Simulator for the Assessment of CCAM Deployment

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**Abstract.** The safe deployment of Connected, Cooperative and Automated Mobility (CCAM) systems needs to take into account advanced human-machine interaction. In fact, CCAM is going to change both the cooperation between the vehicle and the human driver and the interaction with road users. This paper presents DriSMi, an advanced cable-driven dynamic driving simulator that enables safe, affordable and reliable CCAM testing. DriSMi can be used with the objectives of (1) modelling and testing the technology and (2) characterizing and modelling the driver, in particular analysing and modelling the driver's behaviour, ergonomics and safety in different infrastructure/weather/traffic scenarios. After describing the features of DriSMi, a CCAM scenario and a procedure for assessing the acceptability of Adaptive Cruise Control are presented.

**Keywords:** driving simulator · driver behavior · virtual simulation environment · CCAM · Advanced Driver Assistance Systems · road safety

## 1 Introduction

The safe deployment of Connected, Cooperative and Automated Mobility (CCAM) systems needs to take into account advanced human-machine interaction. In fact, CCAM is going to change the interaction between the vehicle and the human driver. CCAM is also redefining the interaction of vehicles with other road users.

Safe and affordable testing is enabled by indoor testing facilities, namely dynamic driving simulators. Testing must also be trustable, which is currently a major concern [1]. A compromise is needed among the potentially conflicting requirements of safety, affordability and trustable testing [1].

Driving simulators are more and more used to cope with the mentioned requirements [2]. Actually, traffic simulations at the micro-scale are now reproducible within a virtual reality environment [3]. This enables to check the performance of CCAM and, more simply, of Advanced Driver Assistance & Autonomous Driving Systems (ADAS/AD), *as they are perceived by vehicle occupants*. Vehicle occupants, i.e. drivers and passengers,

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are the actual actors and judges of CCAM performance. CCAM performance has to be assessed both subjectively and objectively. The objective performance is related to the *Safety of the Intended Function (SOTIF):* in [4] the SOTIF is defined as "the absence of unreasonable risk due to hazards resulting from functional insufficiencies of the intended functionality or by reasonably foreseeable misuse by persons". The subjective evaluation of CCAM performance is more tricky to be defined and actually there is a lack of standardization in this area. Nonetheless the perceived safety and comfort are crucial to the deployment of CCAM [5].

In this paper a new generation driving simulator is presented. Then a brief example of how CCAM performance can be assessed is shown. Finally, a methodology for assessing the acceptability of ADAS by the driver is described and applied to the case of Adaptive Cruise Control (ACC).

## 2 Features of the DriSMi Driving Simulator

DriSMi is a new generation dynamic driving simulator installed at Politecnico di Milano in 2021, able to realistically simulate a driving vehicle (*Ego vehicle*, Fig. 1) in many different scenarios. First simulator in the world equipped with a new technology of cable actuation, it is characterised by realism and immersivity. Its mid-size allows keeping the latency below the threshold that is perceived negatively by the driver.

The simulator structure comprises six electric actuators (hexalift) that can move the driver's compartment in six ways (movements along the x, y and z axis, yaw rotation, pitch and roll). The hexalift system is mounted on three pneumatic pads for moving the driver's compartment on a plane without friction. In addition to five projectors and a 270° screen, a seat with active cushions and tension belts is used to improve the driver's immersiveness during the test. These systems allow long lateral and longitudinal accelerations to be felt. For the purpose of studying comfort and driver behavior, 8 shakers on board reproduce the vibrations that come from the engine and road irregularities. There are an instrumented steering wheel able to measure the forces and moments exerted by the driver, an eye-tracking system for studying the driver's behaviour while driving, and a bio-telemetry system that measures the electrocardiogram and the skin potential resistance during driving. Lastly, there is a cap to make the electroencephalogram to the driver during manoeuvres.

The motion of surrounding vehicles can be managed by:

1. a traffic engine to simulate different traffic conditions based on AI algorithms;
2. directly imposing the trajectory of the vehicles to perform some specific manoeuvres (lane crossing, lane change, emergency braking, etc.);
3. additional human drivers to perform random and/or risky/aggressive manoeuvres (multi-user driving simulation mode).

To enable multi-driver simulations, the DriSMi control room hosts a control station including a high-end gaming steering wheel (provided with a feedback torque device) with gear paddles and pedals and 24" size LCD-display showing the visual field of the vehicle controlled by a second human driver (*Second-Drive*, Fig. 2).




**Fig. 1.** The DriSMi driving simulator at Politecnico di Milano (www.drismi.polimi.it). Copyright Politecnico di Milano, reproduced with permission.

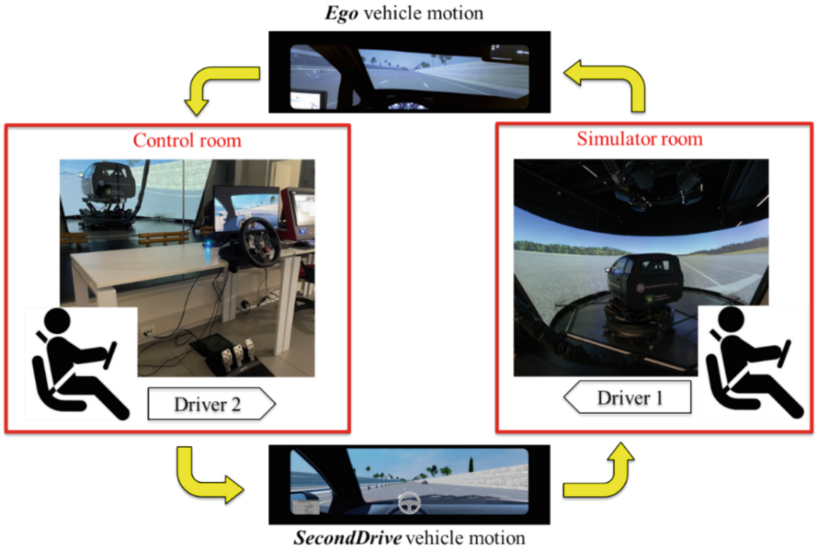



**Fig. 2.** Experimental set-up for the dynamic driving simulator with multi-drivers. Copyright Politecnico di Milano, reproduced with permission.

DriSMi can be used with the objectives of i) modelling and testing active controls, advanced driver-assistance systems, and (cooperative) connected and autonomous driving, and ii) characterizing and modelling the driver, in particular analyzing and modelling the driver's behavior, ergonomics and safety in different infrastructure/weather/traffic scenarios, following the introduction of CCAM systems.

A virtual simulation environment like DriSMi represents a key facility to test the deployment of CCAM/ADAS systems and to assess the driver behaviour and the interaction with the other road users (including vulnerable users such as pedestrians and/or bicyclists). In fact, whereas some systems are already at an advanced stage and available on the market (e.g. lane keeping and adaptive cruise control), open issues are still related to user acceptance. Since these systems substitute the human driver in controlling the

vehicle, it is essential that their behaviour is perceived as safe and comfortable by users [7, 8]. It is therefore clear that driving simulator like DriSMi give the opportunity to deeply investigate all these aspects.

## 3 Multi-Vehicle Interaction Using the SUMO Micro-Simulator

By integrating the SUMO traffic micro-simulator [6], DriSMi provides a virtual environment in which many different drivers interact. SUMO offers the possibility to include driver models such as IDM and Wiedemann. Automated cars can be also included. For example, a CCAM environment was fully reproduced in a case study of the Horizon 2020 project AI@EDGE, which aims to introduce enhanced 5G technology, based on edge computing and Artificial Intelligence [3]. The traffic into a three-leg roundabout was reconstructed, simulating human-driven cars interacting with automated cars driven by an edge controller based on a cooperative artificial intelligence policy.

In the virtual environment, represented in Fig. 2, automated vehicles (AVs) share information with the MEC-EDGE node at the center of the roundabout. The human-driven vehicle is sharing information but not receiving any data. SUMO is used both to drive AVs and to provide the training data to define the policy of the reinforcement learning algorithm, based on a cooperative approach (Fig. 3).

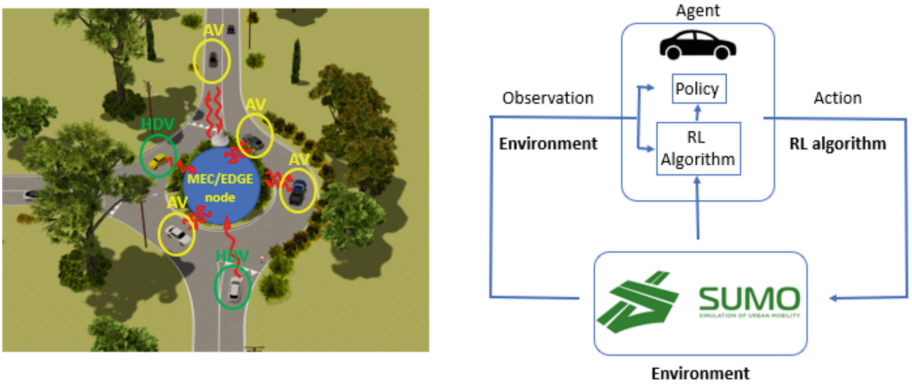



**Fig. 3.** CCAM environment reproduced at the DriSMi. Copyright Politecnico di Milano, reproduced with permission.

## 4 ADAS Acceptability Evaluation

Enabling the reproduction of real-world driving experiences under safe, controllable, and time- and resource-saving conditions, driving simulators such as DriSMi offer the possibility to investigate the acceptance of ADAS. In particular, the Adaptive Cruise Control technology is already at an advanced stage in terms of stability and safety performances, but there are still open questions related to user acceptance, in particular in terms of perception of safety and comfort. Clearly, to gain meaningful data, it is essential to consider a variety of scenarios involving other vehicles.

As an example, a first study was conducted to setup a methodology capable of assessing the acceptability of an ACC. As known, ACC maintains the user-defined speed set-point when the road ahead is clear, switching to distance control whenever obstacles are detected, thanks to the information retrieved from sensors (cameras and radars). Therefore, ACC substitutes the human driver in controlling the longitudinal dynamics of the vehicle [7, 8].

The study was carried out involving 33 volunteers (23 males and 10 females) ranging from 19 to 66 years old (34 years as an average). Among the participants, 14 had previous experience with a driving simulator and 10 had previous experience with ACC systems on public roads. Each participant was required to drive the dynamic driving simulator vehicle (*Ego*), which was equipped with an ACC, while the other vehicles involved in the scenario were either software-driven or driven by a second human driver (*Second-Drive*). The scenario consisted of a three-lane motorway with speed limit at 120km/h. During the test, the participant had to follow a reference vehicle, with a third vehicle (lane-changing vehicle) performing several maneuvers such as lane insertion, lane crossing (see Fig. 4) and sudden braking. Each participant performed four runs:

- RUN 1: ACC system OFF and software-driven lane-changing vehicle;
- RUN 2: ACC system ON and software-driven lane-changing vehicle;
- RUN 3: ACC system OFF and Second-Drive lane-changing vehicle;
- RUN 4: ACC system ON and Second-Drive lane-changing vehicle.

At the end of the test, participants were asked to answer a survey about the driving simulator realism and the ACC system performance in terms of safety and comfort.

A multinomial regression model was trained for correlating comfort and safety subjective ratings provided by the participants and quantitative objective indexes measured during the tests, namely the minimum distance from the preceding vehicle, the time-headway to the vehicle ahead, the time-to-collision, the peak braking acceleration and the rms longitudinal acceleration during the manoeuvre.

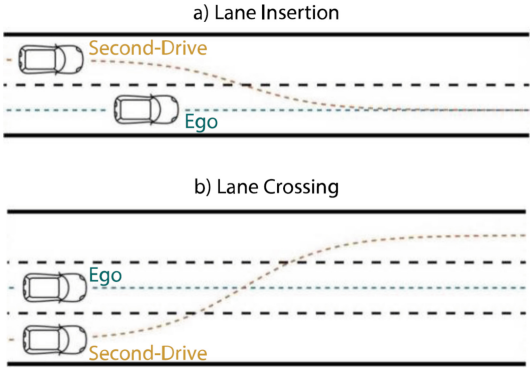



**Fig. 4.** Second-Drive maneuvers

The main results of the analysis can be summarized as follows [9, 10]:

- time-headway is the index most correlated with the driving style: drivers adopting a short time-headway when the ACC is OFF are likely to prefer a more aggressive tuning of the ACC control logic;
- both comfort and safety subjective ratings strongly correlate with the same indexes: minimum distance from the vehicle ahead and time-to-collision. Contrarily to the expectation, the correlation is weak between comfort ratings and longitudinal accelerations perceived by the drivers (both peak and rms values). This means that drivers judge vehicles that are considered safer as more comfortable. As a consequence, making a clear distinction between comfort and safety ratings appears challenging;
- results are consistent both considering human-driven (Second-Drive) or software-driven surrounding vehicles;
- including a Second-Driver into the scenario, however, allows for more aggressive and risky manoeuvres, which better highlight the performance of the ACC in terms of safety. In fact, safety ratings for manoeuvres performed in RUN 4 (Second-Drive and ACC ON) are higher than the ones in RUN 2 (software-driven vehicles and ACC ON).

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# Border Crossing Connectivity for CCAM Vehicles: A Field Test at the Norwegian-Swedish Border

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**Abstract.** For automated logistic transport, cross border issues need to be solved, including technological, organizational, and regulatorily challenges. In this paper we will specifically investigate communication continuity across the border between Sweden and Norway as a use case within the EU financed MODI project, where cross border logistics will be demonstrated driving from Sweden to Norway. The current development within automated vehicles suggests that connectivity will play a crucial role for enabling such solution, including options such as remote surveillance, video stream, downloading map and traffic regulations, retrieving correction data for accurate positioning etc. Driving cross borders poses a challenge in this regard, because roaming to a new mobile network must be performed and typically results in loss of service. In this paper we investigate the expected delays and service behavior when crossing the border and relate the results to the need of the future automated vehicles.

**Keywords:** CCAM · 4G/5G · Navigation · Freight; Automation

## 1 Introduction

Within the EU financed MODI project [1], cross border logistics will be investigated and demonstrated driving from Sweden to Norway at the border of Svinesund (Fig. 1). Border crossing for CCAM (Cooperative, Connected and Automated Mobility) poses several unique challenges. For the envisioned vehicles at SAE Level 4 [2], where a driver within the vehicle is optional, automated driving across the border must be done in a technically and regulatory robust and seamless way. This paper focuses mainly on connectivity and presents results from a field test trial collecting several relevant parameters related to connectivity in multiple runs across the border. Crossing national borders, the LTE/5G communication link will be interrupted because a new roaming mobile network must be selected, and this may create some time without network connectivity. Typically, this happens because the modem tries to use its current network as long as possible. At some point the network quality drops below a threshold, triggering the modem to search for a new network using roaming procedures.

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Level 4 vehicles are designed to operate within its Operational Design Domain (ODD). One requirement may be that it must be possible for a remote operator to supervise the vehicle and take control if the vehicle goes outside its ODD at any time. This will require a reliable communication link with adequate bandwidth. Furthermore, tasks related to the actual border crossing may also need connectivity.



**Fig. 1.** The Svinesund bridge between Sweden and Norway (Source: Per Pixel Petersson, with permission).

Therefore, seamless handover from a network operator to another operator at a border crossing is an important issue to investigate. One solution could be to use alternative communication services for redundancy when crossing the border, including C-ITS communication, relying on the vehicles to have implemented support for hybrid communication. Also, mobile networks are evolving, and new solutions are developed by 3GPP and the telecom industry to utilize 5G capabilities, e.g. [3], where operators cooperate to support seamless handovers between different networks [4]. Cross border roaming and handovers has also been studied in the 5GCroGo project [5]. Fast roaming procedures have been demonstrated at AstaZero in cooperation with Ericsson and Daimler [6], but real condition cross border measurements have not been tested systematically in available published materials.

## 2 Test Equipment and Data Collection Strategy

To test cross border connectivity a test protocol was developed and implemented for Linux and Android to measure relevant quality indicators. The test application sends specially crafted datagram messages to a dedicated server on the internet to facilitate measurement of packet throughput rate and packet loss independently in uplink and downlink directions. Round Trip Time (RTT) was also calculated. On the Android application, parameters such as position, timestamp, signal strength, operator, country code, technology (EDGE, WCDMA, LTE, LTE-CA, 5G-NSA etc.) were measured about every second. Data packet size and rate are configurable independently in uplink and downlink directions. In the tests, uplink packet size 200 with a rate of 2 Hz and downlink packet

size 800 bytes with a rate of 4 Hz were used. The analysis focuses on the downlink packet performance as seen from an application using off the shelf equipment.

Several trips with several smart phones each trip was travelled, resulting in 40 registered trips across the Swedish-Norwegian border at Svinesund in both directions. Both high-end Samsung S21 smart phones with 5G connectivity and low-cost Motorola E6 (without 5G) smart phones where used, with SIM cards from all three national operators in Norway (Telia, Ice and Telenor) used as well.

## 3 Results

Of the 40 trips registered across the border only one trip showed very little to no connectivity challenges driving across the border. In the following we will look closer into the 39 trips with clear challenges detected. In the analysis we will focus on the three parameters "Download package loss", "Signal strength" and "RTT". First of all, we define service loss, or the no service area, as the time period from the first data point with above 90% package loss to the last data point with less than 90% package loss, which for our purpose and application seems appropriate enough. In Fig. 2, the result from one of the trips is shown as an example. In this case we see a total loss of service from about 0.5 km into Norway, lasting for about 3 km or, in this case, 132 s.

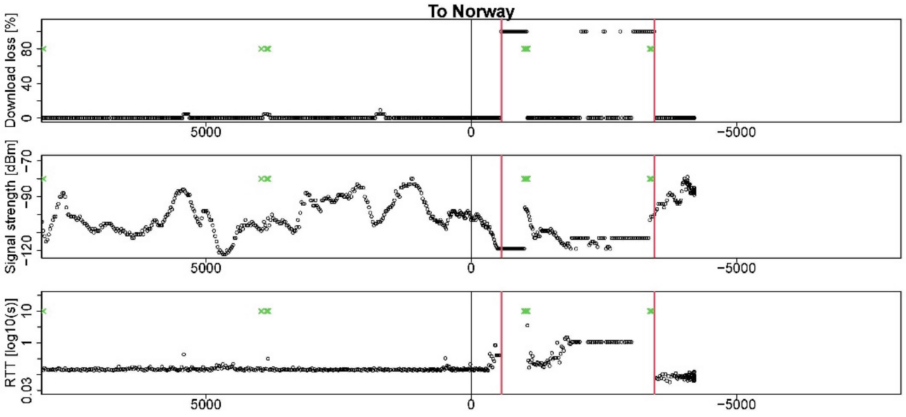



**Fig. 2.** Connectivity measurements for a Samsung S21 with Telia SIM card for one trip going from Sweden to Norway. The x-axis shows distance from the border along the road network, black vertical line being the border, the area between the red vertical lines being the detected no service area, and green crosses representing handover between network cells.

In Fig. 2, one can clearly see a significant drop on the signal strength and increase in the RTT as the vehicle is approaching the no service area, and with no valid measurement for these two parameters for some periods inside the no service area. For the measurements we do have inside the no service area, the signal strength is significantly lower and RTT is significantly higher, compared to the outside measurements, suggesting the connectivity is unstable at best. The green crosses in this picture represent changes

between mobile network cells. From this pattern we see that the low service quality retrieved inside the no service area (approx. 1 km in) is due to a handover to a new cell, however, even though the vehicle at this point is on Norwegian land, this network cell it connects to is located in Sweden. So, the actual handover between Swedish and Norwegian network are not happening before at the end of the no service area (approx. 3.5 km in) for this case.

Many of the other trips are also showing situations where there is a total loss of service inside the identified no service areas, see Fig. 3 for two examples where the identified no service areas are plotted for two additional trips (one in each direction).

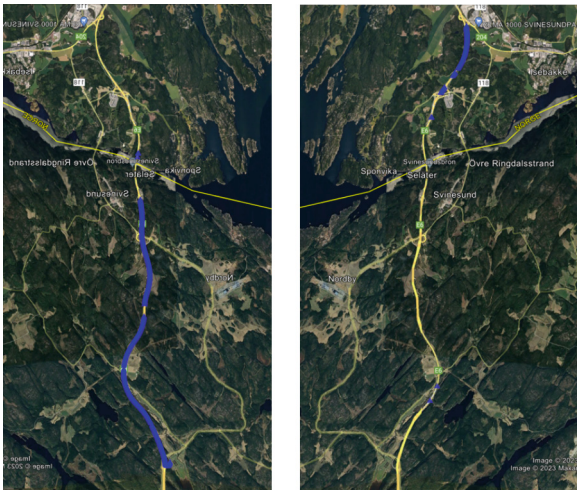



**Fig. 3.** Road segments with service loss marked with blue. Left shows driving from Norway to Sweden (southbound), right shows driving from Sweden to Norway (northbound). The north-south map extent is 13 km (Source: Imagery @2025 Airbus, CNES/Airbus, Lantmäteriet/Metria, Maxar Technology, Map data @2025 Google).

Next, we present some statistics to summarize results from the all measurements, see Table 1 and Table 2 for the distance and time of the identified no service areas, respectively. In the following we will use n to denote the number of observations, $\mu$ to denote the mean of some observations (e.g. the distance of the no service area), and $\sigma$ to denote the corresponding standard deviation.

The speed of the vehicle going across the border in the direction of Sweden to Norway is $(\mu, \sigma) = (17.25, 10)$ and from Norway - Sweden is $(\mu, \sigma) = (25.9, 1.2)$ for all the registered trips. The difference in speed of the two direction is due to congestion being observed for some of the trips going from Sweden to Norway. There seems to be a difference between the distance of the no service area between the two directions (see Table 1), some to be explained by the higher mean speed observed in the direction of Norway to Sweden and some due to topography. Therefore, we pay most attention to the time spent in the detected no service areas in Table 2. Here we also see a difference in the

**Table 1.** Calculated statistics for the distance of the defined no service area for each trip, dividing the results between the three operators and the two directions included in the test.

| Operator | Distance Swe – Nor n, **(μ, σ)** | Distance Nor – Swe n, **(μ, σ)** | Distance both directions n, **(μ, σ)** |
|---|---|---|---|
| Ice | 8, **(2390, 1701)**, | 5, **(5715, 451)** | 13, **(3668, 2142)** |
| Telia | 11, **(3334, 2691)** | 5, **(6544, 743)** | 16, **(4337, 2708)** |
| Telenor | 7, **(2329, 1456)** | 3, **(5840, 965)** | 10, **(3382, 2120)** |
| All | 26, **(2773, 2111)** | 13, **(6062, 752)** | 39, **(3869, 2362)** |

**Table 2.** Calculated statistics for the time spent in the defined no service area for each trip, dividing the results between the three operators and the two directions included in the test.

| Operator | Time Swe – Nor n, **(μ, σ)** | Time Nor – Swe n, **(μ, σ)** | Time both directions n, **(μ, σ)** |
|---|---|---|---|
| Ice | 8, **(203, 94)** | 5, **(220, 21)** | 13, **(210, 73)** |
| Telia | 11, **(208, 113)** | 5, **(251, 31)** | 16, **(221, 96)** |
| Telenor | 7, **(108, 62)** | 3, **(228, 34)** | 10, **(144, 78)** |
| Total | 26, **(179, 102)** | 13, **(234, 29)** | 39, **(197, 89)** |

time with no service for the two directions (179 s and 234 s for Swe-Nor and Norway-Sweden, respectively), which indeed is shown to be significant running a two-sided t-test with p-value = 0.0133. Moreover, there cannot be shown a strong correlation between the speed of the vehicle and time in the no service area (p = 0.132 using Pearson's r statistics), suggesting that the difference in distance of the no service area in Table 1 cannot be explained by the congestion and the lower speeds alone. The longest service loss observed was 6 min and 34 s.

Lastly, there is also a significant difference in the standard deviation calculated for both the time and distance. Whereas the direction of Sweden-Norway are showing a lower extent of the no service both in time and distance than for the Norway-Sweden direction, the opposite conclusion is drawn for the standard deviation, where the direction of Sweden-Norway shows a larger variance in both time and distance. There seems to be very little difference between the operators, with the direction of Sweden-Norway for Telenor being an exception with respect to time, however more observations should be gathered to confirm this.

## 4 Discussions

Our results show that there is a significant connectivity service loss when driving across the Swedish-Norwegian border. The identified loss of approximately 200 s would pose a significant challenge for CCAM vehicles depending on connectivity for their operation. There would mainly be three approaches to prepare for such scenarios, one being

enabling vehicles with additional sensors and local maps to extend the time with valid ODD without connectivity, and the second being developing and implementing solutions in the mobile network infrastructure to reduce the time with loss of service. For the latter, EU projects are initiated [5]. As a third option, also mentioned in the introduction, would be to use C-ITS in a hybrid solution with LTE/5G at the border.

Moreover, connectivity is not the only challenge when crossing the border with a logistic CCAM vehicle. Other technological challenges with respect to positioning include GNSS correction service and map datum issues. Many countries, including Norway and Sweden, have established national NRTK (Network Real Time Kinematic) services that increasingly are getting attention from the ITS and CCAM community for providing highly accurate corrections for GNSS signals, typically 1–2 cm accuracy under good conditions. To use these highly accurate national services a switch between the national services must be established. However, unique subscriptions for each service are needed and a seamless switch between the two is not an option. The NRTK service is accessed over the internet using mobile networks. As an alternative, several GNSS equipment providers develop systems for cross border corrections, typically through PPP (Precise Point Positioning) or PPP-RTK services, but with slightly less accuracy, typically 3–20 cm under good conditions. The innovation in this area is high, including work from 3GPP, where the telecom industry standardizes broadcasting of correction data via the mobile network [7]. Both commercial companies and international organizations provide real-time PPP correction data, the most recent development is the free service from Galileo High Accuracy Service (HAS).

5G mobile network standards describe network elements and interfaces to support fast handovers and fast roaming between different mobile networks. The work done in [5] shows that the time with service loss can be reduced to a few seconds and even down to order of 100 ms for the ultra-tight coupling between core networks and assistance from the user equipment (modems). Many border crossings are in remote or rural areas where mobile network coverage and capacity is limited. Traditionally, mobile networks near borders have been configured to minimize probability for network reselection to be able to keep network traffic in own network for commercial reasons. Given the complexity of the commercial and technical arrangements needed for seamless roaming it is not always a good business case to invest in seamless cross-border connectivity. Furthermore, regulatory requirements on e.g. frequency plans can make this technically challenging.

In addition, several organizational and regulatory challenges do exist, including traffic regulation, cyber security for traffic rules and regulations, and V2X (vehicle-to-everything) communication, vehicle regulations, and particularly important for logistic operations is custom processes and document handling for CCAM vehicles.

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# Definition of the Research Groups and Creation of the Groups of Interest for CCAM User Needs

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**Abstract.** The SINFONICA project aims to develop innovative strategies, methods, and tools to engage CCAM users, providers, and other stakeholders to collect, understand and structure their needs and concerns. This is only possible with the constant involvement of citizens, future users, stakeholders, and service providers linked to CCAM. But how can we be sure that every category is correctly represented? That every voice, every thought, every opinion is expressed and heard? This paper presents a methodology for defining the research groups and so-called groups of interest which is based not just on the analyses of the literature and projects, but also on the involvement of four municipalities across Europe which offer an immersed view within their reality. With numerous geographical, structural, and cultural differences, these municipalities are involved in the co-definition of the research groups and groups of interest so that each group can give voice to all the ones that need to be represented. The results presented in this paper summarize the process of the co-creation of the research groups and groups of interest, their final composition as well as the participatory approaches that will be used with the different categories.

**Keywords:** CCAM · citizens participation · co-creation methodology

## 1 Introduction

Today's transport ecosystems are experiencing a pivotal moment. Smart mobility planning, integrating CCAM (Cooperative, connected and automated mobility) solutions, has the potential to implement greener, safer, and more sustainable means of transport [European Commission, 2023]. However, to achieve social equity for all users and a real change in the entire transport system, the development of CCAM must be holistic, considering users, non-users and relevant stakeholders just as much as technical advancements. The EU project SINFONICA covers this aspect by using co-creation processes that acknowledge the needs of all relevant stakeholders and citizens. The concept of co-creation is a technical discipline and conceptual framework that originates in the transformative process of the entrepreneurial world [Senabre, 2015]. The main

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root of the co-creation concept lies in the participatory approaches used to engage the stakeholders in the decision-making processes. Co-creation processes in the transport domain have become popular in recent years, for instance within the EU projects TRIPS and Cities4People. However, in the field of CCAM, so far, no citizen and stakeholder-oriented co-creation process has been undertaken at the European level. Therefore, the SINFONICA project decided to put human factors at the center of the creation of its work to realize an 'all-inclusive' CCAM as a societal service for European citizens.

## 2 Definition of the Groups of Interest in SINFONICA

The vision of the SINFONICA project is to develop functional, efficient, and innovative strategies, methods, and tools to engage CCAM users, providers, and other stakeholders to collect, understand, and structure in a manageable and exploitable way their needs, desires, and concerns related to CCAM. To build the co-creation on a strong, equal, and inclusive base, the project team decided to begin its work with a theoretical framework about mobility needs as well as the expectations and requirements of citizens and stakeholders. Based on this, we composed the four SINFONICA groups of interest which are defined as follows: groups of people involved in the co-creation activities; comprised of certain users from the research groups (people with mobility challenges), citizen representatives, as well as relevant stakeholders; can be different for the four research site partners; managed by the four SINFONICA research site partners in Trikala, Hamburg, the region of West Midlands and the Noord-Brabant province.

## 3 Inclusivity and Engagement Strategies for People with Mobility Challenges: Building the Research Groups

### 3.1 Activities to Create the Research Groups

An important aspect of the Groups of Interest (GoI) is to represent people with mobility challenges. To include them accordingly within the participatory methodologies of SINFONICA, we first built a theoretical framework to describe people's mobility needs regarding CCAM with a special focus on individuals facing mobility challenges [Anke & Ringhand, 2023]. Coming up from this literature review, we identified eight categories having special mobility needs (low-income and unemployed; elderly; people with disabilities; migrants, ethnic minorities and people with language barriers; young people; women and gender-related aspects; people living in rural areas; digitally non-connected people). Subsequently, drawing from this review, the consortium engaged the research site partners to collaboratively construct a priority ranking. The research site partners were tasked with ascertaining the relative significance of each group of people with mobility challenges within their unique local context as "low", "moderate", or "high". The criteria for determining relevance were inextricably tied to the prevalence and significance of each category within the territorial domain. The ranking yielded a core set of five categories that emerged as universally pertinent across all research site partners, regardless of their respective geographical or sociocultural contexts. These categories included the elderly, individuals with cognitive disabilities, the digitally non-connected,

those confronting gender-related vulnerabilities, and the youth. Consequently, these five categories were incorporated as integral part of every GoI, thereby ensuring their systematic inclusion and engagement.

Furthermore, recognizing the idiosyncrasies of individual research site partners and their unique demographics, each GoI added additional categories that were not defined according to an academic process, but they were chosen because they are particularly important to their respective territories. Trikala enhanced its GoI with the inclusion of individuals residing in rural areas and university students. Hamburg incorporated cyclists and individuals with physical disabilities. Noord-Brabant introduced the categories of migrants, single-parent families, and rural residents. West Midlands added individuals with physical disabilities and individuals from low-income backgrounds. Therefore, in Trikala, Hamburg, and West Midlands 7 groups of people with mobility challenges will be involved in the participatory activities, while Noord Brabant will involve 8 groups of people with mobility challenges.

### 3.2 Definition of Research Groups of People with Mobility Challenges

For the final set of the five research groups being covered by all four research site partners, we provide a summary of the transport challenges that these people experience.

*Elderly:* Regarding CCAM services, elderly people's mobility needs rise in terms of safety, accessibility, and availability, requiring CCAM among others, to be comfortable, easy to use, and allow enough time for hopping on-off and short walking distances. Mobility challenges arise due to biological, psychological, and sociological changes associated with increasing age.

*People with disabilities:* Around 87 million people in the EU have some form of disability. This means that with 448 million inhabitants in the EU, people with disabilities make up 19% of all EU citizens. According to the European Commission [2022], the biggest challenges for people with disabilities are: a higher number of unemployness; a higher risk of poverty and a lower level of education; around half of all persons with disabilities feel discriminated against. Regarding mobility and transport, these groups have other requirements of trip distances than others. Special and unique transport services (especially prototypes) can lead to exclusions if the requirements of disabled people are not considered. But also, in terms of standard options for production manufacturing, they are not considered for cost reasons.

*Women and gender related aspects:* The aim of transportation is to give everyone the same chances to use different transport modes and reduce the dissonance of travel modes [Hu et al., 2023] Mobility patterns and mode choices of men and women differ significantly: women are more likely to have trip chains and combine several trip purposes, they are also more likely to work in part-time jobs [Ortega et al., 2019], with some modes of transport, they perceive difficulties in transporting goods and children [Ramboll, 2021]. Another key issue is how to account for LGBTQIA + people when designing CCAMs. People having sexual and gender-nonconforming identities experience gender and homophobic-based violence and discrimination more often in public transport compared to heterosexual people and they use more expensive travel alternatives or take less direct routes to overcome their experiences of unsafe and inaccessible

public transport alternatives [Weintrob et al., 2021]. CCAMs should provide women and LGBTQIA + people advantage in terms of accessibility, affordability, and safety.

*Young people:* Around 16% of people living in the EU are young people aged 15–29 [Eurostat, 2022] and children younger than 15 years old account for 15% of the total population of the EU. This makes up 31% of all EU citizens, showing the importance of this user group for CCAMs. Young people are dependent on their parents up to a certain age to fulfil their mobility needs and have lesser needs for self-autonomy [Mobility in Germany, 2019]. To get autonomy and have an inexpensive means of transport, young people are very keen on cycling and other alternatives to car transport at this age. However, transportation is crucial in accessing education, work, and social interactions.

*Digitally non-connected people:* Digital inclusiveness is a primary goal for future transport systems. In 2021, people with at least basic digital skills made up 54% of the EU population (aged 16–74). People with low digital literacy and/or no access to digital services (combined: digitally non-connected people) can face difficulties in accessing information, booking tickets, and making payments for transportation services if digital knowledge and access are needed (like cashless paying). They may also struggle with using digital devices like smartphone applications and navigating digital platforms. Further, these people might experience a risk of paying higher fares for paper tickets than for online tickets or fail to be notified of service changes or disruptions. As a result, their mobility patterns can be limited, and they may face greater challenges in accessing essential destinations such as work, healthcare, and education.

## 4 Engaging Citizens: Identifying Relevant Categories and Participatory Approaches

In pursuit of the objective of broader citizen engagement within the ambit of SINFONICA's participatory methodologies, a collaborative decision was reached with the research site partners to orchestrate focus groups, each strategically tailored to capture distinct demographic parameters. These parameters encompassed age cohorts (i.e., 16–35 years, 36–45 years, 46–65 years, and individuals aged 66 and above), income (defined in accordance with the specific socioeconomic criteria relevant to each respective country), and variations in public transport utilization patterns. The methodological design governing the categorization of citizens into these distinct groupings was derived through a collaborative brainstorming process involving a multidisciplinary consortium comprising municipalities, transport engineers, psychologists, and sociologists. This collaborative, interdisciplinary approach was instrumental in refining and operationalizing the delineation of the categories of people that will join the focus groups activities. The selection of focus groups as the preferred engagement modality was predicated upon its inherent capacity to foster a deliberative and comfortable dialogue environment. This approach was deliberately structured to cultivate an atmosphere conducive to the emergence of novel perspectives, innovative ideas, and unexplored possibilities.

Furthermore, this approach reflects a systematic strategy for expanding citizen participation within SINFONICA's initiatives, drawing upon the structuring of focus groups to facilitate nuanced dialogues and engender a deeper understanding of the transformative potentialities ushered in by CCAM within the transportation landscape.

## 5 Stakeholders Engagement: Identifying Relevant Categories and Effective Approaches

Finally, to ensure a complete vision of the world of transport, we focused on stakeholders' participation. The first step was the definition of a long list that included all the categories of stakeholders involved in the transport sector. Starting from those lists, we asked the research site partners to report which categories of stakeholders were present in their territories. We were therefore able to establish a list of stakeholders with whom all research site partners were in contact. This comprehensive stakeholder inventory served as the foundation for deliberations regarding the optimal participatory modalities aimed at their effective involvement. A decisive consensus was reached to conduct a series of three workshops, designed to cultivate robust stakeholders' engagement. This strategic choice was grounded in the anticipation that workshops would furnish a conducive environment for in-depth dialogue, collaborative problem-solving, and the synthesis of diverse perspectives. These workshops, thus, were conceived as the optimal conduits for nurturing multifaceted stakeholder participation and for advancing a holistic understanding of the intricate dynamics within the realm of transportation. In particular, *the first workshop* will develop a critical analysis of the mobility of the present times, discussing the findings of the Focus groups and the semi-structured interviews. This step will allow to identify barriers and potential solutions for the CCAM implementation. The categories of the stakeholders that will be involved in the workshops are: Service providers, Government representatives, Infrastructure managers, Industry representatives, Non-profit organization and representative bodies, Universities and knowledge institution representatives (only part of the first workshop). The *second workshop* is aimed at investigating on the CCAM potential to meet mobility needs, discussing expectations, desires and concerns. The *third workshop* will focus on co-definition of the requirements for an inclusive, equitable, and accessible CCAM deployment. This step will consider the needs of the users, while considering the abilities and constraints that industry stakeholders and policy makers face.

## 6 Conclusion

The formation of the GOI necessitated the development of a methodological framework rooted in the principles of co-creation, serving as a conduit for the convergence of theoretical constructs and practical implementation. In this context, the representatives hailing from the four research sites played a pivotal role, effectively functioning as intermediaries that facilitated a symbiotic relationship between academic researchers and the distinct territorial contexts involved in SINFONICA. The overarching aim of this endeavor was to articulate a comprehensive repertoire of participatory strategies designed to engender the active engagement of a diverse spectrum of citizens, including those confronted with mobility constraints, as well as various stakeholders. The realities on which these groups of interest have been created have been selected in order to guarantee different perspectives and points of view at the geographical level, at the level of digital advancement, at the level of experience and interactions with CCAM.

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# Connected and Autonomous Vehicles and Road Safety: The Role of Infrastructure

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**Abstract.** This paper summarizes work from a BRRC working group with external experts, which examines the contribution of infrastructure to road traffic safety, regarding connected and autonomous vehicles.

We gained insight into relevant traffic safety matters linked to the road infrastructure component. The working group addressed questions such as: are advanced vehicles safer than traditional vehicles? How do new risks relate to potential road safety gains? What relevant background information is available? What about the role of road infrastructure, traffic signs and road markings? How important are digital twins?

Based on literature review and expert discussions, relevant knowledge about road infrastructure issues in relation to the safe authorization of autonomous vehicles was collected and summarized in a BRRC publication for road owners and other partners in the road construction sector. The most important conclusions are presented in this article.

**Keywords:** Connected vehicles · autonomous vehicles · road infrastructure · traffic safety

## 1 The Issue: What About CAV (Connected and Autonomous Vehicles) and the Physical Road Infrastructure?

The introduction of connected and autonomous vehicles adds a digital dimension to the traffic system. The functioning of the system and its road safety performance is largely determined by the quality of the interactions of the system elements ('human', 'vehicle' and 'infrastructure'). This is not different from today. However, the shift to autonomous driving redefines these interactions.

Industry and governments are focusing on research and testing, to gradually introduce vehicles with higher SAE-levels (Society of Automotive Engineers – levels). Research into autonomous vehicles involves many aspects, both on the technical side and the ethical / societal side.

The role of physical road infrastructure seems underexposed within research concerning AV (autonomous vehicle) safety. Car manufacturers tend to downplay the role of road infrastructure and are not always consistent about the need for digital infrastructure. Gradually, government bodies in Europe start asking questions about the investments (often planned long in advance) that are needed, to promote the development of autonomous mobility.

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## 2 What We Found

Autonomous mobility as a catalyst to improved road safety is an important motivation for policymakers and companies. The gradual introduction as an alternative to more traditional forms of travel is a challenge and offers opportunities for a safer traffic system.

### 2.1 New Safety Risks

Based on a literature study, discussions with experts and information from conferences, we conclude that, vehicle automation is not a panacea [1] but can undeniably provide road safety gains. However, **new road safety risks** also arise [2].

Reasons for this include:

- Vehicles with different automation levels will remain operational for a long time.
- Taking over control by a human driver can take up to 10 s.
- Disengagements in more complex situations can be problematic.
- Drivers can gradually lose their driving skills.
- The non-verbal interaction between human road users is difficult to automate.

### 2.2 The Unruly Reality of Vehicle Development

The introduction of autonomous mobility is slower than predicted. In ethical and legal areas, social acceptance or economic viability, reality has proven to be unruly than expected. Additionally, the focus shifts to the development of cleaner vehicles.

Advocates of autonomous mobility argue that there are no technical barriers to authorize autonomous vehicles on the road network, not even in an urban context. They refer to tests outside the EU (European Union) that have gone beyond the level of a pilot project.

### 2.3 Disengagements

Autonomous vehicles are taking increasingly less the initiative for disengagements. This suggests that self-driving vehicles are increasingly reliably. Furthermore, information shows that road infrastructure (e.g., visibility of signaling or defects in the road surface) is not the main reasons for the disengagements (Fig. 1).

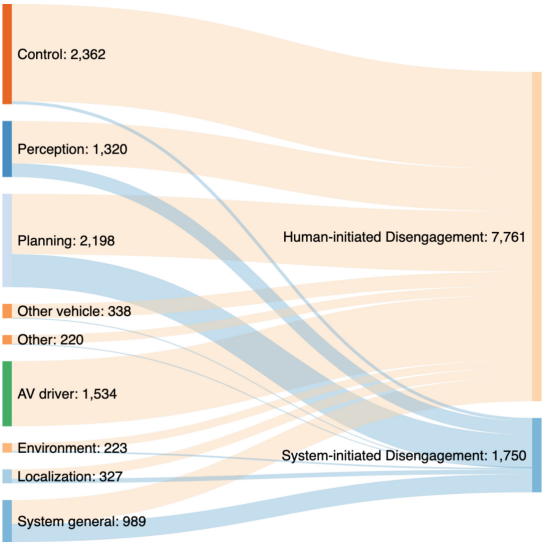



**Fig. 1.** Cause category for two types of disengagement, Zhang, 2021

### 2.4 Confidence in the Technology

Traffic accidents involving autonomous vehicles are widely reported and could compromise consumer confidence. However, research shows that confidence in autonomous mobility increases. When emphasizing on potential road safety gains, acceptance might even further increase.

Public exposure of incidents with self-driving vehicles tends to introduce a certain reluctance from policymakers for introduction of autonomous vehicles. Based on analysis of traffic accidents involving self-driving vehicles, it seems correct that this is (at least partly) unjustified: the cause of accidents often lies with the other vehicle and the severity of accidents is usually lower [3]. (Based on data from tests with AV in the US (United States). The data are several years old, further improvement seems likely).

### 2.5 Evaluating Autonomous Vehicles Safety Behavior

Today, driving skills of human drivers are evaluated during initial training and subsequent monitoring. EU Regulations [4] that define the technical requirements of motor vehicles, progressively introduce mandatory ADAS (Advanced Driver Assistance Systems) functions and methods to evaluate the functionality of these systems.

However, there is no unambiguous method for evaluating the overall road safety behavior of autonomous vehicles (or benchmarking with 'conventional' vehicles). Today, a combination of simulations and pilot projects seems the best way to avoid a biased appreciation of the road safety potential. Tests on public roads is the most reliable method to demonstrate safety. This can be done in full self-driving mode or in so-called 'shadow' mode (human driver behavior is observed by the algorithm and used for further adjustment).

Today, there are no full self-driving vehicles on the consumer market. The most advanced vehicles are SAE level 3, currently only permitted in limited and specific driving conditions. On the other hand, large scale robotaxi services are operational in various places around the world (US, China), usually limited to the home countries of the service providers. EU countries however appear rather reluctant to large-scale testing, among others due to uncertainty about the road safety effects.

Improved safety is an absolute, but not yet fully defined, condition when organizing tests or authorizing autonomous vehicles and successfully introduce such vehicles on EU roads.

### 2.6 Operational Design Domain on Existing Roads

Automotive manufacturers only guarantee the reliable operation of driving support or self-driving functions under specific circumstances; the so-called Operational Design Domain (ODD) [5]. Unfortunately, formal agreements about the parameters that define an ODD are missing today. There is no unequivocal standard for 'the' road that supports autonomous mobility. A definition of the required infrastructure elements to allow autonomous mobility would however be helpful for road authorities for planning future investments or when allowing autonomous driving on specific road sections.

There seems to be a fair consensus among industry and policy makers that autonomous vehicles will use existing roads and construction of roads specifically for autonomous vehicles is not desirable. Particularly in an urban context, that is the only logical approach.

### 2.7 Algorithms Under Development

Traffic accidents with autonomous vehicles can partially be attributed to system errors [6]. This may involve perception errors (hardware errors, software bugs), decision errors (late or incorrect information) and action errors (mechanical faltering of the vehicle). Development of the algorithms and artificial intelligence can contribute to an increasingly reliable system.

Weather conditions influence the functioning of autonomous vehicles. Algorithms of autonomous vehicles are usually designed for a conservative approach and can protect human drivers from taking risks in unfavorable weather conditions.

### 2.8 Traffic Signs and Road Markings

Clear and uniform signaling undeniably contributes to the functioning of new vehicle technologies. However, the correct reading of traffic signs and road markings under unfavorable conditions (bad weather, faded signs…) often remains challenging.

Recommendations for the visibility of road markings are not always achieved. Fortunately, technological evolutions allow AV to deal increasingly well with poor road markings. In addition, vehicles with varying automation levels will continue to use current roads. Maintenance and investments in road markings and traffic signs therefore remain relevant for human road users as well as for autonomous vehicles.

### 2.9 Connectivity

Connectivity can contribute to the functioning of autonomous vehicles. Unintentional or intentional (malicious) dysfunctional connectivity is seen as an argument for not relying on connectivity for at least safety critical functions.

### 2.10 Vision Zero

Traffic policies aspire zero road deaths by 2050. Recent policies link to an integrated approach; the Safe System Approach [2], based, among others, on shared responsibility. It acknowledges that humans make mistakes and promotes system configuration that avoids severe consequences after faulty or unpredictable human behavior.

Also, AV make mistakes, or the algorithm is not yet sufficiently developed to deal with all possible situations. Policies about autonomous vehicles must also take accident prevention into consideration. Concrete: the correct functioning of driving support or self-driving systems depends on the correct configuration of all elements (e.g., safe system, infrastructure) and the interactions between them, on a road environment of sufficient quality and supposing reliable functioning of communication facilities. In this sense, the shift to autonomous mobility even more emphasizes the importance of good cooperation between the various stakeholders (Fig. 2).

### 2.11 ISA (Intelligent Speed Assistance) Reliability

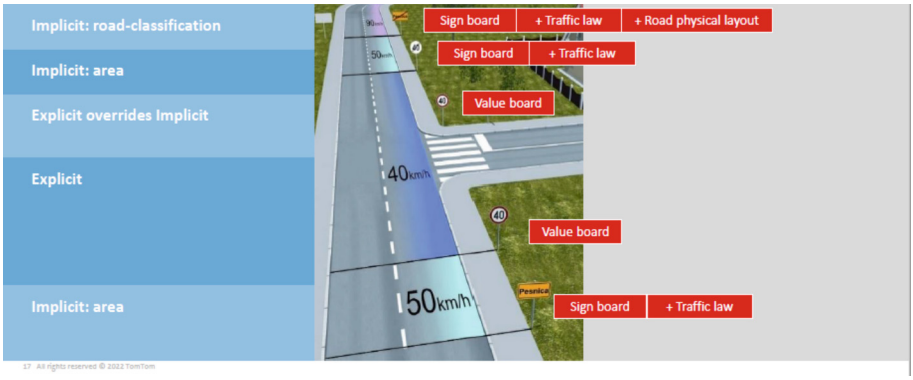



**Fig. 2.** Elements that determine the speed regime (ITS.be, 2022). Reproduced with permission from TomTom Belgium NV, copyright TomTom Belgium NV, 2025.

Insufficient harmonization of traffic signs, reduced visibility, additional (local) rules and implicit rules (e.g., speed regime after the end of the built-up area) make it difficult for ISA systems to reliably identify the applicable speed regime. Increasing the reliability of these systems requires external information sources (digital maps) and additional efforts, including in the maintenance.

### 2.12 Infrastructure Characteristics

Road authorities need recommendations on the infrastructure features that can promote self-driving transport. This concerns a.o. requirements for physical road elements (signaling, surface characteristics), development of AI systems and smart roadside units.

### 2.13 Road Works

The ITS Directive (2010/40/EC) and associated regulations [7] already require certain traffic information (including for short-term road works) to be made available to road users. Advanced (connected) vehicles contribute to do this more efficiently.

## 3 Closing Statement

BRRC publication 'CAV and road safety' discusses the previous elements. It presents an overview of relevant background information, elements of research and testing, road safety policies and objectives and provides more insight into the infrastructure component. This knowledge contributes to short- and medium-term choices made by road administrations.

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# NAITEC URBAN LAB – The Innovative Intelligent Urban Test Bed

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**Abstract.** The objective of NAITEC URBAN LAB is the creation of a reference environment that allows the design, testing, and deployment of the different technologies and functionalities associated with the connected, cooperative, and autonomous vehicle (CCAM). The urban test bed is in Pamplona, Navarre, Spain. It is a circuit in the heart of the city, next to a university campus. In addition to being a real environment in the urban area, it presents some very interesting characteristics in terms of mobility scenarios, having a university, a football stadium, and a music hall in its surroundings. The urban test bed has different sensor systems. It has a network of fibre optic sensors; traffic cameras; a LiDAR for the detection of vehicles and pedestrians; and a network of pollution sensors. It also presents a V2X communications equipment, both in infrastructure and in vehicles. The collected traffic data will be used for the creation and validation of traffic models.

**Keywords:** Urban test bed · CCAM technologies · Traffic management

## 1 Introduction

### 1.1 Objectives

The aim of this project is to establish a benchmark environment that enables the design, testing, and deployment of various technologies and functionalities associated with CCAM, and traffic management.

### 1.2 Description

Situated in Pamplona, Navarre, Spain, the NAITEC urban test bed encompasses a 2.3 km circuit located in the heart of the city. Serving as a real-world urban environment, our test bed showcases compelling mobility scenarios, including the Public University of Navarra campus, the surroundings of Sadar Football Stadium, and the Palace of Navarra Arena (a congress and music hall). Through a collaboration agreement with the Pamplona City Council, responsible for traffic control on the circuit roads, the test bed can be utilized for designed tests, including the closure of traffic if necessary.

The test bed offers the following capabilities:

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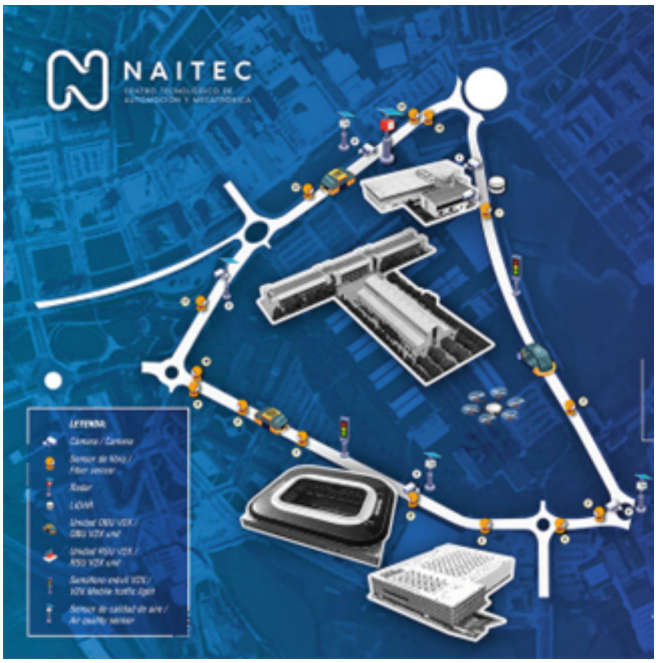



**Fig. 1.** Map of the urban test bed

- Integration of vehicle embedded technologies.
- Implementation of technologies associated with smart and connected road infrastructures.
- Addressing the requirements of Smart Cities.
- Development of information management systems for roads and environments.

## 2 Technical Specifications

### 2.1 Traffic Measurement Infrastructures

The urban test bed incorporates various sensor systems. Firstly, it comprises a network of fibre optic sensors strategically positioned along the circuit to measure vehicle passage, including their direction and speed. These sensors are installed a few centimetres above the track surface at different locations. Additionally, traffic cameras are installed at specific points on the circuit, mounted on poles along the road median to ensure optimal detection.

Furthermore, the infrastructure is equipped with the following sensors: Radar technology to measure the speed of vehicles passing through the four lanes; LiDAR (Light Detection and Ranging) for the detection of vehicles and pedestrians; and an integrated network of pollution sensors consisting of pollutant measurement stations. Each station can measure NO (nitric oxide), NO2 (nitrogen dioxide), PM (particulate matter) in various sizes (PM1, PM2.5, PM4, and PM10), as well as noise levels.

### 2.2 Communications Infrastructures

Concerning communications infrastructure, the installation of V2X communications equipment has been implemented in both the infrastructure and vehicles. This includes OBU-V2X units (On Board Unit), RSU-V2X units (Road Side Unit), and V2X traffic lights. V2X communications play a crucial role in advancing the concept of smart mobility, enabling vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications collectively known as vehicle-to-everything (V2X). These wireless technologies facilitate information exchange between vehicles and their surroundings, enabling the development of use cases such as intelligent traffic lights, protection of vulnerable road users, and optimization of route speed.

### 2.3 Data Platform

All data generated within the circuit is centralized in an open data platform based on FIWARE. FIWARE is an EU-promoted open-source project that enables the development of real-time cloud-based applications. While it is a versatile platform, it is extensively utilized in the realm of Smart Cities. The platform is continuously evolving and currently possesses the capability to visualize some of the systems.

## 3 Use Cases

### 3.1 Traffic Management

The collected traffic data serves a crucial purpose in validating traffic models, which yield fascinating outcomes. These models enable the prediction of traffic evolution by leveraging measurements obtained through circuit sensing. Additionally, they facilitate evaluating the potential effects that can be introduced prior to execution. Thanks to the traffic sensors installed in a distributed manner throughout the circuit, a virtual model of the area is available, which can be used for various studies. Furthermore, this model is scalable to any part of the city. For example, studies can be conducted to analyze the impact of including a new bike lane that requires removing one of the four available lanes. Once the simulation is validated, traffic studies in the area begin. Simulation allows obtaining objective results regarding the traffic conditions in the area. This type of model enables the execution of a multitude of studies, including:

- Low Emission Zone Studies.
- Congestion Zone Strategy Studies.
- Public Transport Planning.
- Studies on the combined behaviour of autonomous and manned vehicles.

### 3.2 Autonomous Vehicle Testing

The urban circuit has been used to validate autonomous navigation applications with different vehicles. In these tests, the circulation of other vehicles on urban circuit has been limited, thanks to the existing collaboration agreement between NAITEC and the



**Fig. 2.** Traffic simulation results

Pamplona City Council. Two in which vehicles move through waypoints established with centimeter precision are to be highlighted. In the first use case, telemetry and navigation electronics are integrated on a vehicle to be able to circulate along the urban circuit autonomously. In this case, a high-precision RTK GPS system is integrated allowing precise positioning and navigation following the defined waypoints. Additionally, a radar sensor is integrated to detect the presence of obstacles in front of the vehicle. The information from the sensor is sent to the navigation system to be able to make a safety stop. In the second case, a robotic platform is used for autonomous navigation in the circuit. The navigation application is developed on a ROS software architecture. One of the most important aspects is the use of SLAM (Simultaneous Localization And Mapping) algorithms using the point cloud provided by a Lidar sensor installed in the vehicle itself. These algorithms make it possible to generate a map of the environment in which the vehicle moves and, in addition, to locate the vehicle on the same map and circulate on the road with precision.



**Fig. 3.** Images of tests carried out on the urban circuit with different autonomous vehicles.

### 3.3 V2X Testing

Using the urban circuit as a testing ground several use cases have been developed in which V2X communications play a fundamental role for intelligent traffic management and improved safety. For instance, a RGB camera with a pedestrian detector is installed on board of a test vehicle. The pedestrian detector is built using a deep neural network. This deep neural network is capable of measuring distances between objects detected in scena.

When the distance measured is less than safety distance, the pedestrian detector asks the On Board Unit V2X interface to send an alarm to the RSU. The event is showed on RSU Web interface. To accelerate the necessary calculations in the deep neural network, a USB Coral accelerator is used. From here, the RSU can send a broadcast message to other OBU devices installed in other vehicles to notify them of this event and be warned of the situation.

## 4 Conclusions and Future Work

Nowadays, the circulation of autonomous vehicles in urban areas is mostly prohibited in Europe, which poses challenges in conducting tests in real-life scenarios that simulate everyday situations. The existence of NAITEC's circuit facilitates the acceleration of CCAM development by providing a controlled testing infrastructure.

NAITEC continues working on technologies related to cooperative, connected, and automated mobility. On the one hand, collecting data from the systems installed in the urban circuit, including high-traffic events. Data inter-operatibiltiy and standardization will be a key issue, with the objective of data globalitation. On the other hand, working with technologies and platforms that allow the generated data to be grouped and put vehicles in communication with the infrastructure and vehicles among themselves, communicating and coordinating air and land vehicles. Finally, a sociological study is proposed to evaluate the acceptance of autonomous last-mile delivery vehicles in the population, in collaboration with other European partners.

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# Road Operation Opportunities Due to Distributed ODD Attribute Value Awareness

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**Abstract.** The paper presents the concept of Distributed Operational Design Domain (ODD) attribute Value Awareness (DOVA) developed by TM4CAD (Traffic Management for Connected and Automated Driving), a CEDR-funded project involving MAPtm (coordinator), Traficon, Transport & Mobility Leuven, and WMG, University of Warwick, as well as Hironao Kawashima from Japan and Steven Shladover from USA as experts. TM4CAD explored the role of infrastructure systems and connected vehicle data exchange in creating ODD (Operational Design Domain) attribute value awareness for Automated Driving Systems (ADS), so that each ADS can be forewarned before it encounters conditions in which it will not be capable of operating, i.e. ODD departure. TM4CAD proposed various approaches for providing distributed ODD attribute value information and its importance, acquisition principles, and corresponding data quality requirements. It also discussed the basic mechanisms of ODD management via specific use cases, which build on the interaction between traffic management systems and the ADS, and highlighted the need for stronger interactions between national road authorities and ADS developers.

**Keywords:** Operational Design Domain · Automated vehicles · Road operation

## 1 Distributed ODD Attribute Value Awareness

### 1.1 The DOVA Framework

The need to monitor or be aware of each ODD attribute puts an additional overhead on the Automated Driving System (ADS) to be able to measure each ODD attribute. However, measuring each ODD attribute may not be practically feasible from a cost and engineering perspective. However, ODD awareness is key to ensuring safe operation of the ADS. In order to overcome this challenge, TM4CAD has introduced the concept of Distributed ODD attribute Value Awareness (DOVA) framework [1].

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The DOVA framework enables the ADS to benefit from off-board sensing infrastructure to become aware of ODD attribute values which it may not be able to measure or sense by itself. For example, an ADS may not be able to detect the severity of a visibility impairment from a fog bank that it is approaching. It may be able to receive such information from a roadside weather station which can provide this information through over the air communication with the ADS. This enables the ADS to have awareness of this current operating condition and compare it with its designed ODD to establish if the ADS is either inside or outside its ODD. While information for some of the ODD attributes could be available via infrastructure, there may potentially be commercial services which can augment ODD information for the ADS [2].

From a road operator perspective, it is important to establish what type of ODD attribute information should be provided via infrastructure and its corresponding quality to enable safe deployment of ADS. It is also important to consider the needs of the road operators and traffic managers to be aware of any ADS approaching the end of their ODD and/or being in a transitional or minimal risk state [2].

The operation of the DOVA framework in practice is illustrated in Fig. 1. The ODD attribute information (or from the road operator perspective, local condition attribute information) sharing plays a major role in influencing the driving behaviour of the ADS-operated vehicle depending on its technical capabilities and the rules of the road. The traffic management operations affect the rules of the road (i.e., the expected behaviour) as well as the status of the ODD / local condition attributes sensed by the vehicle, the road operators' and other stakeholders' monitoring and other data acquisition systems providing the attribute information to the ADS-operated vehicles and other road users.

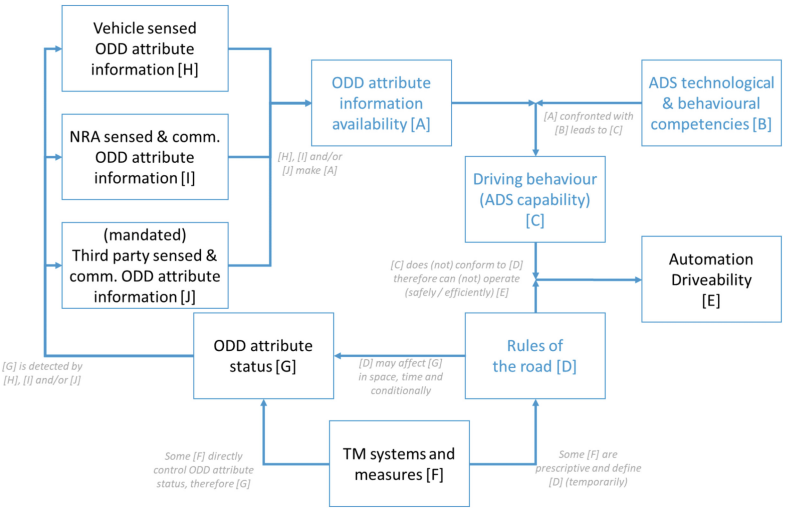



**Fig. 1.** Distributed ODD attribute Value Awareness (DOVA) Framework [1].

### 1.2 Road Operators and Providing DOVA

We found out that any external ODD or local condition information from infrastructure can bring redundancy, i.e., backup for the automated driving systems. The ODD attributed related external information can likely always be regarded at least as "nice-to-have" as it can extend the electronic horizon of the vehicle beyond the range of the vehicle sensors.

In the future, regulations could specify that the road operator or traffic manager must provide specific information attributes to the ADS. Some of these information attributes are necessary for ADS operation while others are relevant to managing the traffic.

Basically, the ODD/local conditions attributes that the AV industry indicated being priority for them, were also considered priority for the traffic managers and road maintenance operators in most of the cases in the scenarios of traffic jam, adverse weather area and road works.

A primary open issue is the basic one of trust. Vehicle manufacturers and ADS developers will use the data as a basis for automated vehicle operation only if they can trust the data to be correct, reliable, and secure. Much work needs to be done to improve the quality of the data, the reliability of the data and its exchange as well as the cybersecurity of the DOVA process to the level satisfying the liability-related requirements of the automated vehicle industry.

In the discussions with the road operators it has become clear that the required major improvements with regard to some quality indicators such as network coverage, location accuracy and timeliness can not realistically be achieved by the road operators on their own but only via information shared by the connected and automated vehicles. This would be a clear future win-win situation where ADS fleet operators achieve trustful ODD attribute awareness for their ADS in use while the road operators have very good awareness of the local conditions on their road networks.

## 2 Opportunities for the Road Operators Brought by DOVA

The opportunities are described below for selected core business areas. Those for the other core business areas are only shown later in Table 1. Note that the opportunities build on the availability of data from automated vehicles utilising the DOVA framework on e.g. the ODD unavailability, carrying out of MRMs, etc. The chapter assumes a much broader information provision from the vehicle side than what is contained in the DOVA framework itself. It is likely that the road authorities and operators expect that in return for the ODD-related local condition information provided to the vehicles and fleet operators these would also provide information essential to the road authorities and operators [3].

### 2.1 Physical Road Infrastructure

Feedback from the automated vehicles concerning the issues related to the ADS engagement enable easier real time analysis of physical infrastructure driveability for highly automated vehicles. This also provides data on the frequency of different types of issues in various parts of the network.

**Table 1.** Road operator opportunities in the other business areas not described in detail.

| Core business area | Opportunities |
|---|---|
| Traffic management and control | Tailored traffic management, merging of traffic and fleet management, new methods due to better compliance, incident prediction/prevention |
| Road maintenance | Automated maintenance vehicles, real-time digital twins, quicker maintenance operations through better predictability |
| Winter maintenance | Automated maintenance vehicles, real-time digital twins, quicker maintenance operations through better predictability |
| Traffic information services | Higher quality data & information via DOVA feedback loop |
| Enforcement | Better enforcement of road works and maintenance operations by contractors |
| Road user charging | Charging granularity can be improved |
| New roads planning and building | More detailed digital twins for BIM (Building Information Modelling |
| Road works planning/management | More efficient road works management due to meeting DOVA needs |
| Heavy maintenance planning | More detailed knowledge for AIM (Asset Information Modelling) |
| New business | New tasks & roles resulting in new services, involvement in ODD & DOVA management, limiting remote supervision |

If the AV fleet operators are willing the share the location and even in some cases the reasons for the issues with the road operator or traffic management centre, the latter can identify the problems related to their responsibility and find solutions to remove these problems. If the solutions are economically and otherwise feasible, the implementation of the solutions can take place.

The data from the automated vehicles on any problems related to the physical infrastructure will provide a new and important data source for the asset management processes of the road operator. This can relate to all physical infrastructure related ODD attributes such as for instance quality of pavement marking and the load-bearing capacity of roadway or bridge structures [2].

### 2.2 Digital Infrastructure

The DOVA framework and vehicle originated data will also provide high quality tools for digital road operation. The setting up of the DOVA framework already will indirectly provide improved quality data for all other digital road operator services as the local

condition data required by the ADS has higher quality requirements than the conventional services. Thereby the benefits to the existing services will also likely increase [2].

The improved and larger sets of data provide also a good basis for the use of AI (Artificial Intelligence) resulting in improved core business services utilising AI-enhanced digital infrastructure [3].

The data in the DOVA and provided in its feedback loop provide also an excellent basis for developing and enhancing the digital infrastructure asset management and its processes. This asset management would likely target at least the digital infrastructure oriented ODD data source such as the availability of GNSS positioning and its differential correction signals or I2V/V2I communications [2].

### 2.3 Incident and Event Management

The sensing by automated vehicles may well be the first source of information about an incident on the road. It could also be the first source to detect the effects of an event on or nearby the road resulting in a sudden end of a stopped or slow queue on the road [3].

The thereby improved location accuracy and timeliness of detection will provide quicker and more effective incident and event management services. In addition to location accuracy and timeliness, the automated driving system originated data will likely provide improved event coverage (proportion of incidents or events detected and reacted to) and road network coverage. The coverage will naturally only improve on roads within the ODD of the ADS systems in question [3].

In addition to the benefits related to incident and event impact detection, the ADS supported by DOVA are expected to react better to incident management and information measures complying more uniformly with them compared to human drivers. This will likely reduce the risks of secondary accidents and lessen the congestion caused by incidents and events and thereby also the journey time and harmful emission impacts [3].

### 2.4 Traffic Management and Control

The DOVA provides a possibility for tailored traffic management for different automated driving use cases and scenarios. This also will require a close cooperation and interaction between traffic managers and ADS fleet operators. This could lead to different types of ODD management use cases where traffic management measures and adapted rules of the road could control, maintain or eliminate the use of ADS on a road section ensuring road safety at the same time [3].

This merging of traffic and fleet management could be especially useful for managing hazardous or XXL goods transports (XXL here means goods with dimensions exceeding the ones accepted by regulations) [3].

The ADS will also comply better with traffic management measures than human drivers. Higher compliance rate with regard to traffic management measures means that new methods of traffic management are required. Conventional traffic management measures for instance for rerouting result in only a moderate part of the vehicle drivers to divert accordingly, which in most cases is useful as high diversion rates could cause

major congestion issues on the detour [4]. With ADS and their high compliance rate traffic managers need to direct the optimal portions of vehicles to specific detours based on the capacity and other characteristics of the detour (e.g. no heavy goods vehicles should be directed through small village communities).

If available, improved and more comprehensive real-time data in terms of floating vehicle data can be used in actual incident prediction and prevention via traffic management tools utilising AI. This can transform the current reactive traffic management to proactive traffic management where instead of reacting efficiently to incidents to mitigate their impacts and to remove them as quickly as possible traffic management focuses on preventing the incidents from occurring at all. This could be possible by detecting the first symptoms of a likely incident and start preventive measures accordingly in good time.

## 3 Conclusions

The opportunities for other business areas are compiled in Table 1. It is evident that the vehicle-oriented data provided related to the operation of the DOVA framework brings a lot of opportunities for the road operators. It is perhaps surprising that opportunities were identified even in core business areas quite remote for traffic management and enabling highly automated driving.

The research was part of the Traffic Management for Connected and Automated Driving (TM4CAD) project funded by CEDR's Transnational Research Programme Call 2020 Impact of CAD on Safe Smart Roads (https://cedr.eu/peb-call-2020-impact-of-cad-on-safe-smart-roads). Note that further information and access to the documents is available at the project website https://tm4cad.project.cedr.eu/.

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# Estimating the Impact of Vehicle Breakdown on Traffic Performances: A V2V Simulation Study of UK Motorways

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**Abstract.** Road traffic congestion has adverse effects on commuter safety and transport network efficiency, apart from its environmental consequences. To address this issue, Traffic Incident Detection (TID) models have been developed, leveraging advanced connectivity technologies. However, ensuring the alignment and effective operation of these technologies within existing systems and contexts is critical. This research aims to create an incident detection algorithm supported by Vehicle-to-Vehicle (V2V) technologies, alerting road users approaching incident zones. The algorithm's effectiveness was assessed through metrics like vehicle delays, travel time, and macroscopic fundamental diagrams (MFDs). Real-time traffic conditions were simulated using VISSIM, employing data from Inductive Loop Detectors (ILDs) and ground truth data from an instrumented vehicle on a UK motorway section. Results reveal varying impacts on delays and overall traffic based on V2V adoption rates. The presence of Connected Vehicles (CVs) ensures efficient traffic flow. These insights benefit network operators, enabling prompt identification and communication of traffic incidents to drivers, roadside infrastructure, and traffic control centers, ultimately aiming to mitigate traffic and safety impacts.

**Keywords:** Motorways · Incident detection · Traffic Microsimulation · VISSIM · Vehicle-to-Vehicle (V2V) communication

## 1 Introduction

Current transport systems need to be more economically efficient, environmentally benign, and safe. Recent advancements in artificial intelligence, connected capability, and vehicle technology have brought about the introduction of CVs closer to reality. CVs can learn, adapt, make decisions, and act independently of human control and are, therefore, envisaged to impact safety, mobility, and society profoundly collisions [1]. For instance, once a traffic incident occurs on a network, CV technology has the potential to detect the incident quickly and mitigate its impact on traffic efficiency and safety.

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While studies have explored on-demand mobility, MaaS, and CVs for detecting unusual traffic dynamics and improving road safety [2–9], limited research addresses mitigating traffic incident consequences with CV technology. CVs offer solutions through V2V tech. While V2V typically focuses on traffic info sharing [10] and route guidance [11], its potential in incident scenarios remains underexplored. It can leverage its route coordination system [11] and online environment [12] to manage incidents, relying on link travel time prediction. A robust wireless communication network forms the core of connected transport systems [13]. Reliable V2V communication is crucial for CV tech to share traffic data, enhance awareness, reduce congestion, and ensure safety.

Detecting traffic incidents on a high-speed road network is a systematic endeavor to locate, react to, and eliminate traffic incidents and re-establish safe traffic capacity within satisfactory timeframes [14]. The research gap of this work is identified as there is a need to quantify the impact of CVs in case of an incident through the formulation of a traffic simulation framework capable of modelling connected vehicles along with traditional vehicles in a variety of pre-defined scenarios, with regards to maximising the traffic performance and road safety on highways.

CV technology enables vehicle communication and navigation enhancements, offering valuable information for informed, safer decisions [15, 16]. CVs create data-rich environments, enhancing road safety, reducing congestion, and improving eco-friendliness [17]. Growing demand for "always connected" vehicles drives innovation for safer, more connected software [17, 18]. Integrating connectivity into CVs requires reliable technologies for deployment, reliability, and functionality in ITS [19]. These technologies ensure seamless data exchange between smartphones and in-vehicle networks [20, 21]. Current wireless CV communication tech includes DSRC, Wi-Fi, and V2V communication [17, 22]. Achieving reliable, secure V2V connectivity demands feasible solutions for integration with CV-installed V2V products [22].

V2V technology in CVs aims for earlier incident detection through smart algorithms [23]. These models offer real-time traffic info before and during incidents, reducing secondary crashes, incident duration, and fuel consumption [14, 24]. Effective use of CV tech like V2V relies on data collection (delays, driver behavior, travel time) and informing drivers to take proactive actions like slowing down and changing lanes [25, 26]. Previous methods like Advisory Radio and Variable Message Signs (VMS) provide traffic info but have limitations [27, 28]. Intelligent options like CVs, relying on wireless communication for V2V interactions, offer more flexible solutions [27, 29].

Although many approaches have been reported, the performance of incident detection models using CV technologies highly relies on their deployment context. Although such models have started to be widely explored and implemented worldwide, no reasonable attempts have been made in the United Kingdom's specific context. In addition, some studies have examined models based on CV technology focusing on recurrent congestion issues [30, 31] and do not address nonrecurrent congestion problems for traffic incident detection.

In this paper, to preach the abovementioned weakness, a smart Traffic Incident Detection algorithm by leveraging the use of V2V communication protocol has been used. This approach is being tested by using various measures of effectiveness. The incident

detection and mitigation model has been used in a section of the M1 Motorway in the UK.

## 2 Methodology

The purpose is swift CV-based traffic incident detection to reduce delays and enhance safety. Prior studies suggest a 50% incident duration reduction could cut total delay by 75% [32]. As real-world CV incident data are unavailable, a simulation approach was chosen. To develop the micro-simulation incident model, three data types were necessary: (1) traffic data (volume, composition, speed, travel time); (2) geometric data (lane count/width, road type); and (3) incident data (type, location, time, duration). Geometric data came from Google Earth and National Highways. National Highways provided traffic and incident data from 2016 to 2019. Inductive Loop Detectors (ILDs) data, available on WebTRIS [33], supplemented the datasets. ILDs collect, process, and transmit dynamic and static traffic data at 500 m intervals.

### 2.1 Incident Detection Algorithm Using V2V

The overall methodology consists of five modules which are briefly discussed below:

1. Understanding existing traffic incidents and their characteristics (e.g., types, location, duration, trends)
2. Developing a traffic microsimulation model in VISSIM (including its calibration)
3. Modifying V2V communication protocol and simulating incidents
4. Creating representative scenarios for incident occurrences based on Item 1
5. Measuring the effectiveness of V2V relative to the base-case scenario

### 2.2 Understanding Traffic Incidents and Their Characteristics

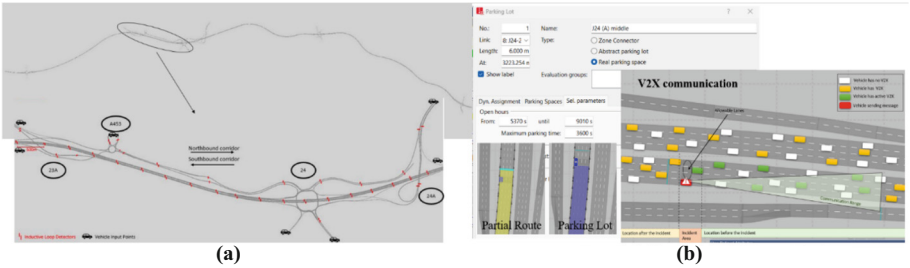
In on-road settings, incident detection challenges include delayed detection and frequent alarm rate [34]. CVs and V2V tech help by instantly notifying following vehicles about incidents ahead, ensuring quicker detection and allowing road users and control centers to react promptly.

### 2.3 Traffic Microsimulation Model - Building Baseline Model

A 100 km stretch of the UK's M1 motorway, managed by National Highways, serves as the testbed. It spans from Junction 23 (west of Loughborough) to Junction 26 (north-west of Nottingham). The area includes the main motorway, six roundabouts, and a parking/rest area, all meticulously designed. Figure 1 represents the whole network as a building in VISSIM.

### 2.4 Calibration and Validation of the Simulation Model

Calibration is an iterative optimization process aiming to minimize the difference between real-world and simulated data. It starts with default parameters, simulating real-world conditions. An initial number of simulation runs are executed to receive a dataset used for comparison with the real world. When simulated data matches real-world data adequately, the process ends. Parameters are then validated similarly. If the error remains acceptable, additional validation follows, including Geoffrey E. Havers (GEH) statistics and Mann Whitney U test. All goodness-of-fit measures met acceptable standards [35, 36].




(a) (b)

**Fig. 1.** (a) Whole simulated motorway network as depicted in VISSIM. (b) The incident simulation in the VISSIM interface

Figure 1a and b are screenshots reproduced with permission from PTV Group, copyright PTV Group, [20, 24].

### 2.5 Simulating Incidents

When an incident needs to be simulated, the method following includes simulating a parking lot that allows the vehicles involved in the incident to stay in the blocked lane during the incident duration, for following vehicles to use the allowable lanes. In this research, for the incident to be simulated, the parking lot was placed on the slow lane in the middle of J24 between an exit and an entry ramp. The parking lot is assigned to the vehicle that caused the incident, as illustrated in Fig. 3. The partial route controls all traffic over created connectors during the incident. Fig. 1b shows the incident simulation in the VISSIM interface.

### 2.6 V2V Communication in VISSIM

To differentiate between the V2V classes of vehicles, several colours were used. In this regard, white (no V2V equipment), yellow (inactive V2V message), and green (received V2V message). VISSIM's user-defined attribute specified these classes. Figure 1 shows car identification, incident simulation, and the attribute. The message is being transferred to a range determined, and the time distribution of transmitting the message is the headway of the vehicles. When approaching the incident location, the vehicles are forced

to change lanes using the allowable lanes. When the vehicles with V2V pass the incident location, they stop receiving the message and turn from green to yellow again.

To simulate V2V vehicles, an event-based Python 3.7 script file was used. It automatically ran several times before the simulation started and when the incident began. The External Driver Model API COM enhanced incident detection with varying CV penetration rates.

### 2.7 Developing Representative Scenarios

Multiple scenarios were developed and examined for different CVs' MPR. The incident happened at 16:30 with an incident duration of one hour out of a five-hour simulation. The scenarios were created:

i. **Baseline Scenario:** 100% normal vehicles, 0% CVs, HGVs
ii. **25% CVs Scenario:** 75% normal vehicles, 25% CVs, HGVs
iii. **50% CVs Scenario:** 50% normal vehicles, 50% CVs, HGVs
iv. **75% CVs Scenario:** 25% normal vehicles, 75% CVs, HGVs
v. **100% CVs Scenario:** 0% normal vehicles, 100% CVs, HGVs

### 2.8 Measuring Effectiveness

The effectiveness of the incident detection model can be tested by comparing the macroscopic fundamental diagrams (MFD), the average vehicle delay, the queue length, and the traffic conflicts detected by the Surrogate Safety Assessment Model (SSAM). Ten simulation runs were performed with different random seeds for each market penetration scenario and an incident occurring in the same location. Each simulation run lasted 10,800 simulation seconds with 1,800 simulation seconds warm-up period to allow the motorway segment to be fully occupied.

## 3 Results

The V2V algorithm was evaluated by comparing MFD, delays, and conflicts between the baseline and other scenarios. Evaluations took place at 16:30 in the simulation. Most scenarios didn't reach the network's full capacity, indicating low congestion when one lane out of four was closed for a one-hour incident. It's worth noting that SRN incident durations vary from 30 min to two hours. Despite minimal traffic congestion at the incident site, increasing the MPR of CVs led to a significant reduction in conflicts. Figure 2 shows MFD for different scenarios, while Fig. 3 displays the average vehicle delay (in seconds) for each MPR scenario (a), queue length results for each MPR scenario (b), and percentage reduction in traffic conflicts with the baseline scenario per MPR of CVs (c).

The MFD for the volume and speed were created using the link segment data from the simulation results. Figure 2 compares the volume and the speed-based MFDs obtained from the granular approximations to check the capacity of the network in a section of the network approximately 2 km before the incident location, from junction 23A to junction 24. Even though different spatial and temporal demand patterns were simulated,

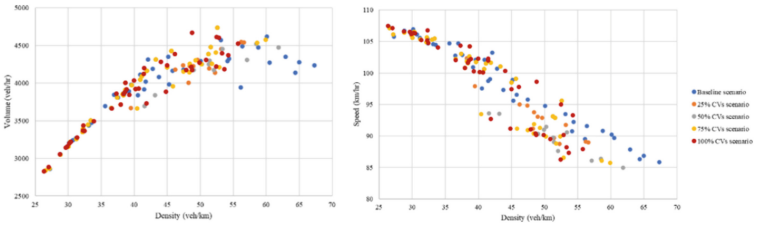



**Fig. 2.** Macroscopic fundamental diagram -Flow and Speed

including different MPR of CVs, the average volume and speed are consistent and closely predicted for all scenarios. Both diagrams depict real-world data used for the simulated network.

For MFD flow/density the maximum flow rate represents the highest traffic flow rate the highway can handle. In the case of the baseline scenario, the capacity reached 4,550 vehicles per hour, while scenarios with 75% and 100% MPR of CVs appeared to have reached more at 4700 vehicles per hour. In contrast, 25% and 50% MPR of CVs reached a slightly lower capacity, just under 4,500 vehicles/hour, even below the baseline.

In MFD speed/density, speed remains constant at capacity levels, indicating smooth, congestion-free traffic flow even at high densities. The road network handles demand without congestion or significant delays. All vehicles in all scenarios maintained an appropriate 110 km/h speed limit in free flow. As average density increases, speed decreases until reaching jam density, where it's lowest. This pattern is observed in the baseline and 50% and 75% MPR CV scenarios, with a minimum speed of 85 km/h and moderate congestion.

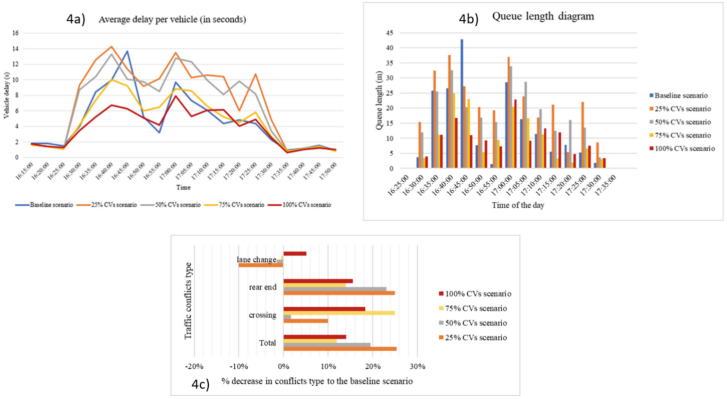



**Fig. 3.** Average delay per vehicle (in seconds) per MPR scenario – a; Average queue length results per MPR scenario – b; Percentage reduction in traffic conflicts per MPR of CVs with the baseline scenario – c.

The effect of the breakdown has also been examined through the average delay of a vehicle in seconds and the average queue length created due to the breakdown per MPR

scenario. In Fig. 3a the baseline case with no connectivity experiences the worst travel conditions, resulting in higher delays compared to the 100% MPR CV scenario, which exhibits improved travel conditions during the 1-h breakdown. The 25% and 50% MPR CV scenarios show increased delays per vehicle, while the 75% and 100% MPR CV scenarios have better traffic profiles than the baseline. Beyond a 50% MPR, increasing MPR may lead to higher average delays due to potential negative effects. Conversely, MPR levels above 75% result in reduced delays compared to the baseline, indicating that the benefits of CV communication and coordination outweigh the potential drawbacks.

Additionally, at high MPR levels, fewer conflicts arise between connected and non-connected vehicles, reducing accident risks and unexpected delays. The lowest delays were seen at 100% MPR of CVs. Similar trends apply to average queue length during the 1-h lane closure (***Error! Reference source not found.***), mirroring vehicle delay patterns. Once more, the shortest stop delays occurred at 100% MPR of CVs.

In ***Error! Reference source not found.***, the percentage decrease in conflict types compared to the baseline scenario is depicted. SSAM identified three conflict types: rear-end conflicts, lane-change conflicts, and crossing conflicts. As expected, ***Error! Reference source not found.*** illustrates that increased adoption of CVs leads to fewer conflicts during traffic incidents, resulting in a positive reduction in total conflicts, ranging from 12% to 25% based on the MPR of CVs. This signifies an overall enhancement in safety, reducing potentially perilous situations during incidents. However, the 25% MPR CV scenario exhibits a negative decrease in lane-change conflicts compared to the baseline, possibly due to behavioral shifts and communication delays. In summary, the baseline scenario had the highest total conflicts, whereas the 25% MPR CV scenario had the lowest, with the other scenarios still delivering positive safety impacts, underscoring the efficacy of V2V technologies.

## 4 Discussion and Conclusion

This research aimed to test V2V technology's impact on reducing traffic incident consequences. It involved real-time incident detection via V2V communication and simulation to study various MPRs of CVs regarding capacity, delays, and conflicts. Simulating CV incidents is a challenging aspect with limited literature coverage.

Simulations showed promising results for mitigating traffic and safety impacts with CV technology. MFD shapes aligned with theoretical relationships, confirming accurate calibration. Outcomes vary with CV MPR and traffic volume. MPR above 75% reduced delays and queues in non-congested areas, with fewer conflicts in high MPR. 100% MPR was the safest scenario, followed by 75%, while no connectivity was the least safe.

This paper demonstrates the effectiveness of V2V incident detection with various CV penetration rates. CVs interact via V2V, with stopped vehicles sending notifications. Following vehicles adjust speed and behavior based on received messages.

VISSIM 2021 validated the analytical method on mixed traffic corridors with varied CV MPRs. Future work should consider HGV connectivity and high-congestion scenarios.

This framework benefits traffic management, car manufacturers, and traffic authorities, aiding safety improvements, CV settings, and traffic demand management. It enables

real-time incident detection and communication for reduced impacts and collision prevention.

In summary, this interdisciplinary research integrated computer programming, traffic, simulation, and V2V communication to create an incident detection framework using VISSIM and API COM Interface. Future extensions could include network-level CV simulations in congested environments and diverse scenarios.

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# Cooperative Mobility: Future-Proofing Motorways Through C-ITS Deployment in Cork City, Ireland

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**Abstract.** Motorways in Ireland have experienced growth in demand over the last few decades due to a rise in vehicular traffic, impacting greatly on the operational capacity of the various high mobility conduits during peak hours. This is especially the case in Cork city on the N40, M8, N8 and N25 motorways on their approach to the Jack Lynch Tunnel and Dunkettle Interchange. Whilst this increased activity may be indicative of economic growth, the recurring congestion resulting from this reduces the mobility of road users at peak hours and is likely to impact the environment negatively through increased greenhouse gas (GHG) emissions. The increased vehicular activity is also highly likely to have adverse implications on road safety across the highly trafficked sections of motorway in and around Cork city. To manage the demand and remedy the impacts thereof, there is active deployment of various Intelligent Transport Systems (ITS), in line with Transport Infrastructure Ireland (TII)'s vision "to ensure that Ireland's national road and light rail infrastructure is safe and resilient, delivering better accessibility and sustainable mobility for people and goods". This paper seeks to highlight the pragmatic approach selected, including the key considerations and the challenges encountered in the development of the concept and design of the EU-funded MERIDIAN Cork Co-operative Intelligent Transport System (C-ITS) on behalf of TII.

**Keywords:** C-ITS · Intelligent mobility · V2X

## 1 Introduction

The Co-operative Intelligent Transport System (C-ITS) is an emerging technology that integrates communication, computing, and sensing technologies to enhance the safety, efficiency, and sustainability of transportation systems. The aim of this technology is to enable transport infrastructure to communicate with vehicles through roadside equipment, and with centralised control systems to disseminate information on prevalent traffic conditions, road construction and maintenance activities, and other relevant factors in real-time. This enables road users to anticipate and react to potential hazards, improving mobility through congestion mitigation. C-ITS enables also the road operators to receive real-time information from individual vehicles, allowing the traffic managers to ascertain the road network's current performance.

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## 2 Overview and Scope of the Project

The MERIDIAN C-ITS is a technology deployment that is currently under development on behalf of TII with the support of the Department of Transport (DoT) and is co-financed by the Connecting Europe Facility of the European Union. The project is looking at the deployment of roadside units on the N40, M8, N25 and N8 motorways and urban roads leading up to Dunkettle Interchange. To ensure economy and sustainability of the deployment, the design of the C-ITS scheme, depicted in the Fig. 1 below, has aimed to co-locate the majority of the RSUs on existing ITS sites with allowance for a few additional Greenfields, in-fill sites to be installed to ensure 100% coverage of the road network.

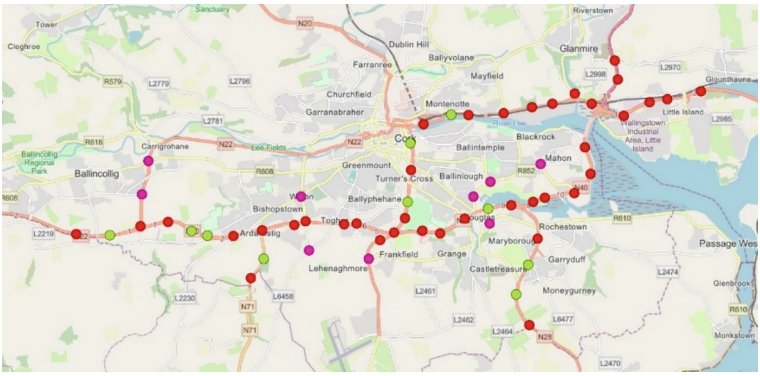



**Fig. 1.** Overview of the Road network and device locations. Image created using ARCGIS Pro.

A key aspect of the project is the installation of 150 on-board units (OBU) will be deployed in vehicles to display real-time road network status updates to the read users. This will also include the necessary graphic user interface (GUI)/on-board screen to allow for effective display of the relevant road status information. The OBUs will be proportionately distributed and installed in light vehicles, heavy duty vehicles, transit, and commuter vehicles, as well as emergency vehicles. A list of stakeholders has been compiled and both private and public fleets will be targeted for the deployment.

The provision of necessary telecommunications technology and software to support the C-ITS equipment is essential and it is necessary to consider additional access switches for the deployment of the RSUs at the existing ITS sites on the N40 and Dunkettle ITS scheme, so these were treated on a case-by-case basis in the design process thus far. A pilot project is currently underway in Dublin City under the C-Roads Platform and the Cork C-ITS has been designed in line with the Pilot to ensure uniformity and interoperability. To that end, the C-Roads C-ITS Standards and Guidelines documents have been key in the development of the concept and design of the system in question. Integration with existing C-ITS and ITS infrastructure will improve the roads agencies' network management capability. Ultimately, this system will provide a link to Cooperative, Connected and Automated Mobility (CCAM) services and the intended benefits

that the mutual benefits that this will provide (i.e. between C-ITS and wider CCAM functions).

A vital part of the C-ITS deployment are the back-end support systems These include the logical infrastructure, consisting of software needed to enable data exchange between vehicles and infrastructure. This includes the TII Network Intelligent Management System (NIMS), which is key in the operation of the Motorway Operation Control Centre. Cybersecurity systems are also critical in the success of the C-ITS deployment in order to ensure data security during the operation of the proposed system and allowance has been made for the devices to support PKI certification for authentication in line with ITS Directive 2010/40/EU.

The goals of the C-ITS deployment are ultimately to improve mobility by reducing congestion, thus improving road safety. The improved mobility will also, in turn result in reduced emissions, leading to a positive environmental impact. The improvement in information dissemination to public and key transport role players will allow better decision making and transport management.

A variety of message types are envisaged to be transmitted via ETSI ITS-G5 and Cellular between RSUs, OBUs and handheld mobile devices. The message types must be consistent with the C-Roads standards and guidelines. The message types that were considered for the C-ITS are DENM, IVIM, CAM, MAPEM, SPATEM, and SSEM.

## 3 Services and Use Cases

For the Meridian C-ITS deployment, four (4) Day 1 services were identified, with a total of nine (9) use cases under consideration. The services selected for the Meridian deployment are as follows:

1. In-vehicle signage (IVS),
2. Hazardous Location Notification (HLN)
3. Roadworks warning, (RWW) and
4. Probe Vehicle Data (PVD)

The selected services are aligned to the services and use cases that are to be deployed as part of the C-Roads Pilot project in Dublin for ease of system integration and interoperability. Stakeholder engagement with TII and the C-Roads pilot project technical team played a critical role in the definition of the services and relevant use cases. Table 1 below shows the selected C-ITS services and relevant use cases.

A high-level operational architecture was developed for each service and respective use cases and an example of the In-Vehicle Signage service in Fig. 2 is depicted below:

**Table 1.** C-ITS Services and Use Cases

| C-ITS Service | Relevant C-Roads Use Case |
|---|---|
| In-Vehicle Signage | Traffic Signs (IVS-TS) |
| | Free Text (IVS-FT) |
| Hazardous Location Notification | Traffic Jam Ahead (HLN-TJA) |
| | Stationary vehicle (HLN-SV) |
| | Weather Condition Warning (HLN-WCW) |
| Road Works Warning | Lane Closure (RWW – LC) |
| | Road Closure (RWW – RC) |
| | Road Works – Mobile (RWW-RM) |
| Probe Vehicle Data | Vehicle Data Collection (PVD-VDC) |

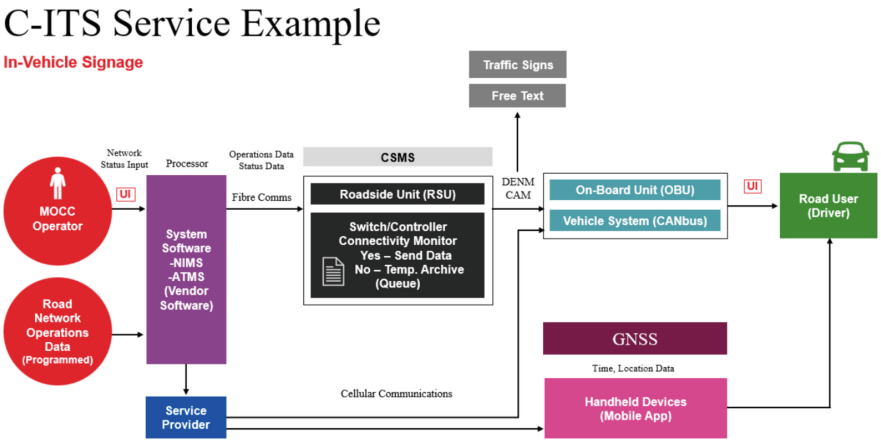



**Fig. 2.** C-ITS Service Example – In-Vehicle Signage

## 4 Operational Impacts

The main changes to the traditional ITS network expected through the deployment of the C-ITS equipment include the broadcasting of safety alerts and warning messages to vehicle operators, improved mobility for vehicles, and once the OBU penetration is optimal, increased volumes of operations data received at the MOCC for strategic traffic management.

The primary expected operational impacts and benefits of the project are:

- Improved information dissemination to the road users (public and private), as well as key transport role players for better decision making and transport management. The C-ITS aims to expand the reach of the incident information dissemination beyond the location of the existing ITS network by providing in-trip and pre-trip information to road users.

- Enhanced road safety through more effective traffic management for road users and construction and maintenance personnel.
- Improved incident and traffic event management through improved information dissemination to upstream traffic, as well as dedicated communication with emergency services. A use case for traffic management using mobile RSUs on emergency and maintenance vehicles. This will ensure dedicated communication for vehicles approaching roadworks, construction zones, and/or incidents.
- Resilience and optimisation of operations by raising the level of underlying roadside technology and in-vehicle functionality to support enhanced control strategies.

Secondary operational impacts are summarised as follows:

- Supporting sustainable growth in the national economy by improving the efficiency of the major traffic routes into and out of Cork City.
- Improved air quality and environmental conservation by empowering road users and operators with information to make informed, evidence-based trip decisions, resulting in reduced congestion and greenhouse gas emissions.
- Reduced disruption due to civils works by leveraging the existing communications ducting infrastructure where possible. This economic approach of colocation on existing ITS devices will ensure time and cost saving for TII and provide a sustainably approach to technology deployment.
- Reduced disruption due to civils works by developing a wireless roadside communications network where existing ducting or cabling infrastructure is not available.
- Extending the reach of the C-ITS Ireland Pilot and charting the way for advances in connected and autonomous vehicle (CAV) technology deployment in Ireland. The Meridian deployment will present TII with the opportunity to evaluate the effectiveness of C-ITS technologies with a view for possible further deployment across Ireland. It is expected that vehicle probe data collection and analysis will facilitate this- exercise.

## 5 Organisational Impacts

The addition of new technology and systems has wide implications on the organisations deploying them. The C-ITS deployment will have organisational impacts on TII and the key stakeholders in charge of operating and maintaining the system. TII, as the owner of the system will have to ensure that operations and maintenance contracts are in place when the C-ITS is operational. The road network operators at the MOCC will be required to train staff on how to operate the C-ITS. Standard Operating Procedures (SOPs) will need to be developed for the C-ITS, incorporating the services and use cases identified for the Meridian Project. The maintenance contractor will be required to ensure that the technicians are trained and capable of performing maintenance on the C-ITS equipment. A clear SOP for corrective and preventative maintenance works will need to be developed so as to streamline the maintenance activities.

Drastic organisational impacts are also expected for haulage/logistics companies, the OEMs/vehicle manufacturers, City Council, construction/maintenance contractors, and emergency vehicle dispatchers. The haulage companies will need to coordinate the installation of any OBUs and any associated in-vehicle equipment. They will need to

train operators how to use the new technologies and adapt their fleet operations to enable the best utilization of the new capabilities brought about by the C-ITS. The Emergency services will need to adapt to their new capabilities, which are expected to be improved response times and more efficient operations.

It is important to note that contingency plans will be required in order to mitigate the risks associated with the deployment of and connectivity to the C-ITS.

## 6 Conclusion

In conclusion, the C-ITS is anticipated to be a ground-breaking project that will have immense impact on the transport network management scene in Cork City and Ireland as a whole. Communication with Original Equipment Manufacturers (OEM) will take place to establish the penetration of vehicles with C-ITS capability in the Irish car market.

It is anticipated to improve road safety and mobility for the road users on the road network in Cork City and accelerate alignment with the greater EU goal of uniformity in digital corridor management. Strategically disseminating information to the public, those involved in transport management and to key transport decision makers will be at the heart of the C-ITS operations. The overall deployment aims of improving mobility, road safety, incident management and reducing emissions to future proof the motorways in Cork City are achievable if all stakeholders work together.

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# Towards Collective Perception Hybrid Testing in a Roundabout Scenario with AVs

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**Abstract.** Collective Perception (CP) allows connected autonomous vehicles to share and fuse processed sensor data via V2X communication. It can potentially allow for an increased object update rate, extended field-of-view awareness, and redundancy but it first requires a thorough evaluation and validation. Due to the CP's field testing practical challenges most of the previous work on CP has considered large scale-simulations with a focus on connectivity/network aspects. More recently, large-scale collaborative perception synthetic datasets and open source benchmarks have appeared, allowing the perception engineers to study CP from a perception point of view, which is missing so far. In this paper, the first building blocks (work in progress) towards CP scenario-based testing for a roundabout navigation use case are been set by proposing a Bayesian CP algorithm and its testing plan. The CP algorithm is described and metrics for CP assessment are discussed focusing on the fused information content produced by the algorithm. The next steps towards a hybrid evaluation plan combining real-world agents and simulation are outlined.

**Keywords:** Autonomous Vehicles · Collective perception · V2X communication

## 1 Introduction

Collective Perception (CP), currently standardized by ETSI as a second generation V2X communication service (but not limited to it), is especially promising for Autonomous Vehicles (AVs), as it allows connected AV agents "see through the eyes of others" who may share processed sensor data via V2X communication. Its benefit is typically assessed in terms of the increased object update rate, extended field-of-view awareness, and redundancy. In this work, part of which is described in this paper, a safety validation proof-of-concept (PoC) for CP scenario-based testing for a roundabout navigation scenario is designed. The

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PoC includes both connected AVs and non-connected vehicles, assuming connected virtual agents that can exchange ETSI-alike Collective Perception Message (CPM) information. Its primary goal is to develop and validate a vision-based CP module able to globally synthesise scene information based on local perception viewpoints produced by the available connected vehicles in the AV's neighbourhood. The secondary objective is the integration of CP information in a V2I-assisted urban platoon setting with reliability guarantees. The work is part of the European project EVENTS' advanced perception, decision making and self-assessment framework, which develops algorithms and methods to analyse the effects of V2X information fusion on AV perception and decision making.

Collective perception information generation serves a double research objective: a) develop algorithms for fusion of object information coming from multiple observers based on probabilistic scene state estimation via occupancy grid maps b) develop data reliability metrics enabling false data detection and object associations' conflict resolution. In this paper, the first point is described in detail, which sets the scene for the following point. Studying CP from a perception point of view implies that the focus is on the task of object data association from multiple observers and hence networking aspects can be omitted for reasons of simplicity (no network co-simulation is employed and ETSI-alike CP messages are assumed available with frequency/delay that can vary).

## 2 CP Module Functional Architecture

In this section, we provide an overview of the architecture of the CP module as this is conceived in EVENTS project experiment no. 2 (EVENTS Deliverable 2023a,b). As shown in Fig. 1, CP essentially replaces the subject AV perception by providing enhanced scene understanding. CPMs received from connected agents sharing the same spatial area (in our case a roundabout area) with the subject CAV under test are fused with CAV's local perception. The probabilistic certainty of collective object detection plus further consistency/plausibility checks between CP output and the (claimed) Field of View (FoV)/perceived object list of each connected (CCAV) agent will be utilized for assessing the reliability of the CP.

In more detail, the collective perception module expects the following five inputs from each CCAV present in the area of interest: **1. Ego FoV angle:** A single front camera implies a FoV angle equal to the FoV of the camera. More cameras and and radar/Lidar sensors may imply a larger FoV angle. In the figures below, a 360o FoV angle is implied. **2. Ego state information:** This information consists of the i. Position coordinates in $x$,$y$ (valid also for CAM originators), ii. Speed vector $v_x$, $v_y$ (valid also for CAM originators), iii. Acceleration vector $a_x$, $a_y$ and iv. Heading (yaw angle). **3. Observed object information:** This information concerns each one of the distinct objects observed by the CCAV and consists of the i. Position coordinates in $x$,$y$, ii. Speed vector $v_x$, $v_y$, iii. Acceleration vector $a_x$, $a_y$ and iv. Heading (yaw angle). **4. Estimated free space:** This field is optional, since it can be partially deduced from the observed objects

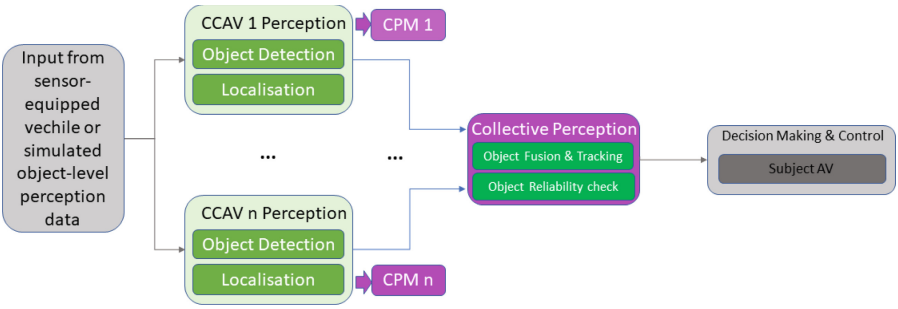



**Fig. 1.** The architecture of the EVENTS experiment.

information. **5. Uncertainty of the measured values:** A quantification of the uncertainty of each measurement via e.g. respective standard deviations.

## 3 CP Module Algorithmic Approach

In this section, the formalization of the output of the collective perception module as a probabilistic occupancy grid is presented. The chosen representation exploits the straightforward and intuitive Bayesian method for fusing observations derived from multiple observers and has been very popular for solving multi-object tracking problems due to its inherent explainability properties leading to well-defined reliability metrics for the output (Godoy et al. 2021; Nuss et al. 2018).

### 3.1 Formalizations and Problem Statement

Consider a 2-dimensional bird's eye view image of the area of interest. We discretize it using a rectangular grid of size $NxN$, whose cells are indexed by $i = 1, \ldots, N^2$. To each cell i we associate the binary random variable $A_i \in \{0, 1\}$ where $A_i = 1$ means "cell $i$ is occupied" and $A_i = 0$ means "cell $i$ is not occupied". A Probabilistic Occupancy Grid is essentially a collection of $N^2$ probabilities $P(A_i = 1), i = 1, \ldots, N^2$, each one indicating the probability with which the corresponding cell $i$ is occupied.

Let the area of interest be an urban roundabout, like the one depicted in Fig. 2. We assume the presence of both connected and not connected vehicles. Connected vehicles have the capability to share information concerning i. their current individual heading, position, speed and acceleration, ii. the presence or absence of objects within their respective individual FoVs, and iii. heading, position, speed and acceleration for each of the perceived objects, in line with the description of inputs in Sect. 2. The ground truth of the scene is a non-random occupancy grid, where we know exactly which cells are occupied or not (middle illustration in Fig. 2). We are now ready to properly state the problem of interest as follows: Given the observations and measurements of each individual CCAV

and their statistical uncertainties/errors, how can we estimate the Ground Truth in terms of a Probabilistic Occupancy Grid?

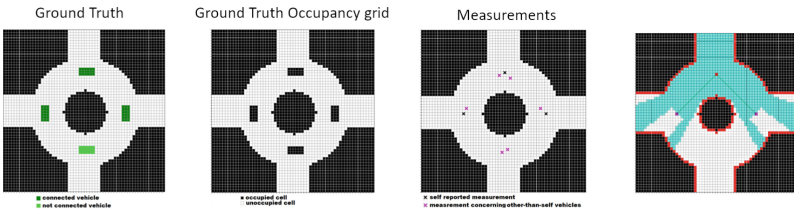



**Fig. 2.** Ground truth, measurements and FoV estimation bird-eye view representation (Hunter 2007)

### 3.2 Algorithm Overview

The proposed algorithm consists of the following four equally important steps.

Step 1: The first step aims at the localization of reporting agents (in our case, CCAVs). For each distinct CCAV we apply a Kalman Filter taking into account only its self-reporting measurements. The rational for excluding other measurements is that self-reporting measurements are based on differential GPS for location and on-board sensors for velocity, acceleration and heading, which can be considered more trustworthy. Apart from that, initial experiments show that clustering measurements around centroids corresponding to unknown guessed vehicle positions can be extremely error prone due to the unknown number of present vehicles and noisy measurements, leading to unstable estimations.

Step 2: The second step aims at estimating the FoV of each CCAV. Each CCAV is placed in its estimated (by step 1) grid position. Each other-than-self measurement (other objects detected around) obtained by CCAV is translated according to the CCAV estimated position and placed in the grid. Subsequently, a custom, GPU-implemented algorithm calculates the FoV of the CCAV, i.e., the grid cells for which the CCAV can provide information on their occupancy status (first 3 figures below). Estimated FoVs may be eroded to account for measurement uncertainties ($4^{th}$ illustration in Fig. 2).

Step 3: The third step aims at fusing the observations of each CCAV to form a probabilistic estimation for the occupancy grid of the entire area of interest. We assume a known individual perception model for each CCAV, provided in terms of the four probabilities $P(M_i = 0|A_i = 0)$, $P(M_i = 1|A_i = 0)$, $P(M_i = 0|A_i = 1)$, $P(M_i = 1|A_i = 1)$ of the standard forward sensor model (Nuss et al. 2018).

With these probabilities and the environment observations of each particular CCAV within the CCAV's FoV, we can take into account all observations regarding the occupancy state of any particular cell by applying Bayes rule recursively.

Hence, when a cell belongs in the intersection of several CCAV FoVs, applying the Bayes rule recursively will allow us to enable the joint consideration of all respective individual observations regarding its occupancy state, ultimately providing a probabilistic estimate constituting the collective perception of the CCAVs.

Step 4: Step 4 aims at tracking the temporal evolution of the occupancy grid. There is a variety of methods to approach this, each one with its merits and disadvantages (Nègre et al. 2014; Nuss et al. 2018). In all of these methods, the basic heuristic idea is common; in each time step, instead of setting the initial prior probabilities $P(A_i = 1)$, $P(A_i = 0)$ equal to 0.5 to reflect the unknown occupancy state of each cell, knowledge regarding the previous time step is taken into account. Specifically, the cells of the previous step occupied with high probability are moved according to corresponding velocity measurements to new cells, and the resulting predicted occupancy grid is used to derive the priors for the current time step (Coué et al. 20006).

### 3.2.1 Metrics for Perception Self-Assessment

Off-line evaluation of the proposed method essentially entails the comparison of the output of the module with the known ground truth. There is a variety of ways to quantify the result of such comparisons;in our approach, we focus on the on-line self-assessment of the module output reliability based on the probabilistic occupancy grid properties. Since this is still an ongoing experimental study, in this section, we briefly mention some examples of such indicators. A straightforward and intuitive indicator of reliability of the output is the set of covariance matrices of the current Kalman filter recursions. For example, differential GPS systems provide measurements with errors in the order of 20–30 cm. Thus, position variance estimations above the order of 20–30 cm can be considered problematic. Both the percentage and the contiguity of grid cell regions with high confidence occupancy values (i.e., very high or very low occupancy probabilities) can also provide a reliability indicator for the output. Such indicators may be also be applied locally, i.e., to quantify uncertainties in current critical regions of interest, like regions to be occupied in the immediate future.

## 4 CP Module Evaluation Plan

To determine the safety improvement thanks to a camera-based CP module (typically hosted off-board, e.g. on a smart road side unit), the authors will a) perform a state-of-the art review (metrics for CP assessment based on sensor data late fusion methods are provided in V2XSim (Li et al. 2022) for instance) b) select a small set of roundabout test scenarios also considering non-line of sight scenarios c) design a simulation pipeline built around CARLA able to model object's presence uncertainties through different added types of artificially generated noise, and d) introduce new metrics, which quantify the AVs' environmental awareness.

For points (a) and (b) generation of new collective perception scenarios using Mathworks RoadRunner, CARLA and ROS/Python external modules is foreseen. A mixed-reality simulation setup will also be utilized for a real vehicle in the loop simulation involving a single-seat Renault Twizy 80 equipped with automated driving software and hardware adapted and owned by TECNALIA (EVENTS partner). The ROS2 bridge will be used by the real AV modules to interact in real-time with the Carla simulator server, while the virtual vehicles will be controlled by CARLA applying autopilot mode through another client. ROS2 bridge will also be used for connecting the proposed collective perception module assumed to sit within a virtual sRSU, and CARLA. For emulating uncertainty in objects' presence, artificially generated noise will be applied on top of CARLA perception groundtruth (filtered objects within AV FoV). The proposed virtual/hybrid validation framework will be used to understand limits and benefits of CPM-enabled perception under assumptions of different object detection uncertainties generated in simulation.

## 5 Conclusion and Future Work

In this paper, a preview of the core algorithmic implementation behind a probabilistic collective perception module is presented. A Bayesian scheme is employed for CP information fusion generated by multiple connected traffic agents due it its inherent explainability which leads to easily defined output reliability metrics. The outlined hybrid validation framework of this CP module will be used to understand limits and benefits (on the perception level) of an ETSI-alike CPM-enabled CP under assumptions of different object detection uncertainties generated in simulation under different operational domain conditions. Proof-of-concept results will be published soon.

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# A Fail-Safe Decision Architecture for CCAM Applications

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**Abstract.** In the context of Connected, Cooperative, and Automated Mobility (CCAM), precise ego-vehicle positioning and environmental status assessment are crucial. However, these tasks can be susceptible to sensor failures, misuse, and cyberattacks. Automation disengagements and system redundancy are common strategies to achieve Minimum Risk Conditions when failures occur. This paper presents a Fail-Safe decision architecture formulated within the framework of the SELFY project (https://selfy-project.eu/). The main aim is to reduce inaccuracies in GNSS-derived positioning through the incorporation of sensor fusion, AI-guided situational assessment, trajectory planning, and mode decision components. Additionally, the architecture has been designed to enable real-time updates and communication with external entities, including the Vehicle Security Operations Centre.

**Keywords:** CCAM · Fail-Safe · Fallback Strategy · Situational Awareness · Decision · Urban Scenarios

## 1 Introduction

Advanced Driver Assistance Systems (ADAS) and Automated Driving Systems (ADS) have enhanced commercial vehicle safety in recent years. However, accurate localisation remains a critical challenge for Automated Vehicles (AVs) in urban environments, necessitating further research. Most systems rely on redundancy or disengagement in case of failures for risk mitigation [1].

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The latest European Commission reports emphasize key developments in communication, cyber-security, onboard sensors, infrastructure, mobility concepts, and city contexts for urban transportation [2,3]. ADAS and ADS employ various sensors, including cameras, Global Positioning System (GPS), and Light and Radio Detection and Ranging (LiDAR and RaDAR), for environmental perception. Perception tasks are critical for increasing automation in AVs developments, as environment recognition must be assured in any scenario. Moreover, their failure-tolerant operation during automated mode is crucial to ensure passenger safety, particularly in emergencies [4].

Some authors have considered sensor data fusion to enhance performance robustness in different contexts, including the perception of the environment [5], localization [6,7], and traffic sign detection and recognition [8]. A detailed description of the most popular methods and techniques for performing data fusion has been explored. The authors conclude that the appropriate technique to be implemented depends on environmental conditions [9]. For example, the most widely used global localization approaches involve global navigation satellite systems. However, these systems have limitations in urban environments due to signal blockage or multipath effects. As a result, alternative localization techniques have been evaluated to address these limitations and improve performance in urban environments.

Research and development efforts are underway to determine when a vehicle should switch to fault-tolerant operation. The SELFY project [10] focuses on initiating this process, either through external commands (e.g., Vehicle Security Operations Centre) or by processing vehicle and infrastructure data (e.g., Vehicle-to-Everything messages). The next step involves selecting a suitable fallback strategy, considering potential failures caused by malfunctioning systems (e.g., electric or electronic devices), performance limitations, and misuse (e.g., sensor limitations, algorithm failures, user errors due to overload or confusion). Ultimately, the resulting fault-tolerant mode defines the system's capabilities [11].

This work presents a fail-safe decision architecture for positioning failures of automated vehicles in urban scenarios. This architecture is based on the framework of the EU-SELFY project, which aims to increase AVs safety, security, robustness, and resilience.

## 2 Fail-Safe Decision Architecture in the SELFY Project

The proposed architecture, depicted in Fig. 1, is part of the Cooperative Resilience and Healing System (CRHS) Toolbox, which includes tools that elicit self-protection actions whenever a compromised situation is detected in relation to assets, vehicles, operations, or the system itself. These actions can be taken locally, or in cooperation with other tools in their environment so that decisions can be taken at the global Connected, Cooperative, and Automated Mobility (CCAM) level.

Overall, the architecture consists of four separate components, including positioning, situation assessment, safety mode decision, and path planning. The

architecture runs in parallel with the normal perception and decision modules and overwrites the path computed by the normal path planner when a localisation failure occurs. It can also receive and send status information to external entities.

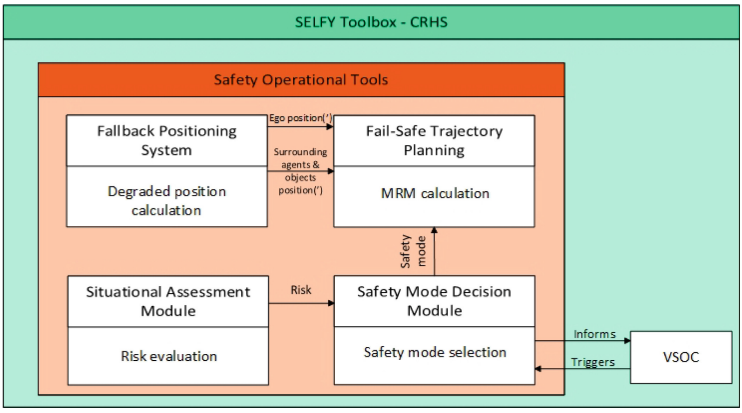



**Fig. 1.** Fail-Safe Decision Architecture in the SELFY Project

### 2.1 Fallback Positioning System

This component in the global architecture provides an alternative solution to localization when the primary source, typically the Global Navigation Satellite System (GNSS), fails. It offers pose and twist estimations with covariance but is less precise. This solution is considered degraded but reliable enough for secure vehicle operation for several seconds.

The module relies on the Extended Kalman Filter (EKF), which blends the kinematic bicycle model of the vehicle with external localization sources, including the degraded GNSS signal with Inertial Measurement Unit (IMU) compensation, cooperative perception via Vehicle-to-X (V2X), and landmark-based localization methods. Mahalanobis gates are employed to reject the sensor and external localization sources that are more distant than the Mahalanobis distance with the kinematic bicycle model. The positioning system is an adaptation of the Autoware EKF localizer [12], which involves amendments to the vehicle model and the localization sources.

### 2.2 Situational Assessment Module

The Situational Assessment Module compares the environment model (fused from RSU and on-board vehicle sensor data), CAN messages from the ego vehicle, Cooperative Awareness Messages (CAM), analyses these data by using Artificial Intelligence-based methods to detect anomalies, misuse, malfunctions, etc.,

and decides the risk level of the current situation. The risk information is provided to the Safety Mode Decision Module.

A method based on distance estimation was developed to prevent GNSS loss or GNSS spoofing. For this method, latitude and longitude data from GNSS, speed and steering data from CAN, and forward acceleration data from IMU were used. These data were obtained by simulation driving in Carla and to calculate the distance between the two time intervals, the Haversine great circle formula, which calculates with latitude and longitude information, was used.

A Long Short-Term Memory (LSTM) model, which is a type of RNN, was used to estimate the distance. Since our algorithm is a sequence prediction problem, a LSTM is a proper model because of its capability of learning long-term dependencies. Speed, steering angle and forward acceleration were used as input data to train the LSTM. The output is the distance between two time intervals. After completing the training on the LSTM model, a fine-tuning operation was performed to enhance its performance and achieve higher accuracy. In pursuit of obtaining closer predictions and improving its capabilities, additional 2 hidden layers were added to the model architecture. By implementing these measures, the aim is to enhance the system's accuracy and performance by improving its capacity to capture intricate relationships. Following the fine-tuning operation, it was observed that the predicted distance values converged towards the actual values and an enhancement in accuracy was achieved. After the distance estimation is completed, a threshold distance value is set according to the vehicle's capacity and the error values in the GNSS signal. When the estimated value exceeds this threshold value, GNSS loss or spoofing is detected.

In addition to the LSTM model development, an innovative approach involving data manipulation techniques was used to further improve the model's robustness and anomaly detection capabilities. To simulate various anomaly scenarios, a custom function that introduces anomalies into the dataset by perturbing the GNSS latitude and longitude coordinates, creating inconsistent speed or acceleration values, and generating outliers in steering angle and speed was developed. These anomalies cover possible GNSS hacking, spoofing, or signal degradation scenarios.

A preliminary NN model was trained and designed as a binary classifier that aims to predict whether a given sample is normal or manipulated according to the provided features. While the simplicity of the neural network may limit its predictive capabilities, it still provides valuable insight into the overall impact of the data manipulation techniques. The successful differentiation of the NN model between normal and manipulated data encourages us to use it to refine and fine-tune the LSTM model for advanced anomaly detection, ultimately leading to a more sophisticated and accurate GNSS anomaly detection solution.

### 2.3 Safety Mode Decision Module

The Safety Mode Decision Module selects the most suitable operation mode according to the environmental circumstances and the ego-vehicle status. The algorithm is capable of switching between three modes of operation, including

*Normal Operation*, *Fail-Safe Operation*, and *Total Failure - Stop*. When engaged, the *Fail-Safe Operation* guides the vehicle towards a safe state, which may not always require an immediate stop. Depending on the situation and the availability of a suitable stop location nearby, the vehicle might have to continue driving for a brief period.

The algorithm is based on Fuzzy logic, considering various factors, including the risk evaluation from the Situational Assessment Module, median control errors, GNSS signal status, surrounding agent detection, and localization covariance. External entities can also trigger the available modes, and the module can provide periodic updates to these entities.

**Vehicle Security Operations Centre.** One entity that further utilizes the information from the fail-safe decision architecture is a Vehicle Security Operations Center (VSOC). Besides communication between cars and exchanging safety modes and risks, a VSOC can further utilize this data. A VSOC is responsible for collecting data from various sources within an environment. In the case of the SELFY project, the VSOC collects data from the CCAM, e.g., including all tools within the SELFY toolbox and OEMs or third-party services (e.g., threat intelligence providers and vulnerability databases). This overview allows the SELFY VSOC to picture the events within the SELFY ecosystem comprehensively. As a result, detecting vulnerabilities, anomalies, and cyber-security incidents becomes feasible. The VSOC utilizes the information from the safety operational tools to define risk values for the vehicle or a group of vehicles. Distributing the risk value can further increase knowledge between participants of the CCAM ecosystem. Implementing dedicated point-to-point communication methods is time-consuming and complex with all the technologies present in modern vehicles and their ecosystems. If the VSOC distributes this knowledge, a more open knowledge-sharing methodology is achieved. Only some participants need to implement a connection to other participants. Instead, a connection to the VSOC allows the tools to send relevant data to the VSOC and receive enriched information from it.

### 2.4 Fail-Safe Trajectory Planning

The last component in the architecture handles Minimum Risk Manoeuvre calculations. Utilizing emergency vehicle localization from the Fallback Positioning System, along with the positions of surrounding agents like vehicles and road users, as well as the initially planned trajectory and lane map data, it continuously computes the minimum risk manoeuvre. This new path is executed only when the *Fail-Safe Operation* is activated within the Safety Mode Decision Module. Under *Normal Operation*, the final path adheres to the originally planned trajectory.

The ultimate goal during *Fail-Safe Operation* is to perform a controlled stop at a suitable location, but this may not always be possible immediately. Longitudinally, the speed is reduced within the legal limits of the road. Laterally, the

calculated path is capable of lane changes, overtaking, and emergency stops, but larger safety margins are built-in and safety is given priority over comfort.

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# Post-quantum Cryptography for Connected and Cooperative Automated Mobility: A Comprehensive Overview

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**Abstract.** Connected and Cooperative Automated Mobility (CCAM) applications, instrumental in enhancing vehicle communication with infrastructure and the cloud, face cybersecurity vulnerabilities due to their intricate components requiring multifaceted cryptographic validation. With quantum computing advancements, traditional public key cryptography becomes susceptible, emphasizing the need for quantum-resistant algorithms to assure long-term automotive cybersecurity. Although Post-Quantum Cryptography (PQC), which provides solutions to counter this quantum risk is still under research, several algorithms have emerged and are under standardization. This paper provides a comprehensive overview of the status of PQC in automotive applications, including a performance analysis of selected algorithms in this research. Further, it presents some potential use cases of PQC (such as Secure Over-The-Air (SOTA) software update and Vehicle to everything (V2X) communication). By relying on PQC, the automotive industry can stay ahead in securing connected vehicles against emerging quantum computer threats.

**Keywords:** Connected and Cooperative Automated Mobility (CCAM) · Post-Quantum Cryptography (PQC) · Automotive Cybersecurity · Long-Term Security

## 1 Introduction

Automotive and CCAM applications promise to revolutionize future transportation, making it safer, eco-friendlier, and more efficient. At its core, CCAM thrives on networks that intertwine vehicles (V2V), infrastructure (V2I), broader networks (V2N), and even pedestrians (V2P). Yet, the weaving of these networks casts shadows of data authenticity and privacy concerns. In the CCAM world, vehicles not only update software and relay information over networks but also utilize cameras for pedestrian detection, vehicle identification, and location broadcasting.

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Consider the potential consequences if a malicious actor exploits shared vehicular information to track a target or even manipulate a vehicle's controls. What if compromised location data or corrupted software updates were broadcast? These scenarios are not just theories. To avoid such risks, we need to integrate sophisticated cybersecurity and data protection measures into CCAM designs. While these systems are designed to be secure for a time, they must be prepared for future threats such as the rise of quantum computing. When quantum computers gain enough power, our existing cryptographic solutions, such as RSA [11], will be broken [12]. This is particularly concerning in the context of CCAM, where there is a threat of a 'harvest now and break later' attack, potentially compromising sensitive information and cryptographic methods used in the CCAM ecosystem.

## 2 Long-Term Security

In the CCAM context, ensuring long-term security is of utmost importance. CCAM represents the integration of multiple advanced transportation systems: connected vehicles, automated vehicles, connected infrastructures and their cooperative operations. Vehicles are designed for 10–15 years, automotive infrastructures even more. Given the nature of these systems and their applications, long-term security is not just a luxury but a necessity. The following Table 1 lists several scenarios and reasons that highlight the need for long-term CCAM security.

Quantum computers present significant challenges to existing cryptographic practices in automotive vehicles. Current vehicles rely on public key cryptography for secure updates, both through cables and wirelessly. While these methods ensure integrity and authenticity, they're at risk from quantum advancements. The RSA encryption, which hinges on the difficulty of factoring large numbers, can be swiftly dealt with by quantum capabilities using Shor's algorithm. Furthermore, symmetric encryption isn't entirely safe, with Grover's search algorithm posing potential threats. Given that vehicles frequently share data with entities like manufacturers and insurance agencies, there's an urgent need to turn to post-quantum cryptography to protect updates and preserve data privacy.

Mosca's theorem helps calculate the quantum threat's arrival, weighing the duration of desired data security against the time required for quantum-safe transition. Given a typical vehicle's 10–15 years lifespan and NIST's aim to standardize post-quantum algorithms by 2024 [10], the race is on. Of all quantum defense strategies, PQC emerges as the frontrunner.

**Table 1.** Long-term security scenarios for CCAM applications.

| Scenario | Description | Cause |
|---|---|---|
| Vehicle Lifecycle Duration | Vehicles have a long lifecycle (typically 10–20 years or more) | Cryptographic methods that were considered secure at the time of manufacture may become vulnerable. This disparity between the rapid evolution of cryptographic threats and the long lifespan of vehicles necessitates long-term security measures |
| Future Interoperability | Vehicles from different manufacturing years will need to interact | Ensuring that older vehicles can securely communicate with newer ones requires forward-compatible security solutions |
| Over-the-Air (OTA) Updates | Vehicles increasingly rely on OTA updates for software patches | To counter vulnerabilities discovered long after a vehicle's production, the OTA update mechanism itself must be secured for the long term |
| Vehicle-to-Everything (V2X) Interactions | Vehicles will interact with other vehicles and smart-city infrastructure devices | The diverse and continually evolving landscape of V2X interactions demands that security measures be future proofed to remain effective in the face of unforeseen challenges |

## 3 Post-quantum Cryptography

In March 2022, ENISA proposed a hybrid approach for transitioning from our current cryptographic tools to post-quantum solutions [1]. This method merges the resilience of pre-quantum algorithms against classical attacks with the defenses post-quantum algorithms offer against quantum attacks. For key establishment, a Key Derivation Function (KDF) is used, while signatures utilize concatenation.

The first NIST's post-quantum competition [10] categorized post-quantum algorithms into five groups:

– Lattice-based Cryptography: Ajtai introduced the SIS (Short Integer Solution) problem in 1996 as part of the first lattice-based cryptographic scheme [2]. Regev formulated the LWE (Learning With Errors) problem in 2005 [2], which was later adapted into the Module-LWE variant [2] for better performance. Separately, the NTRU cryptographic approach, aiming for more compact key sizes, was introduced in 1996 [2].

- Cryptography based on hash functions: The first person to use hash functions to sign documents was Merkle [2]. Later, Lamport [2] and Winternitz [2] showed how to convert Merkle's single signature scheme into a multiple signature scheme. Merkle also introduced a new scheme combining the Winternitz approach with binary trees called Merkle tree.
- Code-based cryptography: The McEliece encryption scheme [2] is first asymmetric method in this field. Its security relies on the difficulty of code-theoretic problems, such as the Syndrome Decoding (SD) problem. Subsequently, Niederreiter [2] proposed a digital signature scheme based on error-correcting codes. A significant drawback of many code-based cryptographic primitives is their large key size. That is why structured variants are developed to reduce key size.
- Multivariate cryptography: Multivariate cryptography is based on the difficulty of solving a system of nonlinear, usually quadratic, equations over a finite field [2]. Most signature schemes in this category are based on the complexity of the MQ problem, finding solutions to a system of multivariate quadratic equations.
- Cryptography based on isogenies of supersingular elliptic curves: This form of cryptography is based on the challenge of identifying isogenies between supersingular elliptic curves [2]. It's used to facilitate a Diffie-Hellman-type key exchange.

## 4 PQC in Automotive: State-of-the-Art and Applications

As vehicles become interconnected platforms, there is an urgent need for stronger cryptographic systems, especially considering quantum computing threats. As a result, the focus is turning towards PQC.

- Hermelink's et al. Introduced a PQC protocol designed for vehicle component communication. This protocol becomes the foundation for **V2X Communication**, ensuring quantum-secure exchanges with infrastructure [3].
- Lattice-based PQC has benefits, especially for **High-Performance Systems**. This approach ensures swift and secure communications, crucial during high-speed driving scenarios [4].
- Wang and Stöttinger emphasized the importance of **HSMs in Vehicles**. They proposed quantum-secure Hardware Secure Modules (HSM) to protect key vehicle functions, such as starting the ignition [5].
- For **OTA Software Updates**, Bos's et al. Suggested using CRYSTALS-Dilithium. This ensures updates remain quantum-secure, reducing the need for future recalls [7].
- Making vehicle **Boot Processes** quantum-safe is another priority. Using PQC, we can ensure the vehicle's software remains untampered each time it starts [8].
- Gonzalez et al. Highlighted **Signature Verification** methods. Their PQC techniques allow for fast validation, especially useful for devices like traffic cameras [9].
- **Vehicle-to-Vehicle Communication** is another focus. Research underscores the need for these communications to be both private and quantum-secure [6].

There's a noticeable increase in research on PQC for the automotive world, highlighting how crucial it is for the future of transportation. The industry is clearly preparing to tackle quantum challenges.

## 5 Performance of PQC in Automotive Systems

Kyber, Dilithium, and Falcon are lattice-based cryptographic methods rooted in 512–1024 dimensional mathematical problems, compete for NIST's PQC standardization [10], with Kyber as a KEM and Dilithium and Falcon as digital signature algorithms. To compare these unique algorithms, NIST uses metrics like Key Length and Algorithm Strength, detailed in Table 2.

**Table 2.** Key Metrics for NIST's PQC selected Algorithms [10].

| Algorithm | NIST Level | Key & Signature/Ciphertext sizes (bytes) |
|---|---|---|
| Dilithium2 | 2 | Secret: 2528, Public: 1312, Signature: 2420 |
| Dilithium3 | 3 | Secret: 4000, Public: 1952, Signature: 3293 |
| Dilithium5 | 5 | Secret: 4864, Public: 2592, Signature: 4595 |
| Falcon-512 | 1 | Secret: 1281, Public: 897, Signature: 666 |
| Falcon-1024 | 5 | Secret: 2305, Public: 1793, Signature: 1280 |

NIST Levels (1–5): Level 1 is the most vulnerable, easily broken in 8 h with a small investment, while Level 5 is the most secure, ensuring ciphertext doesn't reveal plaintext.

In our evaluation of open Quantum Safe (OQS) metrics for connected vehicles, we simulated a road-element-to-vehicle interaction using a client/server model. Due to hardware constraints of the OQS library, two Raspberry Pi 4 with 4 CPU cores and 8 GB of RAM were utilized. The server, operating on port 4433, sent packets of varying sizes- 1 KB, 1 MB, and 30 MB- to reflect common communication sizes. We adopted the Kyber KEM for encapsulation and the Dilithium and Falcon algorithms for signatures, aligning with the latest NIST standards (Table 3).

**Table 3.** Latency from Client Request Launch to Packet Receipt (Seconds)

| Packet weight: 1 KB | | NIST Security Level | | |
|---|---|---|---|---|
| | | 2 | 3 | 5 |
| Dilithium | Kyber512 | 0.072 | 0.072 | 0.073 |
| Falcon | | 0.092 | N/A | 0.095 |
| Dilithium | Kyber1024 | 0.072 | 0.075 | 0.077 |
| Falcon- | | 0.097 | N/A | 0.100 |

Using OQS's OpenSSL 3.2-dev with TLS1.3, the Kyber KEM keys are dynamically generated for each communication and stored temporarily. We employed the Python tool psutil to gauge CPU and RAM performance, capturing data at **10-ms** intervals across 100 iterations for different algorithm/packet combinations. The results, presented in Table 4, provide an averaged view of CPU and RAM (MB) utilization over the process's duration.

**Table 4.** Average CPU and RAM Utilization During Request Lifecycle (packet weight 1KB)

| | Kyber512 | | | | Kyber1024 | | | |
|---|---|---|---|---|---|---|---|---|
| Algorithm | Dilithium2 | Dilithium2 | falcon512 | falcon1024 | Dilithium2 | Dilithium2 | falcon512 | falcon1024 |
| CPU (%) | 3.949 | 3.897 | 3.594 | 2.897 | 3.726 | 4.137 | 3.361 | 3.447 |
| RAM | 1.059 | 1.467 | 1.230 | 1.477 | 1.304 | 1.586 | 1.354 | 1.515 |

## 6 Conclusion and Recommendations

In the face of advancing quantum computing capabilities, current cryptographic practices within the automotive sector, especially in CCAM, stand vulnerable. Vehicles, now more interconnected than ever, demand the robust protection offered by PQC. Our investigation has shed light on the industry's noticeable shift towards PQC strategies, which rely on a variety of mathematical foundations and algorithms. Particularly for processes like Vehicle-to-Vehicle Communication and OTA Software Updates, PQC offers enhanced defense against quantum threats. Practical tests, notably on Raspberry Pi 4, have showcased the effectiveness of specific post-quantum methods. Embracing PQC in CCAM not only bolsters security but also positions the transport sector for a quantum-resistant future, ensuring sustained safety and optimal functionality.

To ensure the seamless integration of PQC solutions into real CCAM and other critical automotive applications, it is important to develop lighter and faster PQC techniques. On the other hand, more suitable hardware tailored for post-quantum secure implementations should be developed, thus bridging the gap between theoretical ability and practical feasibility.

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# SELFY - Self Assessment, Protection and Healing Tools for a Trustworthy and Resilient CCAM

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**Abstract.** SELFY envisions an agnostic toolbox for the self-management of security and resilience of the CCAM (Connected, Cooperative and Automated Mobility) ecosystem, which can be easily deployed to extend the current Operational Design Domain (ODD), providing self-awareness, self-resilience and self-healing mechanisms and enhancing trust between stakeholders. SELFY is based on four pillars: Situational awareness, Resilience, Secure Data Sharing and Trust and provides three groups of tools. SACP (Situational Awareness and Collaborative Perception) tools aim at providing all CCAM actors with a comprehensive understanding of their environment, i.e., the perception of objects, such as other traffic participants and stationary objects. CRHS (Cooperative Resilience and Healing System) tools enable self-protection actions whenever a compromising situation is detected in relation to assets, vehicles, operations, or the system itself. TDMS

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(Trust and Data Management System) tools establish a secure and trusted environment for data in a collaborative and cooperative context, both for infrastructure and assets, as well as for citizen's data, such as drivers or pedestrians with special attention to privacy considerations. By defining a collaborative environment between the different tools to respond to new threats, risks and attacks SELFY facilitates the comprehension of new challenges in the cybersecurity aspect of CCAMs.

**Keywords:** Cooperative Connected Automated Mobility (CCAM) · Cybersecurity · Privacy · Trust · Resilience · Situational Awareness · Self-Management Security

## 1 Introduction and Motivation

Cooperative Connected Automated Mobility (CCAM) will improve the mobility ecosystem of millions of citizens in Europe and around the world. Leveraging artificial intelligence solutions, big data, enhanced connectivity, and digitalization, CCAM will pave the way for smarter cities, enhancing their efficiency, sustainability, and accessibility for all users. However, as defined by the CCAM's SRIA [1] (Strategic Research and Innovation Agenda), Key Enabling Technologies such as cybersecurity are required to provide robustness and resilience. Threats, incidents, and malicious actions as well as system failures must be detected in real-time and reported to a decision-making system to perform response actions. CCAM systems' resilience heavily relies on the data and information fusion, sharing and processing. Therefore, guaranteeing a secure flow of generated and processed data between all stakeholders is vital for a correct, efficient, and robust operation of the different services and systems in the CCAM environment. Ensuring the veracity, quality and integrity of the generated data is essential in the mobility management and control process, both in the stages of persistence, transmission, access and use of information, as well as in the different stages of cybersecurity and security management of the CCAM ecosystem.

There are already some regulations and standards like the UNECE WP.29 R155 [2] and R156 [3] or the ISO/SAE21434 [4] which focus their efforts on providing a more complete cybersecurity management system with incident management and remote software updates as well as defining a framework for including cybersecurity requirements and risk management. SELFY tools like the Vehicle Security Operations Center (VSOC) or Secured Over the Air software update (SOTA) provide a partial solution but go beyond by proposing a collaborative environment between all CCAM elements by sharing and fusing data and increasing the awareness, robustness and trust of the overall CCAM system.

## 2 SELFY Concept

SELFY researches and implements a set of tools that are agnostic to OEMs and suppliers, being easily integrated (ready-to-use and re-use) in service and product development processes from the design stage (resilience by design), considering the full ODD of the

different CCAM scenarios. SELFY toolbox will perform a continuous assessment of the robustness and resilience, based on a process of situational awareness through collaborative perception, a set of cooperative resilience and healing systems services in response to compromised situations (cyber-attack, intrusion, cyber-terrorism or cyber-sabotage), based on the gathering and sharing of data in a trusted collaborative environment. The key technologies underpinning the SELFY toolbox are described in Fig. 1. These technologies are grouped into three categories which in turn are supported by the four cybersecurity innovation pillars outlined earlier. To address the complexity of CCAM the SELFY tools are deployed on multiple layers, e.g., vehicle, RSU or cloud.

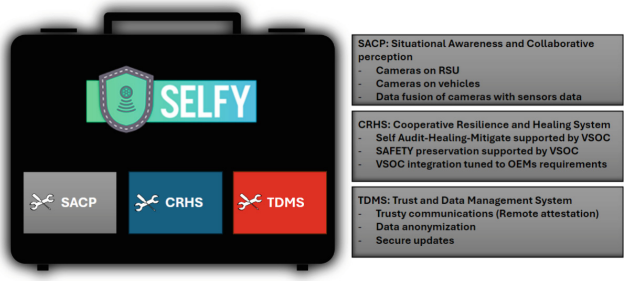



**Fig. 1.** SELFY's toolbox of technologies (source: pixabay.com royalty-free content license)

### 2.1 Situational Awareness and Collaborative Perception (SACP)

The SACP includes a set of tools to obtain a comprehensive understanding of the environment, perception and position of objects by using artificial intelligence and aggregating and fusing data from sensors and V2X.

**Vehicle**

- Situational Assessment Module. It detects anomalies, misuse, malfunctions, etc. The tool takes the environment model (fused from RSU and on-board vehicle sensor data), ego vehicle CAN inputs, ego vehicle trajectory, Cooperative Awareness Messages (CPMs) as input and analyzes the data using AI-Based methods to detect anomalies and assign a risk level to the current situation.
- Vehicle-centered situational awareness tool. It provides a 360º view of the vehicle surroundings using sensor fusion and AI-based object (vehicle and VRU) detection algorithms. This information will be shared to the on-board V2X communication module, and it will be used to generate a Local Dynamic Map (LDM). The LDM will be shared with RSU and other vehicles through V2X channel.
- Aggregation tool. CAMs and CPMs shared from traffic participants and infrastructure via V2X communications are aggregated and fused with the local perception information into a central perception system.

**RSU**

- Traffic Monitoring Tool. It identifies and tracks objects based on video data, results of sensors fusion and V2X messages.
- Threat Evaluation Tool. It identifies different types of threats and makes decisions about how to handle them.
- Sensor Fusion & Anomaly Detection Tool. It analyses and fuses data from LIDARs/RADARs mounted on the RSU. The tool also aims to detect anomalies between a pair of sources.

### 2.2 Cooperative Resilience and Healing System (CRHS)

The CRHS includes a set of tools that will elicit self-protection whenever a compromised situation is detected. The actions can be taken locally or in cooperation at global CCAM level. This global capacity is embodied in the VSOC.

**Vehicle**

- Safety Operational Tool. It evaluates the situational and own risks of the ego-vehicle and modifies the planned trajectory to a minimum risk manoeuvre when needed in the events of system failures such as localization losses.
- Artificial Immune System. It provides a mechanism to detect deviations. If these involve an attack, learn from them and (if possible) mitigate this type of attack. It acts as a swarm that connects all vehicles, updating and sharing the mitigation's solutions.
- ROBUST tool. It provides a set of algorithms that allows designing and implementing physics-based (kinematics/dynamics) schemes for trajectory planning, anomaly detection, and communication protocols that are optimized by design to be as robust as possible (in terms of potential damage to vehicles/infrastructure) against cyberattacks.

**RSU**

- Audit Box. It audits the WiFi and BT interfaces of the vehicle and detects jamming situations. It logs the results and sends it to the VSOC.

**Cloud**

- VSOC. It collects data from the SELFY toolset (through the VSOC API) and detects anomalies within the data of the CCAM ecosystem. The analysis results are prepared and distributed to the SELFY tools through the VSOC API. The API can be used to subscribe to information (e.g., trust score for tool partners and OEMs) and send data to the VSOC.

- Interaction-based V&V (Verification and Validation tool. It is dedicated to conducting formal analyses employing models of interactions akin to UML Sequence Diagrams and Message Sequence Charts. Among the analysis features offered by the tool, we have Runtime Verification (RV), as detailed in [5] and in [6]. This functionality enables the identification of non-conformities against the interaction models, thereby exposing potential security threats within V2X communication flows in CCAM systems.

### 2.3 Trust Data Management System (TDMS)

TDMS includes a set of tools addressed to build a secure and trusted environment for data in a collaborative context both for infrastructure and vehicles as well for citizens (drivers or pedestrians).

**Vehicle**

- Sensitive Data Anonymization tool. It receives the detected objects (vehicle and VRU) from the vehicle-centred situational-awareness tool, detects the sensitive data (human faces and vehicle license plates), and anonymizes such personal and sensitive data by blurring.
- Privacy Utility Tool. It distorts (to enforce privacy) data used for platooning trajectory planning and anomaly detection before sharing via V2X so that sensitive information is hidden as much as possible while preserving data utility.

**RSU**

- V2X Privacy tool. It assigns IDs for describing tracked objects in CPM messages, the assignment of said IDs taking into account change of identity by CAM-sending vehicles so as to avoid leaking vehicle identity through CPM messages.
- Roadside Trust Tool. It assesses a level of trust for each V2X agent based on V2X messages and data from roadside sensors.

**Cloud**

- SOTA tool. It provides methods to ensure secure SW updates for connected and automated vehicles. It focuses on the entire vehicle level and not only on its key components. The entire life cycle of the vehicle within the CCAM shall be addressed at each layer of the CCAM system.

**All**

- PQC provides libraries to use Post Quantum Cryptography as part of a TLS function. Post Quantum Cryptography guarantees that systems will be robust against current and future cyberattacks on crypto-systems

- Remote Attestation System Box. It aims at ensuring integrity verification of various software components running on the vehicle or the RSU.
- Key Exchange/Management Box (KEMS Box). It dynamically generates and updates, whenever needed, the keying material for all the entities that require it for different purposes like data protection, network access control.
- ITS Station. It transmits and receives V2X messages in compliance with the V2X standards. V2X communication can happen either in direct mode (ITS-G5) or through cellular communication (with a relay in the cloud: C-ITS-S) (Not planned in SELFY). It can also route standard IP(v4/v6) messages between components and the infrastructure on the Internet.

## 3 Market Potential

SELFY's significance relates to its potential impact in security, safety, and resilience of the CCAM ecosystem, such as OEMs, traffic management centers, TIER-x suppliers, smart infrastructure suppliers or regulatory and standardization bodies, among others. The market segments are very broad, from automotive OEMs and suppliers, traffic and infrastructure management, road operators to product and service development teams. Considering the new regulatory requirements in CCAM, the market potential is evident, which is estimated [6] at EUR 535 million. It can be reached through three main sources: licensing and subscription fees for using the SELFY toolbox, consultation and customization services for specific needs and maintenance and support fees.

## 4 Conclusions and Next Steps

Cooperative Connected and Automated Mobility requires cybersecurity and privacy tools. New regulations and standards are coming and solutions have to be deployed over the system. Citizens, such as drivers, Vulnerable Road Users (VRU) or pedestrians shall accept and trust the system. SELFY's solution is a cooperative toolbox which addresses all of these issues, increasing perception and awareness, robustness, attack detection and mitigation rate and providing safe states and secure updates, everything orchestrated by a VSOC.

As a next step, SELFY is going to be validated over three main use cases: Resilient Cooperative Mechanisms for VRU Safety, Secure empowerment of backend system for traffic management system and Robust platooning. These validations are going to be separated into three groups: simulation, laboratory and real-world validation and the outcomes of the project are going to be evaluated according to a set of KPIs (Key Performance Indicators) relevant to the CCAM sector.

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# An Efficient and Secure Blockchain Based Homomorphic Encryption for Intelligent Transport System

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**Abstract.** Growing traffic volumes in cities demand new ways to manage routes. Current Intelligent Transport Systems (ITS) face safety and privacy issues, high data costs, and security vulnerabilities. We propose a lightweight system using fog computing and homomorphic encryption. Vehicles anonymously share encrypted travel data with a trusted fog node, allowing the Traffic Control Centre to safely manage congestion without compromising individual privacy. Experimental results show our system outperforms existing approaches, offering a secure and efficient solution for future ITS.

**Keywords:** Intelligent Transport Systems · Safety and confidentiality · Congestion routing management system · Homomorphic encryption · Traffic Control Centre (TMC) · Blockchain system

## 1 Introduction

Due to surging vehicles and communication advancements, Intelligent Transport Systems (ITS) research is flourishing. ITS involves vehicles, roadside units (RSUs), and trusted authorities (TAUs) collaborating for a smart traffic network with V2V and V2I communication. V2V communication enhances safety, while RSU infrastructure facilitates V2I for traffic services [1]. However, security and privacy are major concerns in ITS due to public communication channels, making message authentication crucial for both V2V and V2I [2,3]. Existing privacy-preserving schemes have limitations. The rise in vehicles demands efficient data processing. Cloud computing suffers from high latency due to distant servers [4,5]. Fog computing with Fog Nodes (FNs) at the network edge tackles this by offering low latency, wider reach, and real-time processing for efficient traffic management [6–8] (Fig. 1).

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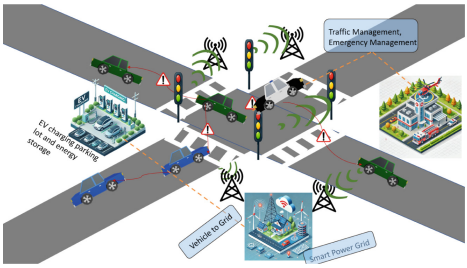



**Fig. 1.** An Intelligent Transport System. (Image produced using Clipart and PowerPoint.)

## 2 Related Work

### 2.1 Confidentiality and Safety Research

While **PKI-based schemes** for ACPP have been explored, they face limitations in storage, revocation costs, and validation delays. **Identity-based schemes** have sought to address these issues through efficient batch signature verification, secret sharing, and substituted vehicles. However, **privacy-preserving methods** often rely on computationally expensive pairing-based encryption. Our work investigates Group Diffie-Hellman encryption as a more efficient alternative.

### 2.2 Blockchain-Based Verification Strategies

While prior research has investigated blockchain for VANET verification, limitations persisted, including reliance on certifying agencies, frequent CA updates, limited rogue vehicle tracking, and domain-specific designs. Other efforts focused on fog-based validation, smart contract-based key management, and zero-knowledge proofs for privacy.

### 2.3 Systems of Verification that Utilize Fog

Many Recent works leverage fog computing in VANET's, proposing a real-time roadway monitoring architecture and designing a secure aggregation scheme for fog-based safety alerts, ensuring both location awareness and privacy preservation. Some introduce a privacy-preserving contracting framework for vehicles using fog nodes. While some developing a compact verification technique for location-aware privacy protection under specific conditions in fog-based VANETs. These efforts showcase the potential of fog computing to enhance VANET security and efficiency.

## 3 Description and the Backstory

Homomorphic Encryption **(HE)** safeguards sensitive data by allowing computations directly on encrypted data. Public and private keys, generated using large

primes, facilitate encryption and decryption [1]. Blockchain technology, known for its use in cryptocurrency, offers a secure and tamper-proof method for storing data through linked blocks. Its cryptographic techniques ensure data immutability [2]. The Diffie-Hellman **(DH)** algorithm [6] enables secure key exchange on insecure networks. It leverages a mathematical group and a large prime number **(p)** for two parties to establish a shared secret key **(K)** without prior knowledge. The security of blockchain technology relies on the difficulty of solving the discrete logarithm problem **(DLP)** [9]. Smart contracts, envisioned by Nick Szabo, propose a revolutionary key management solution for vehicles using blockchains like Ethereum. These tamper-proof systems manage tasks like owner verification, unlocking, and access control (Figs. 2, 3 and 4), fundamentally changing how we trust and share car keys. This section lays the groundwork for understanding the technical aspects of the proposed secure Intelligent Transport System **(ITS)**.

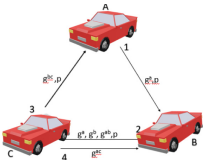



**Fig. 2.** DH Exchanged Messages for 3 vehicles (Image produced using Clipart and PowerPoint.)

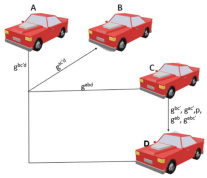



**Fig. 3.** Deployment Of Smart Contract (Image produced using Clipart and PowerPoint.)

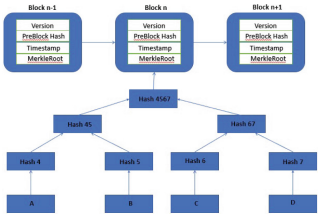



**Fig. 4.** Block structure of blockchain. (Image produced using Clipart and PowerPoint.)

## 4 Proposed Scheme

This section outlines a multi-step process orchestrated by TAU. Firstly, TAU bootstraps the system and handles registration requests from both vehicles and fog nodes. Next, vehicles authenticate and register themselves, while fog nodes securely combine their submitted routes into a single encrypted bundle. The Traffic Management Center (TMC) then receives this combined ciphertext, decrypts it, and utilizes the decoded routes to manage traffic flow. A straightforward mechanism is also implemented to allow for password changes and the removal of unauthorized vehicles. For your reference, key notations and their corresponding meanings are provided in Table 1.

### 4.1 Automobile Registration

Vehicles undergo a secure registration process with TAU before leaving the manufacturer. This involves encrypted communication to establish a pseudo-identity and obtain a confidential key. Details of this interaction are explained below.

1. The driver chooses a password ($PWV$) and user ID ($UID$), calculating $UPWV = h1(UID \parallel PWV)$. Encrypted credentials ($IDV, UPWV$) are sent to TAU for secure registration.
2. TAU verifies if the vehicle ($V$) is registered or blacklisted. If not, registration proceeds.
3. TAU generates a secret key ($skv$) for $V$, a pseudonym ($PIDV$), and additional cryptographic elements.
4. TAU transmits these elements ($Bi, Ci, skV, PIDV, n, g$) to $V$ for secure storage and uploads $PIDV$ and the public key ($VPK$) to a smart contract.

**Algorithm 1.** Function to Update A Smart Contract

**Input:** bytes32 newVPK,address user, bytes32 VPK, uint256 txid
**Output:** Bool
1: function updateVPK(address user, uint256 txid, bytes32 VPK, bytes32 newVPK) public returns (bool) {
2: require(contractStatus.isActive == true);
3: require(msg.sender == TAU, "Only Trusted Authorities can update VPKs.");
4: for (int i = 0; i ¡ vpkTransfers.length; i++) {
5: if ($vpkTransfers[i].vpk == currentVPK$) {
6: $vpkTransfers[i].vpk = newVPK$;
7: return true; 8: } 9: }
10: return false; 11:}

**Algorithm 2.** Function to Query A Smart Contract

**Input:** address user
**Output:** result in bool
1:function checkVPK(bytes32 VPK) public view returns (bool) {
2: require(SC.status == true,);
3: for (uint i = 0; i ¡ VPKT.length; i++) {
4: if (VPKT[i].VPK == VPK) {
5: return true;
6: } 7: }
8: return false; 9: }

### 4.2 Registration on Fog Nodes

The fog node securely communicates offline with TAU to obtain a private key for the subsequent signing process. Details of this interaction are explained below.

1. Fog node (FN) selects an identifier (IDF) and sends a registration request to TAU.

2. Upon receiving the request, TAU checks if the IDF is available. If unavailable, TAU rejects the request. Otherwise, TAU generates a secret key ($skf \in \mathbb{Z}_q^*$) and computes the corresponding public key ($fpk = skfP$).
3. The TAU then sends $skf, fpk$ and broadcasts $fpk$ onto the fog node.
4. FN completes registration by storing the secret key ($skf$) securely.

### 4.3 Sign-In Stage

This phase is to check the legality of the automobile's user.

1. User in vehicle $U_i$ enters $\{ID_V, PW_V, UID\}$ into the On-Board Unit (OBU) of vehicle $V$.
2. The $V$ calculates $U_{PW_V} = h_1(UID||PW_V)$ and $A_i = B_i \oplus h_4(ID_V)$. It then verifies if $C_i = h_3(A_i||U_{PW_i})$ holds. If the equation is true, the login is approved, and $V$ proceeds. Otherwise, $V$ rejects the attempt immediately.

### 4.4 Request for Route from the Fog Node

1. The FN generates a random value $xz$, calculates $Xz = xz \cdot P$. It then creates a signature $F1 = \text{skf} + xzh2(\text{ID}_\text{F}||\text{RS}||Tj1) \mod q$ using its private key and

**Table 1.** List of Notations and Definitions

| Notations | Definitions |
|---|---|
| TAU | Trust authority |
| TMC | Traffic control center |
| V, FN | i-th vehicle and j-th fog node, respectively |
| IDV, IDF | Real identity of vehicle and fog node, respectively |
| UID | Real identity of user |
| PWV | Password of vehicle |
| s, Ppub | Private key and public key of TAU, respectively |
| skv, skf | Private key of vehicle and fog node, respectively |
| VPK, fpk | Public key of vehicle and fog node, respectively |
| PIDV | Pseudonym of vehicle |
| Ti1, Tj1, Tj2 | Latest timestamp |
| M | Message sent by vehicle and fog node |
| concat | Concatenation operation |
| xor | Exclusive-OR operation |
| DH | Diffie Hellman algorithm |
| G | Additive group with order q |
| P | Generator of the group G |
| h | Secure one-way hash functions |

a formula involving its identity,route request list, and timestamp. It then broadcasts $M1 = \{\text{IDF}, Xz, \sigma_{F1}, \text{RS}, Tj1\}$ to nearby vehicles.
2. Upon receiving transmission $M1$ from FN, $V$ validates timestamp $Tj1$. If valid, $V$ verifies Eq(1). If confirmed, $V$ acknowledges communication and proceeds.

### 4.5 Reporting Route to the Fog Node

For privacy, vehicles encrypt routes before sharing them with the fog node. This homomorphic encryption allows manipulation and aggregation of the encrypted data for efficient package handling, without decryption. This protects user privacy by hiding individual travel patterns from the fog node.

1. V efficiently reports its route information in binary format: $\{F_1(V), F_2(V), ..., F_m(V)\}$, each $F_i(V)$ is a bitwise where the final bit indicates V's intention to use route NO.$i$. The bit length of $F_i(V)$ aligns with the base 2 log of the maximum V's supported by a fog node. (e.g. $\{000, 001, 000, 001\}$) signifies travel on Routes No. 2 and 4.
2. $V$ selects random $r_i \in \mathbb{Z}^q$ and encrypts it as $\varphi_i = g{\cdot}F_0(i)|F_1(i)|F_m(i){\cdot}r_n i \bmod n^2$. $V$ chooses another random $d_i \in \mathbb{Z}^q$ and calculates $D_i = d_i \cdot P, where i = h_5(PID_V \,|\, D_i \,|\, \varphi_i \,|\, Ti1)$. $V$ creates a signature $V = sk_v + d_i \cdot \beta_i \bmod q$, wherein $T_{i1}$ .
3. At the very least, $V$ sends the information $M_v = \{\sigma_V, i, D_i, PID_V, T_{i1}\}$ to $FN$.

### 4.6 Management of the Traffic Route

The TMC first validates the timestamp Tj1 before confirming the validity of Eq. (1). If Tj1 is not valid, the TMC denies the communication. Otherwise, it proceeds with the subsequent actions.

$$\sigma_{F2} \cdot P = sk_f + y_j \cdot h_2(IDF||\phi_{sum}||T_{j2}) \tag{1}$$

Following this, the TMC utilizes the private $(\lambda, \mu)$ to decode all aggregated travel routes $\phi_{sum}$ by determining $L(\phi_{\lambda sum \bmod n_2}) \cdot \mu \bmod n$, where $\mu = (L(g^{\lambda \bmod n_2}))^{-1} \bmod n$, $L(x) = \sum_{i=1}^{n}(x-i)/n$, and recovers the route information.
$RI = F_0(0) \cdot \sum_{i=1}^{k} P(F_0(i)^{\lambda \bmod n_2}) \cdot \sum_{i=1}^{m}\sum_{j=1}^{k} P(F_j(i)^{\lambda \bmod n_2})$. Though meticulously dissecting our final findings to grasp the plan's entirety, the precise forces propelling it remain elusive. For every automobile's journey. every route has 5 portions, each of which is denoted by 3 bits. This is based upon the assumption that 6 automobiles would give their own future driving routes. V3's path is 001 000 001 000 001, and the TMC may obtain the total number $\sum_{i=0}^{5} F_1(V) = 2, \cdots, \sum_{i=0}^{5} F_5(V) = 6$.

### 4.7 Vehicle Revoke

The smart contract governing vehicle V's voting rights automatically revokes them (via DeletePK) if, a) V encapsulates and broadcasts a voting transaction, exceeding a predefined threshold (VCT>THD), or b) TAU finds V's public key invalid during routine checks. This ensures bad actors are swiftly penalized within the trusted execution environment.

## 5 Performance Analysis

We evaluated our GDH-based key generation algorithm for high-mobility VANET's using ns3 and SUMO on a simulated 5 km interstate network with 40 cars. Focusing on group key generation (KG) time, we found it increases with vehicle count due to more computations but is minimally affected by speed. G and G1 components are 320 and 1024 bits, respectively, while our 3-stage authentication incurs 3040 bits of overhead. Compared to Shen (6592 bits), Khaled (4736 bits), and Cui (2720 bits), our scheme offers a competitive overhead while providing strong security for high-mobility VANETs. This is the first simulated GDH-based KG with MIM defense for such networks, establishing a benchmark for future research.

### 5.1 Blockchian's Feasibility Analysis in Practise

We validated our car data management smart contract on the Rinkeby testnet, deploying it via Solidity and assessing gas costs for key tasks like public key management. Using Remix and querying methods, we found deployment a one-time cost of about USD 41.50, and common operations under USD 5.71. These reasonable costs demonstrate the feasibility of our approach for secure and cost-effective car data management (Table 2).

**Table 2.** Gas Cost of Smart Contract

| Operation | Gas Used | Actual Cost (ether) | USD |
|---|---|---|---|
| deploy | 431800 | 0.022198040 | 41.4998 |
| update | 59375 | 0.003051900 | 5.7141 |
| query | 25742 | 0.001324936 | 2.4812 |
| delete | 37580 | 0.001934640 | 3.6235 |

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# Impact Assessment of Governance Models on the Integration of Connected and Autonomous Vehicles

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**Abstract.** The development of Connected and Autonomous Vehicles (CAVs), with vehicle-to-everything (V2X) communication technologies, has catalyzed the digital transformation of the vehicle and infrastructure automation industry. These advancements aim, among others, to benefit users by reducing traffic congestion and emissions, enhancing safety, providing comfortable travel, and saving fuel costs. Although many studies have investigated the influence of CAVs on traffic congestion, there exists a lack of governance policies and regulations related to the uptake of CCAM. To fill this gap, we review the regulatory frameworks already implemented in Europe and we investigate through a stated preference survey important aspects related to the barriers of using CAVs. Finally, we analyze the results of the surveys resulting in a well-educated selection of targeted actions that can increase the uptake of CAVs throughout Europe.

**Keywords:** Connected Autonomous Vehicles (CAVs) · Governance · Policy · CCAM · vehicle-to-everything (V2X)

## 1 Introduction and Background

The current requirements for frequent and driverless travel, combined with the evolution of technology, have led to the development of vehicle automation on a European level. The European Union (EU) estimates that the replacement of Conventional Vehicles (CVs) by Autonomous Vehicles (AVs) will occur within the following decades. Conversely, issues concerning the legal framework and road infrastructure have yet to be resolved [1]. The objective of this study is to review the existing advantages and barriers of adopting this new technology and to determine how the EU intends to resolve them. Finally, using a stated choice survey, we analyze and conclude the key factors influencing the European citizen's opinions and explore strategies to enhance automation adoption, mitigating its barriers.

Autonomous driving offers numerous advantages; however, integrating autonomous vehicles brings challenges like ambiguity over infrastructure, legal framework, and ethics, including concerns about personal data leaks [2]. Global collision legislation

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gaps make determining liability for operators or manufacturers challenging [3]. Economic hurdles include high costs, job shifts, and the potential rise of ridesharing and pay-as-you-go transport models [4].

In Europe, the ongoing debate revolves around creating new tech-specific laws or revising existing ones [5]. Key goals are consumer protection and promoting innovation [6]. Integrating tech into legal frameworks necessitates international changes [5]. Despite rapid tech advancement, the EU aims to establish common rules, posing legislative challenges. Countries like Denmark, the US, and South Korea have already created legal frameworks for automated driving, focusing on ethics and guidelines [7].

The European Commission (EC) plans an EU-wide platform for testing autonomous vehicles in various transport modes, emphasizing data protection and accident responsibility [8, 9]. The EU AI ethics' guideline is under development, emphasizing respecting human dignity and freedom of choice [10]. Balancing data protection with operational needs poses challenges in autonomy, information, and surveillance privacy [2]. In conventional vehicles, drivers are primarily liable for accidents, except for cases involving defects where manufacturers can be held accountable if drivers are unaware of the defect [11, 12]. Highly automated vehicles shift liability to software, involving manufacturers, software engineers, or road designers if they significantly influence vehicle movement [11]. There is ambiguity about whether automation fits within existing legal frameworks, and whether vehicle software is considered a service or product.

To enhance road safety, Europe needs harmonized traffic rules and innovative infrastructure, given unmanned vehicles sharing roads with others [10]. The EC introduced in 2016 a Strategy for Cooperative Intelligent Transport Systems (C-ITS) to align EU investments and regulations, enabling effective information sharing among road users and traffic management [1].

**Societal Acceptance of CAVs**

The societal acceptance of CAVs depends on multiple factors like public awareness, perception, safety concerns, and cultural differences. Despite increased awareness, the concept of CAVs remains poorly defined, leading to confusion about their benefits and risks. Safety is a major concern, with many skeptical about machines' ability to navigate traffic safely. Acceptance varies by demographics, with younger individuals generally more open to CAVs compared to older generations [13–15].

Machine learning techniques have been used to forecast AV adoption rates by examining users' perceptions and their intention to adopt CAVs. Factors influencing adoption include safety, trust, privacy, accessibility, and ethics, with surveys confirming these factors' strong impact. Notably, Fuzzy Logic outperformed other classifiers in predicting user adoption, highlighting its potential in understanding public attitudes [16]. This aligns with findings that trust, compatibility, and perceived usefulness significantly influence acceptance, with social influence and personal innovativeness playing crucial roles [14].

Several studies emphasize shifting AV research from technical aspects to broader societal impacts, including societal acceptance, societal implications, and governance of the AV transition. This holistic approach shifts focus from consumer adoption to citizen

acceptance, considering long-term impacts like accessibility, well-being, social inclusion, and public health. Participative governance is advocated to balance AV deployment with desirable future outcomes for citizens [17, 18].

Public engagement is crucial in building trust in AV technology. A lack of knowledge among non-experts contributes to trust deficits. Enhancing public understanding of CAVs' benefits and involving the public in development from the design phase can foster trust and acceptance. Practical demonstrations and engaging diverse user groups through workshops, training, public consultations, and trials are effective measures [15]. Practical experience with AVs can help the public appreciate their benefits and address safety, legal responsibility, and privacy concerns [14, 15].

Research initiatives in Europe and the US focus on AVs' transformative impacts on society, the economy, and the automotive and public transport industries. Efforts aim to improve environmental sustainability, collision avoidance, and traffic management while addressing safety, security, privacy, and ethical issues. Current efforts include integrating security measures into safety-critical systems and developing automotive cybersecurity standards to ensure safe and secure AV systems [19]. These initiatives address the complex challenges posed by AVs and ensure their safe and beneficial integration into society [19].

In conclusion, the studies collectively highlight that societal acceptance of AVs depends on multiple factors such as safety, trust, privacy, accessibility, and ethics. Effective regulation, public involvement, and clear communication are essential for fostering acceptance. Common themes include the need for trust-building measures, practical demonstrations, and addressing safety and ethical concerns. However, limitations include the emerging stage of AV technology, lack of empirical data, and the need for long-term impact assessments.

## 2 Data Collection, Results and Analysis

To assess European citizens' views on adopting highly automated vehicles, a Stated Preference (SP) survey was conducted with 171 participants [20]. The survey, developed with European partners, was translated into English, Greek, Spanish, and German.

In addition to the SP survey, the questionnaire collected sociodemographic data, mobility patterns, and perceptions of AVs. Topics included satisfaction with current transport options, public transport adequacy, primary transport modes, and trip purposes. Questions about autonomous vehicles covered safety, trust, economic considerations, and data privacy. The SP survey assessed five key parameters: affordability, passenger safety, data privacy protection, road infrastructure, and legislative frameworks for CAVs. Respondents chose their preference for AVs when one parameter was negative and the other four were positive, answering four "Yes" or "No" questions without constraints.

The socio-demographic profile and key findings on respondent mobility are presented in Table 1 to understand factors impacting AV acceptance. The online survey included diverse respondent categories: 60% employees, 25% university students, and 10% self-employed. Gender split: 53% female, 45% male, 2% diverse. Age distribution: 85% university students or employees, few under 25 or over 56. Respondents represented ten countries: Belgium, Germany, Greece, Italy, Luxembourg, Netherlands, Portugal, Slovenia, Spain, and the UK.

**Table 1.** Sociodemographic information

| Sociodemographic | Responses, N = 171 | | | | | |
|---|---|---|---|---|---|---|
| *Gender* | *Male* 45% | *Female* 53% | *Diverse* 2% | | | |
| *Age* | *18–25* | *26–35* | *36–45* | *46–55* | *56–65* | *>65* |
| | 22% | 40% | 14% | 16% | 7% | 1% |
| *Professional status* | *University student* | *Employee* | *Self-employed* | *Unemployed* | *Retired* | |
| | 25% | 60% | 10% | 4% | 2% | |
| *Monthly Income* | *<1000€* | *1000–1500€* | *1500–2500€* | *2500–3500€* | *3500–5000€* | *>5000€* |
| | 36% | 26% | 18% | 11% | 6% | 2% |

Regarding respondent mobility (Table 2), satisfaction with available transport modes is generally high, though public transport adequacy shows dissatisfaction, with 14% finding it completely inadequate and 30% rather inadequate. Travel purposes include 46% primarily for work, 17% for entertainment, 12% for education, and 12% for family duties. Main transport modes are 35% public transport, 31% driving, 6% as passengers, 20% walking, and 5% cycling.

In terms of autonomous driving knowledge and perception, 47% claimed ignorance, while only 6% had complete knowledge, and 58% had not driven an automated vehicle. Regarding safety, respondents tended to agree that AVs are safer than conventional ones. Additionally, 46% were willing to use driverless public transport, with 41% expressing potential interest.

**Table 2.** Mobility behavior information of the respondents

| Mobility behavior | Responses, N = 171 | | | | | |
|---|---|---|---|---|---|---|
| | *1 = totally dissatisfied* | *2* | *3* | *4* | *5 = totally satisfied* | |
| *Satisfaction with transport modes* | 4% | 19% | 40% | 29% | 8% | |
| *Adequacy of PT service* | 14% | 30% | 27% | 21% | 7% | |
| *Main transport mode* | *Vehicle as driver* | *Vehicle as passenger* | *Public urban transport* | *Motorcycle* | *Bicycle* | *On foot* |
| | 31% | 6% | 35% | 4% | 5% | 20% |
| *Main trip purpose* | *Work* | *Education* | *Entertainment* | *Leisure trip* | *Shopping* | *Family duties* |
| | 46% | 12% | 17% | 4% | 7% | 12% |

Moreover, respondents were asked about trust in autonomous vehicle operation in city centers and on highways (Table 3). Highways garnered more trust compared to city centers. Economic affordability is key, with 51% saying it must be accessible to all, and 22% saying it should be. Two other factors considered for AV preference were data privacy and user familiarity. Additionally, 76% knew of autonomous public transport in European countries.

**Table 3.** Preference for Autonomous Vehicles

| Autonomous vehicle | Responses, N = 171 | | | | |
|---|---|---|---|---|---|
| Preference | *1 = absolutely not* | *2* | *3* | *4* | *5 = absolutely yes* |
| *Driving in a city center* | 9% | 30% | 27% | 27% | 7% |
| *Driving on a highway* | 11% | 19% | 28% | 35% | 7% |
| *Economically accessible to all* | 5% | 5% | 16% | 22% | 51% |
| *Data privacy issues* | 18% | 13% | 30% | 27% | 12% |
| *Ignorance of AVs* | 15% | 15% | 30% | 22% | 9% |

As mentioned earlier, the stated preference experiment assessed five factors influencing autonomous vehicle adoption: affordability, safety, data privacy, road infrastructure, and legislative framework for CAVs. For each, a scenario with one unfavorable aspect and four positives was presented. Results are summarized in Table 4.

**Table 4.** Preference on choosing an Autonomous Vehicle considering different factors.

| **Would you prefer an Autonomous Vehicle when:** | the vehicle is financially affordable? | there is an adequate legislative framework? | there is sufficient road infrastructure? | the car industry guarantees for the safety of its passengers? | the protection of data privacy is ensured? |
|---|---|---|---|---|---|
| The vehicle is not financially affordable, but | - | **51%** | **55%** | **60%** | **53%** |
| The legislative framework is insufficient, but | **64%** | - | **55%** | **51%** | **60%** |
| There is no road infrastructure, but | **76%** | **68%** | - | **61%** | **71%** |
| The car industry does not guarantee for the safety of its passengers, but | **85%** | **80%** | **81%** | - | **84%** |
| The protection of data privacy is not ensured, but | **51%** | **53%** | **51%** | **57%** | - |

*Note: percentages associated with a higher "Yes" proportion are highlighted in green.*

The table above reveals safety as the primary factor influencing European citizens' preference for autonomous vehicles. Over 80% would not choose one unless it is guaranteed safe, and 85% would not even if it is economically affordable. Road infrastructure is the second most important factor, with preferences ranging from 61% (with passenger safety guaranteed) to 76% (with affordability). Adequate legislation is crucial, with 64% avoiding AVs, even with reasonable prices, and 60% being cautious despite data privacy guarantees. Data privacy has mixed effects; 55% would abstain even with good road infrastructure, and 51% would do so even if passenger safety is assured. On the other hand, data privacy protection varies: 57% prefer AVs for safety even at the expense of data privacy. However, 53% resist even with sufficient legislation. Economic accessibility matters least; 60% would choose AVs if safe, 55% with good infrastructure, and 51% with strong legislation. Nonetheless, 53% would not choose AVs even with data protection.

## 3 Conclusions and Future Research

This paper aims to uncover the benefits and challenges of implementing CAVs and explore the EU's mitigation strategies. We examined legislative frameworks, with a focus on European cases. We further reviewed studies on the societal acceptance of CAVs. Five key factors affecting CAV acceptance emerged: passenger safety, road infrastructure, data privacy, legislation, and affordability. To assess the governance models' impact on CAV integration and understand adoption factors, we conducted SP surveys focusing on the five CAV utilization obstacles. We then analyzed survey results, emphasizing sample socio-demographics, daily mobility, and attitudes toward these influencing factors. Survey participants prioritize passenger safety as the most crucial aspect when considering autonomous vehicles. Governments should also focus on road infrastructure sufficiency and robust legislative frameworks for accidents or data privacy issues. Economic affordability, while important, is a consideration for most citizens, who believe CAVs should be accessible to everyone.

Based on our literature review and SP survey findings, on CAV regulatory frameworks and influencing factors, we suggest the following research directions:

- Develop a binary logit model to quantify each influencing factor's impact on CAV acceptance.
- Enhance sample socio-demographics with vehicle ownership and trip mode data.
- Conduct cross-country or regional comparisons of the results.

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# How to Deliver a Large Scale National Connected Vehicle Pilot

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**Abstract.** Understanding how road operators can harness a paradigm shift in traffic management operations through increased vehicle connectivity, is a key objective of Ireland's Cooperative Intelligent Transport Systems (C-ITS) pilot project. Transport Infrastructure Ireland (TII) and the European Commission are co-funding the C-ITS pilot deployment including integration into their traffic management system. This is one of the first C-Roads participating countries to integrate C-ITS as part of day-to-day traffic operations. This paper discusses the practical challenges and some of the key activities undertaken to implement and evaluate an effective and interoperable large-scale C-ITS pilot.

**Keywords:** Connected Vehicle · C-ITS · Pilot

## 1 Introduction

Transport Infrastructure Ireland (TII) is implementing a European Commission co-funded national pilot across approximately 355km of the trans-European transport network (TEN-T) that connects Dublin with Cork, Limerick and Northern Ireland. The pilot is delivering 14 C-ITS use cases, representing a mix of Infrastructure-to-Vehicle (I2V) and Vehicle-to-Vehicle (V2V) services, including some urban specific applications in Dublin. The connected vehicle services are being fully integrated into TII's live traffic management system, being one of only a small number of Member States to achieve this. The pilot is currently in its implementation/data acquisition phase, with numbers of participants growing to a target level of approximately 1,500.

A key objective of Ireland's Cooperative Intelligent Transport Systems (C-ITS) pilot project is to understand how road operators can harness a paradigm shift in traffic management operations through increased vehicle connectivity.

There is no tried and tested blueprint to deliver a large-scale national pilot, as every deployment is different, with differing objectives, stakeholder requirements and different operating environments. There are though some principles that are likely to be common to other connected vehicle deployments.

This paper describes the challenges, outcomes and lessons learnt from TII's national connected vehicle pilot that may provide insight to other road operators looking to deliver service improvements by capitalising on an increasingly connected vehicle fleet.

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## 2 System Design, Development and Testing

Prior to receiving Connecting Europe Facility (CEF) funding, a series of overarching pilot objectives were developed focusing on testing, validating and evaluating of a mix of 'day 1' and 'day 1.5' C-ITS services via ITS-G5 and cellular networks, to understand the impact of C-ITS operations from technological, safety, traffic efficiency, environment and compliance perspectives. The C-ITS services selected for implementation have the potential to support TII deliver specific policy objectives (e.g., support progress towards vision zero) or address location specific issues (e.g., significant adverse weather). The pilot impact evaluation will inform TII on how best to invest in scaling and enhancing C-ITS services.

A robust procurement plan will facilitate efficient and effective pilot delivery. Naturally, existing appropriate routes to market should be explored as they offer significant programme-based advantages. Given the nature of a pilot e.g., emerging standards and specifications, there is a need for contracts to support collaboration between contractors, designers and client to facilitate effective research and development related activities. Furthermore, the contract needs to support efficient change management without undue contractual/commercial negotiations to maintain momentum and avoid unnecessary delays. Consideration should be given to the number of equipment suppliers awarded contracts. Having more than one can support the demonstration of interoperability, reduce the impact of vendor lock-in, provide flexibility in the event of product delays and provide competition to drive improved value for money.

The specifications for the core components to implement C-ITS pilot were based on a number of inputs, including C-Roads specifications, C-ITS standards, regulations, policies and guidance from other pilots. The core system components are set out below along with key considerations for what should be included in their specification.

**Central C-ITS station** (C-ITS-S) –acts as the central control centre for I2V C-ITS services. A large-scale pilot will likely necessitate integrating C-ITS-S with the traffic management system (TMS) for traffic management data. The C-ITS-S relies on data from the TMS for generating C-ITS messages for implementing I2V C-ITS use cases. Further, the generation of C-ITS messages will require more data than the data currently provided by the TMS. Since there was no one-to-one mapping between the TMS data (e.g. incidents records, response plans etc.) and the data required for C-ITS uses cases, operational policies were defined together with appropriate tools for providing required data to the C-ITS-S for implementing the I2V use cases. Also, there is no standard for a common communication interface between the C-ITS-S and the field devices – for this, an Apache Pulsar based pub-sub messaging system was defined for procurement and implementation. This pub-sub messaging system was also used to deliver C-ITS services to road users via cellular networks.

**Roadside C-ITS stations** – the C-Roads Ireland pilot has equipped approximately 60km of motorway network (M50 and a southern section of the M1) with ITS-G5 roadside C-ITS stations, known as roadside units (RSUs). The rest of the pilot routes are served with cellular network coverage only. A specification for the supply, installation, testing and maintenance of RSUs was prepared. A C-Roads roadside system profile specification was used for ITS-G5 communication and security requirements. In addition, the RSUs were required to use the Apache Pulsar based pub-sub messaging system

for communication with the C-ITS-S. Locations for RSU installation were chosen based on site survey and radio coverage modelling. Site selection considered a range of technical and practical factors, including radio parameters, key physical barriers for radio signal propagation, access to power, access to motorway telecommunications network for backhaul communication and location of safety barriers. The radio modelling work helped to reduce the number of sites required for continuous ITS-G5 signal coverage along 60km of the pilot routes from an initial estimate of 108 to 74 - delivering significant cost saving for the pilot.

**Vehicle C-ITS stations** – the C-Roads Ireland pilot required a mixture of participants equipped with OBUs and bespoke C-ITS smartphone apps. OBUs with hybrid communication (i.e., ITS-G5 plus cellular) capability were procured. The specifications covered equipment supply, their installation, testing, maintenance, as well as use case application software development. C-ITS smartphone app development for the required use cases was also specified. The OBU and smartphone app specifications also included the interface to the C-ITS-S for C-ITS services via cellular/IP networks. The OBUs and smartphone app were required to log all application data exchanged with other C-ITS stations and upload the log data to a central data storage for evaluation.

After contracts were awarded, an extended period of design development with the appointed contractors was necessary to: 1) understand the maturity/level of compliance of each of the C-ITS key system components; 2) set out the necessary tasks to achieve compliance or, where necessary, to develop alternative solutions; 3) identify the steps to develop the necessary interfaces between system components; and 4) prepare an outline testing strategy including end to end integration of all system components.

The testing strategy involved individual functionality testing and validation of each C-ITS system component. A cycle of 'define-develop-test' was followed until the expected level of performance was achieved. As a result of testing, new or modified requirements were added to meet the expected performance. Should new requirements impact the interoperability of the equipment/functionalities/services the change needs to be aligned across the end-to-end chain – this requires close collaboration between contractors and the client representatives throughout all the stages of the pilot.

The system also enabled use cases to be operated based on simulated events, thereby providing greater flexibility to evaluate certain use cases that operationally would have been challenging, e.g. emergency electronic brake light.

## 3 Evaluation

A series of evaluation questions were developed covering a range of technical (e.g. system performance etc.) and impact related aspects of C-ITS (quantitative and qualitative assessment as a result of behaviour change). These questions sought to clarify a wide range of C-ITS uncertainties through the course of the pilot. The data required to answer these questions was identified, along with key performance indicators, e.g. vehicle speed, acceleration/deceleration, location.

Understanding desired outcomes and data specifics at the beginning of the pilot enables evaluation requirements to be incorporated into the relevant specifications, e.g. specific data capture or, the ability to administer HMI 'off' or 'on' conditions for the comparison of 'baseline' and 'treatment' data.

A key part of the evaluation was to help understand how effective C-ITS might be in reducing collisions, improving journey times and cutting carbon emissions. The design of the pilot focused on developing systems and tools to answer these evaluation questions, e.g., the GDPR implications of the type of data needed will affect system design decisions (outlined in the data management section) and how the data analyst may want to process data to understand how a driver changes their behaviour based on receiving C-ITS information. In addition, microsimulation traffic modelling tools can be used to understand the impact of C-ITS at different levels of market penetration. Ireland has developed a model to assess the impact of a number of use cases. It is planned to refine the driver behaviour parameters within the model, based on empirical evidence gained from field data, to provide extra confidence in the results.

University College Cork and South East Technological University are providing expertise in supporting some of the more technical, research orientated evaluation questions on communications performance and data security and privacy. Engaging with these academic institutions to advance areas of research will fill gaps in understanding and help inform TII when considering communication infrastructure performance and scalability, as well as identifying their role supporting safe and secure data exchange.

## 4 Legal and Ethical

Central to the success of any pilot is the effective management of ethical and legal issues, encompassing, data governance, GDPR compliance, equipment certification, equipment installation liabilities, legal disclaimers and insurance related matters.

Setting out the risks associated with implementing the pilot is key to progressing and informing discussions with stakeholders such as TII's insurance and legal representatives. To that end, a *Safety plan* was prepared, informed by relevant TII publications, standards, and other C-Roads tried and tested approaches to safety risk assessment. The plan included a range of measures to reduce the risks associated with trialing C-ITS technology on public roads to as low as reasonably practicable.

The early identification of evaluation data requirements supported the development of a data protection impact assessment (DPIA) and a range of measures to facilitate a GDPR compliant pilot. Appropriate lawful bases were identified for the processing of personal data and advice from lawyers and insurance professionals identified relevant risks and appropriate mitigation measures for the project team to implement.

To address specific equipment installation and participant related liabilities, a range of assessments were undertaken. Firstly, to assess whether the various contracts in place with the providers of OBUs and the entity installing the OBUs were robust (i.e. did the contracts have appropriate clauses and warranties around performing services with reasonable skill and care, products supplied are fit for purpose and that they require the contractors to maintain and evidence appropriate insurances etc.). Followed by an assessment of whether participants using the OBU/HMI or the smartphone app could sign a legal disclaimer of the type usually used by similar apps such as Waze/GoogleMaps. Finally, an assessment of whether participants having an OBU installed in the car have: 1) signed a consent form acknowledging such installation and accepting any associated risks; and 2) notified their own insurers that the OBU is installed to ensure that the participant's insurance is still valid and not affected by the addition to the vehicle.

Participants were required to give their consent to the processing of personal data and accept a set of terms and conditions that encompassed all of the above in order for them to be eligible to participate.

## 5 Data Management

An understanding of what data is needed, and its sensitivities should be established as soon as possible. The identification of data requirements to answer the evaluation questions provided a good initial steer. As personal data was needed, it was necessary to prepare a DPIA. The DPIA described a process to identify risks of processing personal data and to minimise these risks as far and as early as possible.

It was necessary to identify the legal basis for the processing of personal data and to understand any secondary implications e.g. as consent was part of the legal basis, then the system needed to be able to handle the identification and selection of an individual's data should they want access or delete it if they wish to withdraw from the pilot.

Developing a system that you want to learn from as part of a monitoring and evaluation campaign, imposes new data management/handling functionality on systems and processes that typically providers of operational systems do not provide. System providers naturally want to limit the collection of personal data and the overhead associated with its storage. Managing this tension was key to enabling a robust evaluation.

Two different data platforms were developed to support the Irish national pilot. One to manage the administrative side of pilot participation and the other to store log data to enable the data analysis to pilot operations and answer evaluation questions.

## 6 Pilot Participants

Two types of participants were involved: 1) contractors and design team members to support the testing of C-ITS system by performing a series of on-road drive tests; and 2) a representative mix of road users from the public to measure the impact of the pilot and to determine how effective connected vehicle services are in terms of improving safety, traffic efficiency and reducing carbon emissions.

A social research company was appointed to assist with the marketing, advertisement and recruitment of members of the public to participate in the pilot. A questionnaire was designed to identify eligible participants based on a range of criteria, such as journey frequency (regular journeys on the TEN-T network), demographic (representative range of age groups), gender, work status etc., vehicle type (representative vehicle mix), geographic spread (where RSUs are deployed and where there will likely be a prevalence of C-ITS events). In addition, the participants' preferred device type, i.e. OBU or smartphone was ascertained.

Recruited participants had to complete a registration process, administered through a web platform. This entailed reviewing information on what to expect, key safety related information, OBU/smartphone app user guides, consent agreement, data protection notice and TII's terms and conditions. The last mandatory step in the registration process was to complete a user acceptability questionnaire. To maintain participants' cooperation during the data acquisition phase (up to 12 months) and maximise data

collection for evaluation purposes, participants were given the opportunity to opt into a points-based reward program. The program was developed to maintain participation without encouraging additional journeys.

## 7 Managing Unforeseen Challenges

Throughout the preparing stages of this pilot, there have been many unforeseen challenges. Perhaps most notably was the complexity associated with integrating C-ITS into a live traffic management environment and the level of testing required. From a pure pilot perspective the level of testing was disproportionate to the scale at which services were deployed and the very nature of a pilot – to learn from its implementation, make refinements and redeploy. However, from a live traffic management operations perspective, with C-ITS being integrated, it was treated as a full operational system and underwent a commensurate level of testing.

Another unforeseen challenge was the need to support a change in thinking from a road operators perspective, from how traditional ITS schemes inform drivers, i.e. fixed information points on the network (gantry locations, VMS sites) providing limited information on speed, lane closures, VMS free text, to C-ITS, which is event based, that is to say that wherever an event occurs on the network, provided it is identified, advance information can be provided to the driver at any point on the network. And that C-ITS is not about mirroring extant settings on VMS and message displays on gantries, whilst there are use cases capable of achieving this (a short-term fix), the notion of C-ITS should not be limited based on where roadside infrastructure is currently installed.

Lastly, there was an unforeseen challenge in harmonizing in-vehicle service presentation with road-side message displays. Service presentation is outside the scope of C-Roads, as it is typically left to service providers and OEMs. However, TII were keen to harmonise C-ITS displays with roadside signage to provide a consistent experience for users and to minimise any perceived confusion for drivers. To achieve this, contactors changed pictograms from signs defined in the Vienna Convention on Road Signs and Signals to Irish specific pictograms based on the Irish Road Signs Manual.

## 8 Conclusions

This paper has described how TII has implemented a large scale national pilot, including lessons learned, guidance and considerations that may offer some valuable insight to other operators looking to implement something similar.

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# Developing EU-CEM: A Common Evaluation Methodology for Evaluating Co-operative, Connected and Automated Mobility

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**Abstract.** Co-operative, Connected and Automated Mobility (CCAM) is of increasing interest to the transport community across the world, though is still maturing. The Horizon Europe project FAME is developing a European framework for testing CCAM on public roads. As part of this, a common evaluation methodology (EU-CEM) is being developed, which provides guidance on how to set up and carry out an evaluation or assessment of direct and indirect impacts of CCAM solutions on different user groups and wider society. Objectives include ensuring that evaluations can be complementary planned with results that are easy to compare, as well as establishing a common vocabulary to support projects in the CCAM community. This paper sets out how the EU-CEM is being developed and embedded into CCAM research in Europe, with a particular emphasis on how the project has adopted an agile and iterative approach to the CEM development alongside meaningful and sustained engagement with stakeholders.

**Keywords:** CCAM · Evaluation · Impact Assessment

## 1 Introduction

In a world of increasing digitalisation and connectivity our transport systems are undergoing dynamic change. Currently in its early stages as a viable transport option, Co-operative, Connected and Automated Mobility (CCAM) is considered by many to offer opportunities for a safer, more efficient and more equitable alternative to conventional modes. However, without large scale deployment, there is a lack in empirical evidence from impact assessment and evaluation studies to support these claims.

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The EU introduced their Cooperative Intelligent Transport Systems (C-ITS) strategy in 2016 [1], which set out their goals towards deployment and regulation of CCAM. This was followed in 2018 by a strengthened commitment to CCAM through a strategy for mobility of the future [2], where a role of CCAM in shaping the future of transport is recognized alongside a vision to be world-leader in CCAM deployment through an ambitous research and innovation programme and development of a legal framework. Part of this was a commitment to establish a single EU-wide platform to coordinate testing and deployment of CCAM. The 2020 Sustainable and Smart Mobility Strategy [3] made a policy ambition of large scale CCAM deployment by 2030. Set within this landscape, the Horizon Europe programme has funded the FAME [4] project to establish a European framework for the testing of CCAM on public roads. Building on the previous projects ARCADE (2018–2022) [5], CARTRE (2016–19) [6], VRA (2013–16) [7] and the three FOT-Net projects (2008–2016) 8], FAME will develop tools to facilitate collaboration between CCAM stakeholders.

In this paper we will present one component of this, the development of a European Common Evaluation Methodology (EU-CEM) that provides guidance on how to set up and carry out an evaluation or assessment of direct and indirect impacts of CCAM solutions on different user groups and wider society.

## 2 Background

The EU-CEM builds on experience from the widely adopted FESTA methodology for Field Operational Tests (FOTs) [9], which has been successfully used in large-scale European and national projects. However, FESTA has recognised gaps with specific research boundaries when it comes to CCAM, such as achieving a realistic user experience with prototype vehicles, agreed principles for data-sharing, adaptation to local circumstances of pilot sites and standardised future scenarios. FESTA was originally developed for evaluating driver support systems and other intelligent in-vehicle systems that were relatively mature prototypes, providing well-defined functions. CCAM systems and services that are tested in CCAM projects are far more wide-ranging, and often still quite experimental. Automation is often not limited to a specific set of driving tasks but can take over large parts of these tasks or even completely. Also, CCAM is not only related to vehicles but also services making use of the vehicle to be evaluated.

Automation in road transport will have wide-ranging implications. FESTA addresses impact assessment in the areas of safety, efficiency, environment, mobility, safety and user uptake. However, CCAM may have far wider impacts, not only on the traffic system and scope of impacts but also on society and liveability of cities and regions. The traditional impact areas are no longer sufficient for determining the full impact of road automation. The Impact Assessment Subgroup of Trilateral Working Group of Automation in Road Transportation[1] identified direct impact areas as safety, vehicle operations, energy/emissions and personal mobility, and as indirect areas network efficiency, travel behavior, public health, infrastructure and land use, and socio-economic impacts. These indirect impacts on societal level are difficult to establish. FOTs and other experiments

[1] The group is an initiative of the European Commission, the United States Department of Transportation and the Japanese Ministry of Transportation.

provide important information of driving behaviours but these are usually not sufficient to determine wider impacts on a societal level. Other data are needed, for example about future demographics, as well as simulations using different penetration rates of CCAM. In consultation with stakeholders and projects in the ARCADE and FAME projects, a wide range of needs for guidance and recommendations on performing studies and impact assessment were identified, which are not provided in the FESTA methodology. In addition, there is a growing need to harmonize (or even standardize) the way in which studies on CCAM are performed in order to get a more nuanced picture on what CCAM will mean for society in the future. This includes having common elements in projects such as vocabulary, key performance indicators, common research questions, and standardized ways of describing scenarios, use cases and Operational Design Domain (ODD).

## 3 Methodology for EU-CEM Development

The overall scope of the EU-CEM is to provide guidelines and share best practices for planning, conducting and reporting of CCAM evaluation, especially impact assessment. The EU-CEM will be written down in the form of a handbook. It will provide a complete plan that explains what is needed to plan and carry out an evaluation of direct and indirect (wider socio-economic) impacts, and which is firmly anchored on field experiments combined with a wider scope aiming to reflect impacts beyond what can be tested on roads. Guidelines are given on how to conduct impact assessment of (an assumed) mature CCAM technology while the field experiments are done with prototypic systems. An important ingredient of the EU-CEM is a list of commonly used key performance indicators and guidance on how to define these indicators for specific evaluation areas. To complement this, a common vocabulary (taxonomy) of CCAM terms is being developed.

The EU-CEM development commenced in July 2022 and the initial content has been developed iteratively by the project team through a series of workshops and engagement with stakeholders involved in previous and ongoing CCAM projects. As a timely and state-of-the-art tool for CCAM evaluation, the EU-CEM is being developed in line with the following high-level principles:

- **Guiding star.** To provide a common evaluation methodology for all CCAM tests, setting minimum requirements for evaluation.
- **Collaboration.** To provide evaluation guidance inspired by lessons learned and best practices of CCAM tests.
- **Comply-or-explain.** To provide guidance which should be followed by projects, and if that is not possible or desirable projects will be encouraged to provide explanations of the motivation for different choices.
- **Agility.** To provide recommendations to encourage agile ways of working in developing the project evaluation plans.
- **Flexibility.** To provide guidelines allowing for flexibility in adapting the EU-CEM to projects' specific evaluation needs.

The EU-CEM targets large scale projects but can also be applied to smaller studies. The focus will be on:

- Automation of road transport of people and goods, all vehicle types (specifically cars, trucks, shuttles, buses);
- Higher-level driving automation (SAE level 3 and higher), with and without connectivity;
- Use cases on public roads, likely with specified operational design domain (ODD), operating in mixed traffic.

Even if this is the focus, the framework and CEM will cover testing of e.g. safety critical scenarios on test track to supplement the on-road testing, or driving in confined areas, when the automated vehicle interacts with humans or non-automated vehicles.

### 3.1 EU-CEM Taxonomy

To minimise confusion and misunderstandings, a taxonomy was developed. The EU-CEM taxonomy aims to provide a common language set for the EU-CEM develop-ment and in light of this, for the CCAM large-scale piloting, demonstrations and evaluations. To achieve high readability, the taxonomy has been visualised and made navigable with an ontology software. This depicts the multiple relationships between concepts and provides easiness in using the EU-CEM when doing a CCAM evaluation.

### 3.2 EU-CEM Inventory

The goal of the inventory was to provide the CEM chapters with additional input and context which are not easily found in literature. This was done by comparing CCAM evaluations, their approaches, methodologies, best practices and things to avoid. Furthermore, the findings from the inventory highlight the need for a CEM, through examples of knowledge gaps or deviations from initial evaluation plans, which can aid future CCAM evaluations. The inventory is based on four sources;

1. An analysis on 14 recent CCAM evaluations, in which projects were analyzed on (among others) used methodologies, use of research questions and hypotheses, types of use cases, ODDs, impact areas (direct/indirect), etc.
2. Out of the 14 evaluation plans, 7 interviews were organized with the project managers in which further context was gathered, such as best and worst practices.
3. A FAME workshop on methodological challenges and recommendations.
4. An ARCADE gap analysis including a long list of methodological challenges.

### 3.3 EU-CEM Chapters

The EU-CEM is set out in different chapters to guide the project team (especially those responsible for evaluation) through the different phases of carrying out the evaluation of a CCAM large scale demonstration from planning of the proposal to evaluation of the processes and outcomes when the project ends, as set out in Fig. 1.

The proposal preparation phase provides guidelines for the preparation of the project proposal, laying a strong foundation for successful evaluation. It covers the development of the project structure, setting up the project governance as well as scoping and setting up of the evaluation to align with the main aims of the proposed project plan.

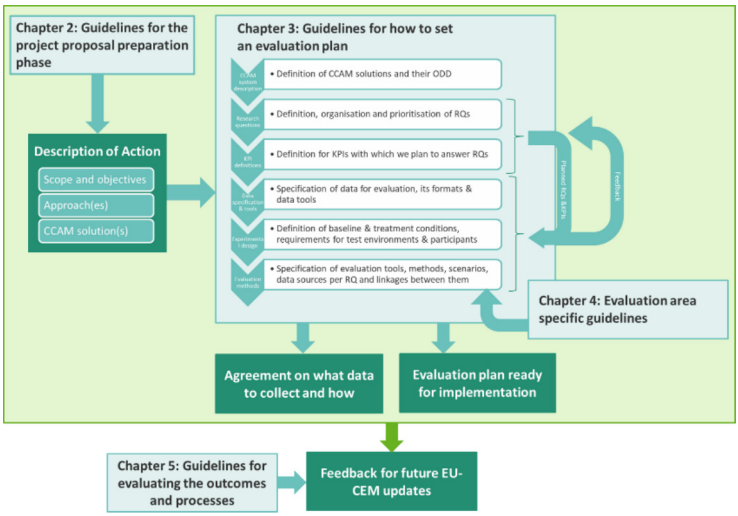



**Fig. 1.** EU-CEM Main Chapters

Detailed planning takes place at the beginning of the project. The EU-CEM provides guidelines for how to set a solid evaluation plan, including the iterative process of setting up research questions, KPIs, data requirements, experimental design and evaluation methods. Once the experiment is set up, the data collection phase can begin following what was agreed on the specification of data collection for evaluation and related tools. If something unexpected happens, the governance structures set to ensure good dialogue within the project allows adaptation of the plans in different work packages affected.

The actual final evaluation phase can occur alongside and/or after data collection. The EU-CEM sets out evaluation area specific guidelines on Vehicle (technical functions, driving behavior), Human (user evaluation, personal mobility, quality of life), traffic and transport (services and operations, good logistics, safety, traffic and network performance, energy and environment) and Society (land use, liveability, equity, growth and employment, socio-economics and sustainability).

After the evaluation has been completed, EU-CEM provides guidelines how to assess the processes and outcomes, and identify new practices for future EU-CEM updates or provide feedback on guidelines that should be modified.

### 3.4 EU-CEM Piloting and Validating

From May 2023, the project team hosts online methodology clinics for CCAM projects on a regular basis. Topics cover the need for new tools and evaluation methods, data communication, standardised KPIs, the difficulties of interdisciplinary comparison stakeholder networks and knowledge co-creation with stakeholders and citizens. The EU-CEM will be piloted and validated through engagement with ongoing CCAM projects. In particular, those involved with evaluation within the projects will be invited to in-person workshops and a summer school to learn how to engage with the EU-CEM,

prior to piloting. Learning from these projects and feedback from the pilots will allow refinement and finalization of the EU-CEM.

## 4 Next Steps

The first full draft of the EU-CEM was completed in early 2024, ready to be validated and piloted in actual CCAM projects that need to prepare for an evaluation or impact assessment. Workshops and a summer school were hosted in early 2024 with these projects to provide guidance in its use. The EU-CEM Handbook for CCAM [10] was finalized in May 2025 and is expected to be used by Horizon Europe CCAM projects.

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# 5G-Based Digital Transformation at SNCF Voyageurs Maintenance Centre

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**Abstract.** The development of broadband connectivity is a key issue, both for industrial activities and for the performance of the service provided to customers by SNCF Voyageurs. It is a major issue in terms of economic performance, sovereignty, confidence, and sustainability. The introduction of high-speed connectivity should revolutionize the activities of rolling stock maintenance centres, with the development of supervision of assets and robotization of process and supervision, in conjunction with BIM (Building Information Modelling) and digital twin technologies.

**Keywords:** 5G · Connectivity · Positioning · Internet of Things · Product Service System · BIM

## 1 Private 5G: A Game Changer for SNCF Industry 4.0 Strategy

### 1.1 SNCF Rolling Stock Maintenance Facilities

The SNCF itself maintains its rolling stock in 9 entities, which carry out complete mid-life refurbishment operations, and 27 centres for routine maintenance ("*Technicentre de maintenance*"), spread across the whole of France (see Fig. 1).

In this context, a consortium formed by SNCF, Fraunhofer, Nokia, CRAN and Evocortex has recently launched 5G-ILABB project (French-German 2022 research call "5G for industry") which is taking place at Bischeim maintenance centre. SNCF addresses renovation and modernisation of the whole stock of high-speed trains in France. Bischheim centre is holding a full digitalisation of its processes at assets by providing the first BIM of the centre (which is 10.000 sqm and 2000 workers on site). Thanks to a private 5G network and 5G-based localisation techniques the consortium will implement concrete applications to the industry 4.0 evolution at SNCF.

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**Fig. 1.** Map of 27 centres for SNCF routine maintenance for TGV and TER. Copyright SNCF Voyageurs, reproduced with permission.

### 1.2 Goals of SNCF "Direction Du Matériel"

The work environment in the rolling stock production and storage facilities is particularly complex, with a typical size in the range of 10 to 30 Ha, concrete and steel buildings, faraday cages, catenaries, and other elements with strong impact on electromagnetic waves. 5G local networks are unprecedented opportunities for the digital transformation on industrial centres. The key points to be addressed are Enhanced connectivity, Real time assets tracking and Automated/Guided intelligent vehicles.

**Enhanced Connectivity.** Performance improvement expectations can be achieved in costs, quality, security of workers, real time monitoring and control, supervision, automation, environmental impact. 5G connectivity is nowadays an emergent solution even though some problems are still to be solved requiring research and development efforts. Testbeds design such as Living Labs 5G project proved the coverage improvement when deploying a 5G network (in N77 and N38 bands) in Rennes industrial centres compared to existing public 5G and WiFi networks.

**Real Time Assets Tracking.** Thanks to the BIM model of Bischheim building coupled with 5G connectivity, real-time tracking and localization can be achieved, thus allowing all employees elsewhere to access actual notifications and command installations remotely.

**Automated/Guided Intelligent Vehicles.** Diverse range of vehicles using 5G connectivity can be included in the maintenance processes to assist the human operations and make their worktime safer when working on big train pieces.

## 2 Technologies for the Digital Transformation

The increase in data acquisition systems presents in industrial environment couple with increase of number of users in a same and wide area need dedicated cellular networks. After 4G, 5G technology allows the industrial clients to build their desired network providing the coverage and functionalities needs.

**Relevant Communication Technologies.** Wireless networks most widely used in industry are currently WiFi, LPWAN (Low Power Wide Area Network as LoraWan, SigFox, NB-IoT) and 4G, each having functional and technological characteristics tailored to different performance requirements in terms of throughput, distance, payload, and energy consumption [2]. 5G which technology is the newcomer in industrial application stands for Fifth Generation Wireless technology initially used for voice and data calls. The initial 5G NR (New Radio) specifications are published by the 3rd Generation Partnership Project consortium (3GPP) in dec. 2017 [3]. 5G is cellular wireless technology like GSM (2G), CDMA (3G) and LTE (Long Term Evolution) (4G) [4].

*5G Networks and Applications.* Currently three types of 5G Networks utilize a wide range of bands from lower bands like 3G and 4G up to very high-frequency bands: Low Band 5G: below 1 GHz, 20% faster than 4G LTE, Mid Band 5G: below 6 GHz, 6 times faster than 4G LTE represents the currently commercial 5G available, and finally High Band 5G: above 6 GHz up to 50 GHz even more hopefully 100 GHz, is 10 times faster than 4G LTE (See Fig. 2). While Sub-6 GHz 5G networks can handle more users than 4G networks, this new technology they do not show substantial speed improvements compared to 4G.

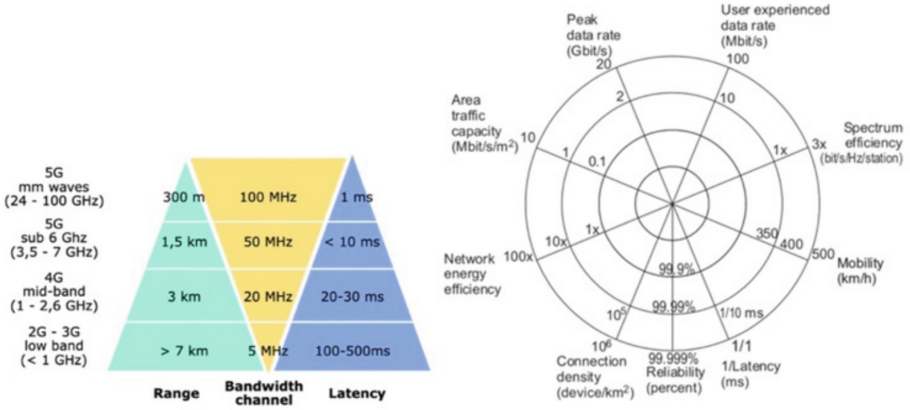



**Fig.2.** 5G technology KPIs, and 2G to 5G Spectrum outlook overview (Source IDTechEx: 5G Technology market and forecast 2022–2032)

High band 5G referred as 5G mm Wave which lives operates between 24 GHz and 100 GHz, has weak penetration and an ultra-short-range characteristics due to its physical and technological limitations. This type of 5G can handle a large chunk of data allowing minimum 1 GBps throughput and should support 20 Gbps downlink and 10 Gbps uplink as claimed by 5G operators [5]. Performances can be affected significantly by doors, windows, walls, trees, vehicles and even humans, so that indoor coverage is a real challenge. Whereas 4G networks require 8 to 10 base stations per km2, 5G networks would need as many as 40–50 base stations per km2.

*5G Networks Profiles and Key Performance Indicators (KPI).* To evaluate the performances of a 5G network, the IUT-R (International Telecommunication Union) a United

Nations specialized agency for information and communication technologies has elaborated 8 KPIs including data rate, energy efficiency, connection density, latency, etc … as shown in the spider graph in Fig. 2. considering that a single 5G cannot performs on all KPIs, there are several 5G network configurations or profiles.

The complete 5G System includes 3 scenarios which refer to different application domains that can leverage on 5G New Radio technology:

- eMBB (enhanced Mobile Broadband) as specified in 3GPP Release 15–2018 for high-bandwidth services for wireless connectivity with peak data rate up to 20 Gbps and high mobility of about 500 km/h.
- URLLC (Ultra Reliable Low Latency Communications) 3GPP Release 16–2020 for ultra-reliable and responsive communication services with air interface latency less than 1 ms, and low to medium data rates (about 50 Kbps to 10 Mbps) for mission-critical needs.
- mMTC (massive Machine Type Communications) 3GPP Release 16–2020 dedicated to secure communication for very high density of devices (billions of devices) about 2 x $10^5$ in $10^6$/$Km^2$, at low data rate (1 to 100 Kbps), so it leverages benefits of ultralow cost of M2M (Machine to Machine communication) to offer up to theoretically 10 years battery life of 5G connected device.

However, full implementation of these three scenarios is not yet possible simultaneously within the same network. A 5G network can only be configured and designed in a way to optimally support one use case. As an example, it can offer either the highest possible data rate or the lowest possible latency. So that achieving both at the same time on the same network is impossible. Finally, 5G technologies promise new opportunities and experiences for industrial applications in diff. Rent situations from device type communication in Internet of Things architecture up to highly mobile broadband communication for high level applications.

**State of the Art of 5G Positioning.** Precise positioning with 5G signals and meter-level positioning accuracy has already been specified by 3GPP in the so-called release 16 in 2020 [6]. Future releases 17 and 18 focus on detailed advancements towards achieving low decimeter-level positioning capabilities [7]. But the maturity of the technology for industrial use is still uncertain, as prototype systems for tests in industrial settings are not available yet [8]. Fraunhofer IIS has therefore created a Proof-of-Concept (PoC) 5G system that allows the early evaluation of real-world 5G positioning applications. During the 5G-ILABB project it will be adapted and extended to test use cases within the environment of SNCF in Bischheim. The goal is to enhance the accuracy and robustness of positioning compared to simple time-of-flight methods by exploiting the channel information of 5G signals by machine learning [9, 10]. In this way precise positioning is even possible in complex industrial environments with multipath propagation of radio signals, including scattering, reflections and blocking of signals.

**Asset Monitoring and Servicing.** Asset monitoring has become a major focus of various industrial sectors to optimize the process flows from accelerating inventories, improving production organization to reducing maintenance costs. By enabling the tracking of physical assets remotely asset monitoring provides real-time asset information on

asset reference, status, performance and sometimes ambient conditions, and obviously precise location. The advent and application of Internet of Things (IoT) concepts and technologies for asset management opens exciting opportunities to optimize equipment efficiency and asset management and tracking. IoT devices are mainly used for data collection and transmission over a wireless network. Further exploitation can be carried out on an IoT device when it is affixed to an asset to perform the calculation of various services embedded on the asset while meeting the requirements of low consumption and small size.

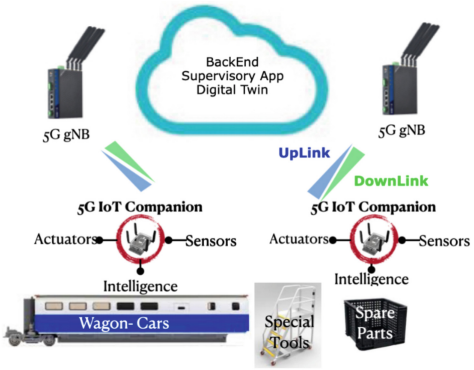



**Fig.3.** 5G IoT-Companion concept for Supervisory, Remote Control and Tracking of Assets. Copyright CRAN-Université de Lorraine, reproduced with permission.

This is the aim of Product-Service System achievement (PSS) in IoT applications, which needs concept and hardware considerations [1]. By associating an industrial asset with an IOT device and leveraging on 5G network functionalities we provide delivery of added values and services linked to the asset and available in real time for all the actors of the process. Figure 3 presents the concept of 5G IoT Companion as a brick for PSS achievement in production and maintenance facilities.

Digitalization of physical assets is a key element of the project with the aim to transform physical industrial assets into seamlessly connected and controllable [device thanks] to 5G networking connectivity, and high-level services with intelligent routines attached to currently passive assets. The project proposal is to design a 5G-based autonomous intelligent device so-called «5G IoT companion» as a generic solution to be linked closely to selected physical industrial assets that are highly relevant to process performance improvement and visibility (e.g., wagon, mover, spare parts bin, special tooling, ladder platform, …). Though according to an IoT approach any physical asset will gain extended capabilities continuously at anytime and anywhere in the plant facility thanks to its personal 5G-IoT Companion. Asset embedded functionalities such as sensing capabilities for environment and status monitoring, for safety and security issues of people and assets, and actuating capabilities for remote control operations, and bidirectional 5G connectivity for data transfer with upper layer will allow advanced remote supervisory and control of physical assets with low latency as expected by 5G networking application. A 5G IoT companion is designed to carry a hierarchical and multi-layer decision-making

model supported by rule-based engine embedded on the device. companion is dedicated to feed high level cloud application with inputs about process situation for data analytics algorithms. moreover, 5G connectivity will provide 5G intrinsic geolocation for precise positioning within the facility.

## 3 Conclusion

The creation of the industrial 5G lab in Bischheim as part of a joint program of the French and German economic ministries, and that of the "Living Lab" in Rennes, have fostered the opening of the first 5G networks in the maintenance centers of SNCF rolling stock, in France. This significantly more efficient connectivity will enable R&D work on the geolocation of assets and their real-time monitoring, with Fraunhofer institute and Université de Lorraine, as well as the implementation of new operational solutions which make these maintenance centers a new kind of innovation labs.

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# Integrated Design Flow Methodology for Open-Source Innovations in Smart Transportation: Empowering Accountable AI and Cybersecurity

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**Abstract.** Spearheading the adoption of trustworthy AI and cyber security across the triad of automotive, transportation, and logistics embark on rigorous evaluations of applications rooted in open hardware/software ecosystems. Open innovations at chip, embedded and/or system level foster research on security-, safety-, privacy-, and accountability-by-design. Cyber-physical system of systems amplifies the fortress of AI-powered solutions and cyber-physical security, with particular emphasis on open-source frameworks. This paper presents an integrated design flow methodology that incorporates chip, embedded and system-level design and development. The proposed methodology is aligned with the recent trends and state-of-the-art dealing with open-source hardware and software development.

**Keywords:** Integrated Circuits (IC) · Trustworthy AI · Accountability · Cyber Security · Smart Transportation · Open Source Innovations

## 1 Introduction

As digital transformation is getting widespread, dependency on Information and Communication Technologies (ICT) has covered a wide range of technological advancements starting from chips to the cyber-physical system (CPS) of the systems level. The automotive, transportation and logistics sectors, as they are getting smarter and more connected, cooperative, and autonomous, cities are evolving to more digitised, AI and IoT-powered. However, this transformation can be blocked due to serious problems like chip shortages, supply chain inefficiencies, multimodal transportation inadequacies, cyber-physical threats, accidents and safety challenges.

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In this technology battlefield, open-source hardware and software (OSH and OSS) innovations present a game-changer strategy to reduce research, development, testing and consequently manufacturing or deploying costs and durations. For instance, RISC-V [1] had been promoted as a free and open-source computer instruction set architecture first introduced in 2010 and it has become a new trend in the open HW domain to develop secure processors and AI-on-chip solutions. Within the scope of emerging needs and trends of the semiconductor industry, the RISC-V open instruction set architecture (ISA) has been well-positioned, as a pioneering open innovation initiative, for the transportation, mobility and automotive market. Similarly, formalizing organizations' approach to OSS management and strategies to increase the uptake of open source tools are increasing to boost the efficiency in development processes and minimize the risks of implementation and dependency on expensive solutions in the market. This paper first aims to present an overview of the current status of the research and innovation strategies, like the European Chips Act, or global OSS strategies led by the Linux Foundation. Then, the paper will introduce a design flow methodology that can be used in CPS design starting from the chip level and covering the embedded level towards the implementation of a system of systems.

## 2 Current Status Update

The projected growth of the global automotive software (SW) and hardware (HW) market is about 6% CAGR from 2019 to 2030 and is expected to reach $460 billion [2]. This is parallel with the rising importance of open-source automotive SW and HW in the overall market. As vehicles become more advanced and integrated, the complexity of the systems involved also increases substantially. Managing this complexity and ensuring the seamless operation of numerous on-board systems, such as electronic control units (ECUs), as well as the transportation/mobility grid infrastructures in premium vehicles is a significant challenge faced by automakers. A well-designed Electrical/Electronic (E/E), or cyber-physical in general, architecture ensures efficient and trusted communication and coordination between different on-board and external systems. This is crucial for the proper functioning of advanced features like autonomous driving capabilities, infotainment systems, safety mechanisms, and recent third-wave AI solutions enabling the trustworthy, efficient and fair use of AI [3].

As evident from the chip shortages and the indispensable side-effects of the COVID19 outbreak, the chip industry has faced with serious problems listed below that cannot be solved by self-contained and private investments of large semiconductor companies: i) Integration and Validation; ii) Budget Allocation; iii) Reliability and Safety; iv) Scalability; v) Cybersecurity and Trustworthiness; vi) Collaboration and Standards. Establishing industry standards, especially for OSS and OSH architecture promotes interoperability and facilitates the development of compatible components and systems. Navigating these challenges requires proactive supporting acts to encourage stakeholders to continuously adapt to new technologies, industry standards, AI-powered smart systems and cybersecurity practices to ensure the seamless integration of SW and HW in modern vehicles and transportation infrastructures. For instance, the European Chips Act [4] identified RISC-V as one of the key disruptive technologies in which Europe

should invest. The RISC-V strategy is expected to be a key market driver for the new generation Integrated Circuits developed for more digitised services in the automotive and logistic domain, i.e., connected and/or autonomous vehicles, communication infrastructures, SW-defined cars, connected and collaborative mobility and smart logistic services enhanced with System-on-Chip. Similarly, formalizing an organization's approach to OSS management, and strategies to increase the uptake generated through open source will most likely boost the efficiency associated with product development. At the same time, it will minimise the risks of locking future developments into specific technologies that are not controlled internally. For example, The European Commission has already adopted the benefits of OSS by approving the OSS Strategy 2020–23 [5].

Although the automotive sector is quite conservative to open-source solutions, a tremendous effort can be observed to utilise the OSH and OSS as evident from the recent advancements in autonomous driving and smart transportation and mobility. Recent approaches orient technology providers to open HW and open-source technologies, for instance, mixed-criticality multi-OS architecture for automotive ECUs [6] or open cooperative driving automation in transportation and mobility [7]. The development of commercial embedded AI and AI accelerators is continuously rising, but in exchange, they are very expensive. On the open-source and affordable HW side, championed by RISC-V, will bring forth a new generation of open-source chipsets designed for specific ML and DL applications at the edge. The High-Performance Embedded Architecture and Compilation (HiPEAC) Vision 2023 [8] report classifies the embedded architecture goals around "the race for" the "next web", AI, sovereignty, and sustainability.

The cyber-physical security is a paramount need in new-generation OSH [9] or OSS [10]. RISC-V-originated HW solutions are still open to HW or architecture-related vulnerabilities. From the HW perspective, the core RISC-V design carries some specific security improvements relative to the long-established ARM RISC design, but is lagging in practical security technique implementations due to its competitive disadvantage in terms of R&D up-front investment compared to, for example, ARM implementations by commercial ARM developers [11]. This relates in particular to an incomplete cryptographic instruction set, access security, HW-assisted security extension units, instruction set architecture security extensions and the memory and side-channel attack protection of silicon implementations of the RISC-V design.

## 3 Proposed Design Flow Methodology

The paramount take-away message of both state-of-play and state-of-the-art is that the design and implementation of a CPS supported with OSS and OSS is based on a complex life cycle. To tackle the challenges addressed in Sect. 2, a three-step agile methodology is proposed for the industry so that the developers can formulate their work and assess and verify the design and implementation steps throughout the development life cycle (As depicted in Fig. 1).

**Step-I: FPGA/ASIC/Hybrid Chip Design:** Since ASIC design itself requires too much effort and time, and might be expensive, FPGA-based design can also be implemented in parallel for IC prototyping. The ASIC design process (digital chip) includes

function description, module division, module code input, module-level simulation verification, system integration, and system simulation verification, synthesis, STA (static timing analysis), formal verification. Similarly, the complete FPGA design process includes functional description, circuit design and input, functional simulation, synthesis optimization, post-synthesis simulation, implementation and placement and routing, timing simulation, board-level simulation, verification, debugging, and loading configuration. FPGA verification is an important part of ASIC design. After that, it is necessary to introduce the ASIC version source code, insert IO PAD, DFT, power consumption estimation, and perform other back-end processes. It can be said that 50–80% of the entire ASIC process is completed by completing FPGA verification.

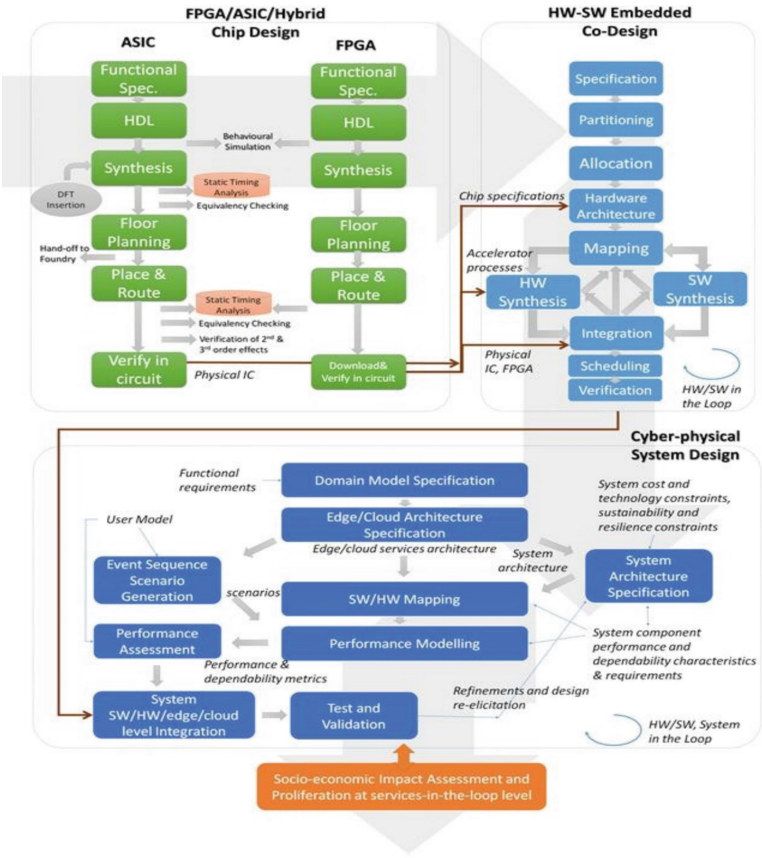



**Fig. 1.** Proposed Design Flow Methodology

**Step-II: HW/SW Embedded Co-Design:** The co-design methodology encounters the following steps to come up with an embedded device (such as telemetry devices, gateways, ECUs, Embedded AI devices, etc.): i) Specification: consists of a collection of metrics, both functional and non-functional, which provide a precise description of

the top-level system attributes and requirements. ii) Partitioning is the action of breaking the system functionality into small domain-independent, concurrent and interacting/communicating processes. Iii) Allocation is the action of assigning each process to either the HW or SW domain. Communication bandwidth alternatives/limitations between HW and SW should be considered. iv) HW Architecture means describing what HW components should be used and how they should be connected to support the execution of the processes. v) Mapping is the selection of specific HW components and mapping the processes onto parts of the HW architecture. vi) Synthesis is the implementation of the HW/SW processes for the selected HW. Vii) Integration is the recombination and testing of processes and interfaces after implementation. Viii) Scheduling is the assignment of resources to all system processes such that their execution requirements are satisfied including interprocess communication dependencies.

**Step-III CPS Design:** This approach is useful to distinguish among a variety of alternatives, both good and bad, assess the impact of architectural choices, predict potential bottlenecks, and size of the HW components, and evaluate if a proposed architecture will meet the performance requirements under the expected workload. The main thrust of this iterative method is to ensure, by successive refinements, that the architecture meets the performance goals set forth in the requirements analysis and specification phase. There are five basic inputs to the method (shown in dark blue) functional requirements, user model, performance requirements, system cost and technology constraints, and system component performance.

The applied methodology considers the following steps: i) Domain model specification is developed to reflect the interaction among the main system components in order to satisfy the functional requirements. ii) Edge/Cloud architecture specification is used to derive a client/server and edge/cloud SW architecture, which depicts the message exchanges between nodes and services in the system. Iii) System architecture specification is used to specify the method, the type, the number of components of each type, and the connectivity used to link them together. iv) Event sequence scenario generation: Event sequence scenarios are created by taking a user model, which provides a detailed description of the user interactions with the system mapping them to the edge/cloud architecture. v) Performance annotation of event sequence scenarios: The event sequence scenarios are further annotated with performance parameters such as request arrival rates, data volumes per request, server processing and I/O requirements per request. vi) HW/SW mapping: The components of the system architecture are assigned performance characteristics (e.g., network segment speeds, router latencies, I/O subsystem bandwidth, processor speeds). Then, the performance annotated scenarios, the HW/SW map, and the system architecture performance characteristics are combined to generate input parameters for a performance model. Vii) Performance modelling: The outputs of the performance model include response times and throughputs for each type of request submitted to the system. An analysis of the results of the performance model reveals the possible bottlenecks. If the architecture does not meet the performance objectives, architectural changes at the HW and/or SW level have to take place. Viii) Integration is implemented and SW, HW, edge/cloud and system level. ix) Test and validation of the CPS take place by checking the performance and dependability metrics.

## 4 Conclusion

This paper presents a three-step design flow methodology that can be used to develop FPGA-level or chip-level HW, embedded devices and system-level solutions for the CPSs specified for the automotive, transportation and logistic systems of systems. The paper emphasizes the uptake of the OSS and OSH to present quick and low-cost AI and cyber security solutions in the targeted domains. The proposed methodology has been conducted in two ongoing European projects, ESCALATE and OPEVA, which address the utilization of heavy-duty and lightweight connected electrical vehicles in intercity or urban logistics and fleet management, respectively. Note that this methodology can be adapted to any CPS. The technical details of this use case are left for further study.

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# Collective Perception Virtual Safety Validation in Urban Environments: Scenarios, Tools, Metrics

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**Abstract.** Collective perception (CP) enables connected and automated vehicles (CAVs) to exchange driving environment perception data in order to improve their on-board perception, essentially creating a redundant 'sensor' for the CAV and extending its (on-board) Field-of-View (FoV). The use of CP for mixed traffic environments that include CAVs requires a thorough evaluation and validation. Due to the CP large-scale field testing infeasibility and based on the ETSI work, most of the previous work on CP has considered large scale-simulations with a focus on connectivity/network aspects. More recently, large-scale collaborative perception synthetic datasets and open source benchmarks have appeared allowing the perception engineers familiar with CARLA to study CP from a perception point of view missing so far. This work reviews recent achievements in this direction to bridge this gap and motivate future research. As a result of this critical state-of-the-art review, we also produce a set of high-level safety validation requirements for CP testing in simulation, by focusing on urban environments, where non-light-of-sight scenarios hinder the traditional on-board perception task.

**Keywords:** collective perception · virtual testing · validation requirements · safety argumentation · V2X communications; CCAM technology

## 1 Introduction

The on-board sensors of connected and automated vehicles (CAVs) are limited by their range and inability to see around corners or blind spots [1]. Collective (or cooperative) perception (CP) is a multi-agent system [2] in which agents share perceptual information such as their state (e.g., vehicle position, pose, speed, acceleration), their tracked object list or even their tracked objects' intentions. CP is currently standardized by the European Telecommunications Standards Institute (ETSI) as a second-generation Vehicle-to-Everything (V2X) communication service. In that context, the CP testing has been studied more as an instantiation of a Vehicular Ad-hoc NETwork (VANET), via a combination of traffic/network simulation environments and targeting at answering questions such as up to how many connected agents per topology, communication protocols, latency and frequency of messages to be broadcasted, without studying the

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collective perception content generation (e.g. fusion techniques) and the assessment of the derived (collective) object detection.

Based on the above, the problem is cast as a multi-agent perception testing problem where the focus is on the shared information content (pre-processed sensor data) and how this is affecting (i.e. what sensory data needs to be shared, at which resolution, etc.) the CP information fusion on the CAV side under the presence of occlusions and sensor measurement uncertainties (uncertainty propagation). CAV control layer, i.e. which cooperative strategies should be implemented are out of scope (for a broader specification of cooperative driving automation goals, see SAE J3216), since the present work focuses only on the perception layer.

Following this trend, the goal of the present analysis is to explore requirements towards building a virtual safety validation framework for urban CP testing, concretely addressing current gaps with respect to (a) metrics for assessing CP from a perception point of view when late fusion is employed, i.e. where detected bounding boxes and confidence scores are shared – following the ETSI CPM formulation, (b) interesting scenarios for (a), and (c) which types of simulation tools are necessary for (a).

## 2 Related Datasets and CP Studies Benchmarks

Several surveys of highly qualified content have been released in the last two years trying to cover the CP task research and development challenges, proving the growing interest of both automated driving (AD) perception and VANETs communities [3–5]. In parallel, two surveys on object-level perception and CP safety assessment [6, 7] have also appeared, inspired by the recent ISO work on SOTIF [8]. Reviewing the aforementioned surveys and some of the works they are including, in the following sub-sections, we highlight certain aspects relevant to our CP testing context.

In recent years, there are many efforts on introducing large-scale CP datasets, for the automotive context, which are mostly generated by simulation and are appropriate for CP modules testing. This advent is partially due to the introduction of and community support for CARLA open source driving simulator [9] which makes easy the generation of virtual sensor data and offers a variety of ground truth data (incl. Instance semantic segmentation data that yields a unique pixel value for every object in a scene and pedestrian skeleton data). In July 2018, version 0.9.0 introduced the multi-client multi-agent support that opened the road for cooperative agents. CARLA supports basic sensor modeling for several sensors such as cameras, depth cameras, LiDAR (simulated ray cast), IMU and RADAR.

CP datasets generated in simulation: The first big contribution was made in 2021 by UCLA Mobility lab with the release of OpenCDA dataset and simulation benchmark [10] which supported testing both on individual autonomy level and traffic level and built a co-simulation platform (CARLA is part of it), a full-stack prototype cooperative driving system, and a scenario manager. OpenCDA also offered benchmark testing scenarios, state-of-the-art benchmark algorithms for all modules of an AD stack, benchmark testing road maps, and benchmark evaluation metrics but focusing on cooperative driving applications and not on CP. It is also noted that type of data exchanged among traffic agents are freely explored and not restricted to the messages already standardized by ETSI.

OpenCDA has grown since then and today it constitutes an Open-source Ecosystem for Cooperative Driving Automation Research with an active community developing part of it around the globe [11]. Two similar efforts followed focusing on multi-agent perception: OPV2V [12] and V2X-Sim [13]. Both datasets provide object-level annotations from CARLA towns in order to support detection, tracking and segmentation perception tasks deploying early fusion/feature-fusion/late-fusion approached for CP content generation. OPV2V is implemented by the COOD framework which supports multi-GPU training and is used by V2VSet [14]. Scenarios supported by all the simulation frameworks above focus on urban, rural and more seldom on highway operational domain and include V2X in straight and curvy urban road segments, urban intersections, rural areas where only V2V applies and highway on-ramp scenarios. The aforementioned CP simulation benchmarks are equipped with RGB cameras and Lidar, allowing the collection of more than 10,000 frames and each scene contains at least 2 vehicles. As discussed in V2XViT [14], in simulation different perception error models can be introduced (pose error, agents' synchronization error, time delay in V2X communication).

CP datasets from real-world recordings (incl. Infrastructure data): DAIR-V2X, OpenDAIR-V2X and soon to be released V2X-Seq [15] are the first real-world datasets for research on V2X AD. It comprises image data and LiDAR point cloud data from different observers. Notably, it supports early fusion and late fusion CP methods while it is planned to also support feature fusion.

Notably, in the initial OpenCDA benchmark, metrics for CAD safety assessment are proposed but metrics focused on CP are missing. Metrics for perception or CP based on sensor data late fusion methods are provided in OpV2V, V2XSim and V2XViT [14] depending on the CP algorithms in use. Still, as argued in [6] metrics and criteria that explicitly distinguish safety-relevant from safety-irrelevant perception errors are still under-explored.

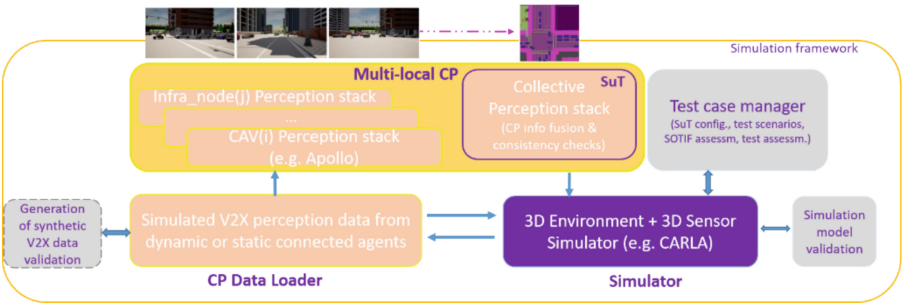



**Fig. 1.** Proposed CP simulation framework conceptual architecture with identified subsystems Images on top are captured from ICCS customized versions of CARLA v0.9.4. CARLA is an open source software available at https://carla.org.

## 3 CP in an AD Scenario-Based Virtual Validation Pipeline

Starting with the three core subsystems, namely the task manager, the simulator and the simulation model validation, identified in the SUNRISE harmonized V&V simulation framework conceptual architecture [16], the System-under-Test (SuT) and problem formulation for the CP assessment task are discussed hereafter with the help of the diagram of Fig. 1.

In our setting, SuT is the local or distributed CP subsystem of the CAV under test as part of two possible CP system configurations, inline with [17]:

a) Multi-local CP system: allows sparsely distributed agents to form a global view on a common spatially distributed problem without any direct access to global knowledge and only based on a combination of locally perceived information. The main question is how to share and to combine the estimated information to achieve the most precise global estimate in the least possible time.
b) Global and Multi-local CP system: allows sparsely distributed agents to form a global view on a common spatially distributed problem based on a combination of locally perceived information and (partially available) global knowledge provided by a monitoring sensor-equipped infrastructure node.Studying CP from a perception point of view implies that the focus is on object detection/data association from multiple observers/scene understanding tasks and that networking aspects can be omitted from the present study for reasons of simplicity (no network co-simulation is employed and ETSI-alike CP messages are assumed available with frequency/delay that can vary and with encoding that can be customized to the perception task in hand). Realistic traffic generation (through a traffic simulator) can be also omitted in the first proof-of-concepts where multi-agent scenarios may include equal or less than 3 virtual traffic agents sharing the same urban area. SOTIF and cybersecurity considerations for CP imply the consideration of perception uncertainty created from information fusion coming from multiple moving observers as well as the consideration of compromised information (by a remote attacker). In current approaches, the CP problem is commonly addressed from the subject vehicle perspective. However, a system of systems approach shall be considered in the near future for holistically tackling CP SoTIF/FuSA aspects.

## 4 CP High-Level Validation Requirements

The goal of this section is to propose high-level validation requirements for urban CP scenario-based testing.

### 4.1 Scenario Generation

Support for multi-agent scenarios is required where mobile and static traffic agents can be a) non-connected, b) connected and transmitting their state information, c) connected and transmitting their state and perception information. For urban complex ODDs, scenarios shall include a sufficiently big number of traffic agents, e.g., vehicles, parked buses and vulnerable road users. Additionally, smart infrastructure nodes with or without sensors should be allowed to be added as static “connectivity” agents.

A small list of urban safety-related test scenarios in three target Operation Domains, namely in urban roads, intersections and roundabouts, are outlined in D7.1 [18].

### 4.2 Metrics and Considerations for CP Evaluation

With respect to object-level CP performance, a set of Key Performance Indicators (KPIs) can be considered such as (a) fused object localization performance, (b) fused object detection performance, (c) fused object classification performance, (d) fused object clutter rate, (e) fusion runtime performance, (f) robustness to perception errors, (g) robustness against CP messages delays. All KPIs shall be measured in various conditions of CAVs/AV penetration rate. Models for object-level perception data uncertainties generated by virtual road agents or infrastructure need to be assessed based on perception error models from real sensors across various environmental conditions.

Extra KPIs for the simulation validity may include correctness of the assumed perception uncertainty/error models. In that regard, a set of KPIs can be used when a real vehicle is part of the simulation scenario (hybrid testing setup) in order (including but not limited) to i) assess runtime capability of the hybrid setup by e.g. measuring the vehicle to simulation environment uni-directional or bi-directional real-time info sharing (ms), and ii) compare synthetic object detection noise in simulation against proving ground tests with a perception platform equipped vehicle.

### 4.3 Test Environment and Tools

Three test environments are considered for CP testing and validation:

Physical testing: Python or ROS modules and custom visualization using ideally real-world data.

Simulation only: all data from all cooperative nodes are simulated. CARLA is a good candidate for the environment/driving simulation as it binds well with external ROS modules that are needed for CP synthetic data generation.

Hybrid setup: a CAV tested physically in a controlled field area that is mapped into CARLA, exchanging real-time data with (cloud) simulation environment (digital twin). Matlab RoadRunner is a good candidate for map and scenario generation.

## 5 Challenges and Conclusions

In the present work collective perception validation challenges were discussed in detail based on comprehensive SoA review. Moreover, a preliminary set of high-level safety validation requirements for collective perception scenario-based testing in simulation is derived, by focusing on urban environments.

Future work will include application of these requirements for assessing a Bayesian-based CP module supporting virtual agents that can exchange ETSI CPM information and corresponding CP system safety validation in CARLA.

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# EALU-AER: Enhanced Automation for U-Space/ATM Integration

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**Abstract.** EALU-AER is a proposed scalable U-Space ecosystem technology infrastructure integration and demonstration project to establish Ireland's first Digital Sky Demonstrator (DSD), enabling the smooth transition towards smart cities and is centered at Future Mobility Campus Ireland's (FMCI) recently established vertiport site, in the vicinity of Shannon Airport, Ireland, therefore inside controlled airspace. The project focusses on deploying a reliable infrastructure, catering U1 and U2 services with higher levels of performance, refinement, and integration to enhanced levels of automated interface with the ATM/ATC, aiming to drive and support U-space regulations and standards development along with global interoperability between Uspace and ATM in a cross-border dimension. This allows for a safe and co-operative integration of zero-emission drones into the airspace that will perform different Urban Air Mobility (UAM) missions. The infrastructure will be facilitated by a mature USpace Services Provider (USSP) platform (WebUAS), a backhaul network for secure data exchange within the ecosystem (ARINC Ground Network (AGN)), Command and Non-payload Communication (CNPC) ground solution (CNPC 5000) and advanced three-dimensional ground surveillance RADAR. The project builds on the reliable integration of these technologies, to provide an autonomous, connected, and collaborative ecosystem ready for U3 and U4 services provision. In this paper, we build the case for the need of such efforts, provide a deep dive into the solution structure the project proposes and describe the operations planned, to validate the system architecture and infrastructure put in place for the same.

**Keywords:** Automation · UAM · ATM/UTM Interoperability · U1/U2 services · Digitalization · Regulation and Standardization

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# 1 Introduction

To unlock the potential of the drone economy and enable urban air mobility (UAM) on a wide scale, a new air traffic management framework for low-altitude operations needs to be put in place. Known as U-space, the framework foresees a set of new services relying on a high level of digitalization and automation of functions and specific procedures designed to support safe, efficient, and secure access to airspace for large numbers of drones. As such, U-space is an enabling framework designed to facilitate any kind of routine mission, in all classes of airspace and all types of environment - even the most congested - while addressing an appropriate interface with manned aviation and air traffic control [1]. This is a key requirement identified and captured under the vision of the Digital European Sky and hence many of the projects in the innovation pipeline of Single European Sky ATM Research (SESAR) have been designed to deliver this ideology at a solution level ready for market, with some project focusing on driving the deliverables to market uptake. To deliver the Digital European Sky, the SESAR research and innovation programme is designed as an innovation pipeline, made up of exploratory research, industrial research and validation, fast-track innovation and uptake, and very largescale demonstrations/demonstrators, where ideas are transformed into tangible solutions [1]. EALU-AER project falls in the category of 'Digital Sky Demonstrators'. Aimed at closing the gap between applied/industrial research and industrialization, the success of these projects will depend on involvement of early movers, while maintaining the solution architecture to be closely tied and aligned with the relevant standardizations and regulatory activity bodies.

The rest of the paper is structured as follows: Sect. 2 focuses on the U-space architecture, its requirements, projected delivery time scale and connection with current regulations and standards in place. Section 3 provides a deep insight into EALUAER, to understand the overall project aim, deliverables and strategy and finally Sect. 4 allows space for remarks.

# 2 U-Space

## 2.1 Introduction

Following on the comments made in Sect. 1, U-space is a set of services and methods designed to ensure safe and efficient access to airspace for many Unmanned Aerial Vehicles (UAV), and which are based on highly of digitalized and automated structures. The purpose of U-space is hence to achieve fully automated UAS management and integration, allowing for a large set of operations, simultaneously on most events, and all of this in harmonious co-existence with the ATM system. The services are also envisioned as a further goal to be modified for and adopted by the ATM ecosystem,

enabling automation and optimization in manned aviation, noting the foreseen increase in flight services demand.

The question then to answer next is what and how are the services expected to be implemented, in terms of performance expectations, workflow setup, integration and interoperability needs and expected outcomes. This was the key aim of the SESAR project, which ran from 2017 – 2019, namely Concept of Operations (ConOps) for

European U-space services (CORUS). Four editions of U-space Concept of Operations document have been produced because of this project, the latest one having been published in 2023, which considers additional Urban Air Mobility (UAM) needs, adjustments to reflect regulatory evolution and incorporation of learnings from various U-space projects commissioned. The European Union regulations, primarily 2021/664, 665 and 666 known as the U-space regulatory framework, sets the minimum requirements for the U-space in terms of seven services, six functional plus "common information."[2].

The document lays out an expected evolution of U-space, as many of the services requirements identified and expected to be fulfilled require technological and infrastructural advancements, that are yet to be achieved. To simplify the discussion around the challenges this rise in traffic will pose, and the solutions that U-space should provide, the CORUS-XUAM project groups the expected traffic evolution into five eras [2].

The "U levels" or "U blocks" as defined in the U-space Blueprint [3] are assumed, as shown in Fig. 1.

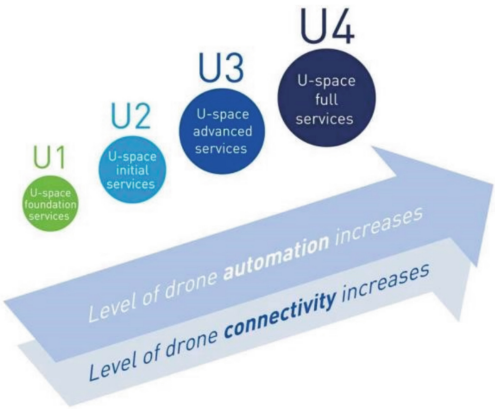



**Fig. 1.** U-space Levels [2]

The idea behind these levels is to divide and set the roadmap of services development, allowing for viable and achievable maturity of a full scale U-space deployment. To briefly summarize each of these stages [2]:

- U1 (Before 2023) - States are setting up registries and defining geographic areas in accordance with the UAS regulatory framework. Drones flights without U-space services. Manual coordination with and authorizations from the involved authorities are usually required. ATC procedures make Visual Line of Sight (VLOS) flights possible, though sometimes requiring some effort. Beyond Visual Line of Sight (BVLOS) flights are limited, time consuming and expensive to set up.
- U2 (2023 – 2030) – EU Regulatory framework has been issued. A minimum set of services, with the expected performance and availability needs, data exchange/report and expected outcome has been defined. Based on these, the services development is except to enhance and evolve, with many of the SESAR project focused on catering

to develop, enhance or validate the provision of these services and set the base ground for U3/U4 deployment.

- U3 (2030 and beyond) – U-space airspaces exists in controlled and uncontrolled airspace. Most drone operations are performed in Very Low Level (VLL) airspace. For UAM use-cases, corridors are defined and declared.
- U4 – Full U-space integration in place. The timing for this level to be reached is difficult to gauge, but the expected outcome is most professional aerial operation are uncrewed and fully utilizing the whole suite of U-space services available. The U-space airspace is widely defined and infrastructure in place is highly automated, integrated, fully operational and scaled to facilitate dynamic and all ranges of U-space flight operations.

The U-space services have hence been classified along these 4 'U-levels', providing a guidance path for industry progression and development to cater to these service requirements. Details of exactly which service falls under which U-level can been found in the CORUS-XUAM ConOps documents. Most of the explanation in this section will be based on the ConOps defined by the document provided in reference [2], as this sets the base strategy of the various exploratory, industrial, and demonstrative projects planned in the U-space domain.

### 2.2 EU Regulatory Framework

This section aims to highlight the regulations that have been put in place by the EU, to provide structure and guidance as governments, Air Navigation Service Providers (ANSP), Aviation authorities, airports and private entities work together on implementing viable, scalable, and commercial solutions in place for the U-space economy.

The Commission Implementing Regulation (EU) 2021/664 of April 22, 2021 was published on April 23 2021, on a regulatory framework for U-Space that will allow the start of the U2 phase of provision of services with drones within the U -Space for drones. This regulation represents a great step forward for the development of UAVs "U-space is a way of responding to the growth of UAV operations in European airspace", adding "A U-space regulation must promise equitable access to operators of unmanned aircraft systems (UAS) to airspace in a gainful way through a competitive.

services market", that is, it is the step towards the widespread usage of drones as one more element of airspace and, consequently, the take-off of this ecosystem. The entry into force of this regulation has resulted in regulatory modifications through Commission Implementing Regulation (EU) 2021/665 of April 22, 2021, which modifies Implementing Regulation (EU) 2017/373 as regards the requirements for air traffic management / air navigation service providers and other functions of the air traffic management network in designated U-Space airspace in controlled airspace and the Implementing Regulation (EU) 2021/666 of the Commission of April 22, 2021 amending Regulation (EU) No. 923/2012 as regards the requirements for manned aviation operating in U-Space airspace. Hence, bearing the concept of EALU-AER in mind, essentially all three regulations are applicable, in terms of ensuring that our solution design and architecture, from a user, services, equipment and data perspective, is well aligned with these.

## 3 EALU-AER

Based on the call objectives and priorities, the project aims to:

- Prove feasibility, reliability and operational efficiency of transport services provided by various Electric Vertical TakeOff/Landing (eVTOL) aircraft for a variety of use cases and applications that range from freight delivery to autonomous air taxis.
- Foster and accelerate the development of autonomous software solutions for the control, monitoring, data gathering/orchestration and overall interaction and safety of eVTOL aircraft.
- Develop, deploy, and continually test/optimize the use of UAM, rural/remote air transport/freight delivery, and systems in support of eVTOL services.
- Develop, deploy, and refine operational systems in general eVTOL-based USSP services across multiple use cases and political jurisdictions.
- Define possible Separation Standards Aircraft and UAVs in Controlled Airspace (CAS) through partnership with Irish ANSP (Air Nav Ireland).

To demonstrate a range of UAM operations, across the range of U-space services projected through the SESAR U-space ConOps, the project will execute several use-cases across the period of the program that capture the operational requirements, vehicle dynamics, and technology demonstrations associated with the projected near-term UAM services market.

Use Case 1 – BVLOS Validation. Supporting technological deployments are as follows; Phase 1 - The first phase per the simplest ConOps defined as a VLOS flight leverages WebUAS connectivity to the ground control station and Shannon air traffic control utilizing the ARINC Global Network Point of Presence (PoP) and Network Monitoring. Phase 2 - The second phase adds Skyler Surveillance and extended line of sight operations.

Use Case 2 – Remote BVLOS. Supporting technological deployments are as follows; Phase 3 - Addition of CNPC C2 ground network and integration of CNPC onto a test platform.

Use Case 3 – Remote BVLOS, Use Case 4 – BVLOS Cross Jurisdiction and Use Case 5 – Remote/Mobile Launch. Supporting technological deployments are as follows; Phase 4 – BVLOS corridors and additional C2 links (i.e., SATCOM) to add robustness through redundant and dissimilar C2 methods.

## 4 Concluding Remarks

Within Ireland, the facilities in FMCI and the program proposed in EALU-AER are a first for the country. The AAM/UAM market, like the rest of the world, is in a start-up or wait and see phase, where new actors are establishing themselves (such as Manna Aero) and large players who may exploit UAM/U-Space (for example FedEx) are exploring the market opportunities through demonstration and collaboration activities. The infrastructure leveraged through the EALU-AER will make the FMCI campus in Shannon a world class facility for testing AAM platforms, testing operating use-cases, evaluating standardization and certification of systems, and catalysing further research and development for U-Space.

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