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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ISSN 2196-5544 ISSN 2196-5552 (electronic)
Lecture Notes in Mobility
ISBN 978-3-032-06762-3 ISBN 978-3-032-06763-0 (eBook)
https://doi.org/10.1007/978-3-032-06763-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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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Contents

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 3–12, 2026.
https://doi.org/10.1007/978-3-032-06763-0_1

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).

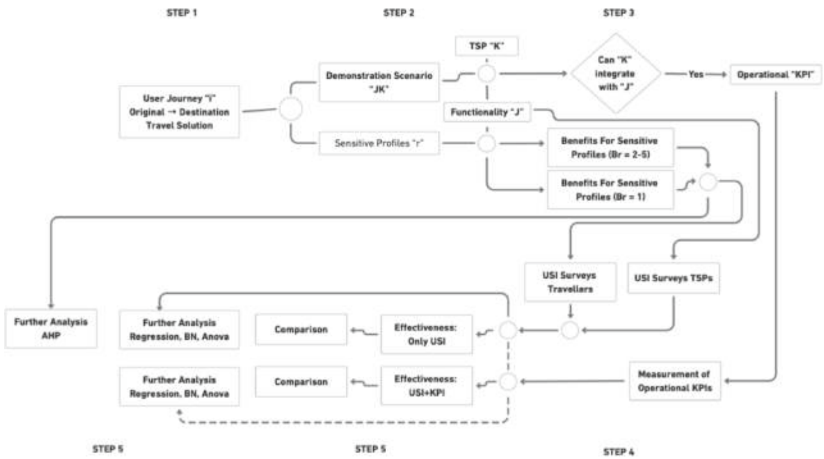

Fig. 1. General lighthouse methodology for the assessment of IP4 innovations.

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:

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

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 15th to 19th 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.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 13–19, 2026.
https://doi.org/10.1007/978-3-032-06763-0_2

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.

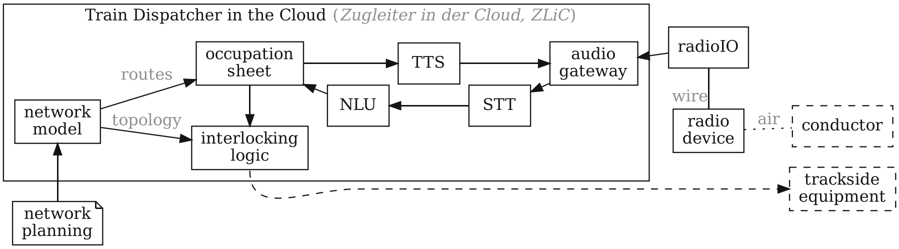

Fig. 1. ZLiC central (large box), distributed, input, and related (dashed) components.

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.

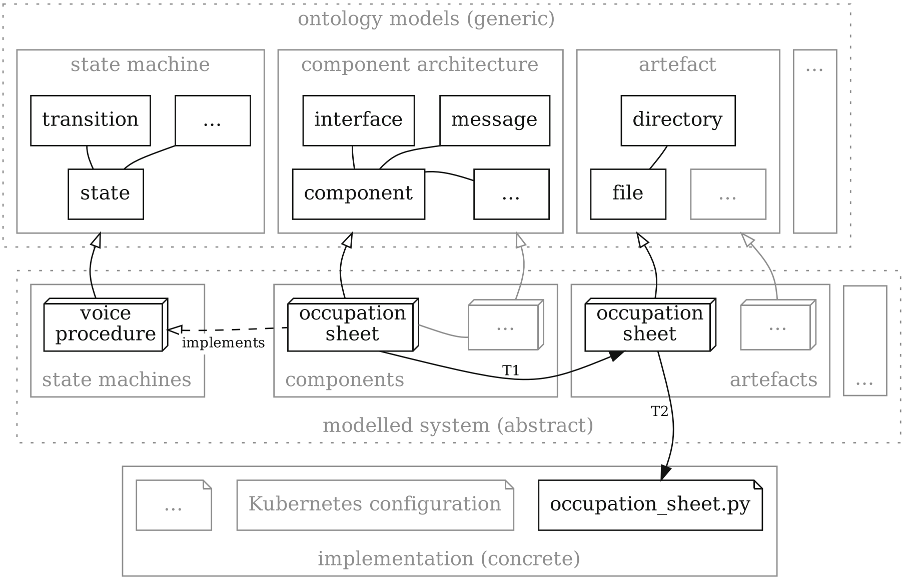

Fig. 2. Exemplified and simplified path from the modelled system to the implementation. All models relate to the ontology. `T*` represent some implemented transformations.

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).

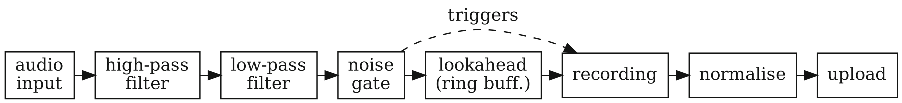

Fig. 3. Processing chain for automatically forwarding audio from the radio to the ZLiC.

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,

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 20–26, 2026.
https://doi.org/10.1007/978-3-032-06763-0_3

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 • 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 • Flexible use of track • Overtaking is more feasible, assisted by trains running closer together	Allocate buffer time and extra running time where needed, squeeze trains together where possible Case specific calculations for every train Use the flexible working opportunity
Automated operational control means:	
• ATO precisely controls train's trajectory • 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.

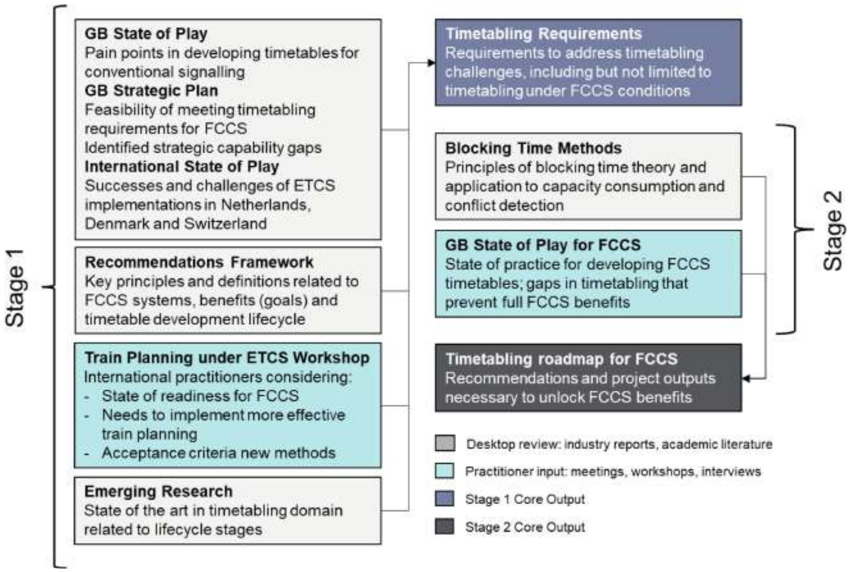

Fig. 1. Summary of Timetabling Project

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.

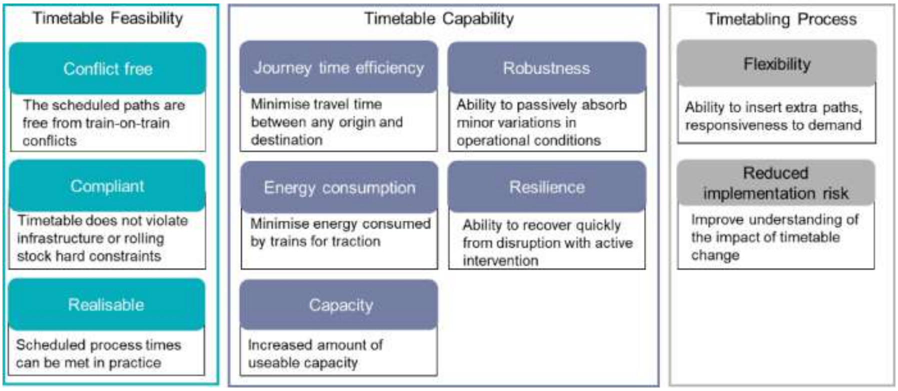

Fig. 2. Timetabling goals, their definitions and categorisations

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.

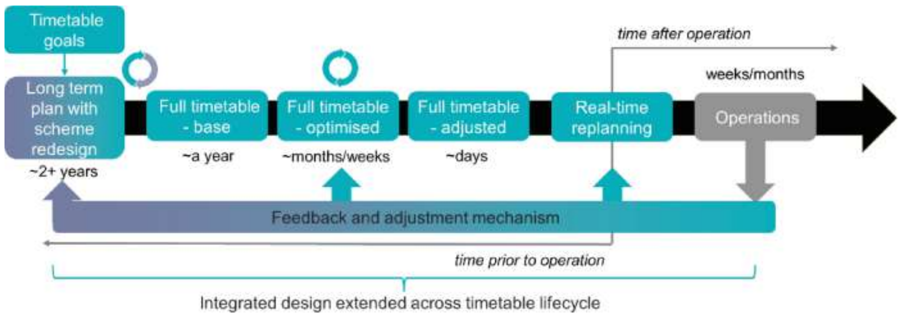

Fig. 3. Future Timetabling lifecycle

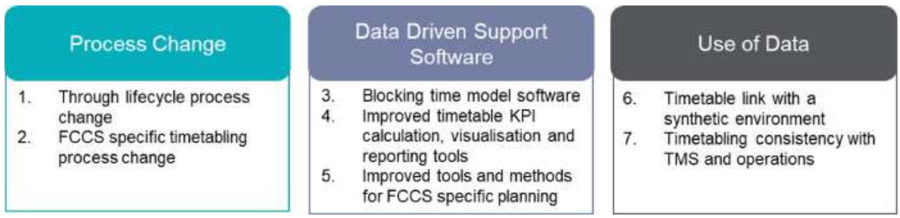

Fig. 4. Outputs from the project recommendations

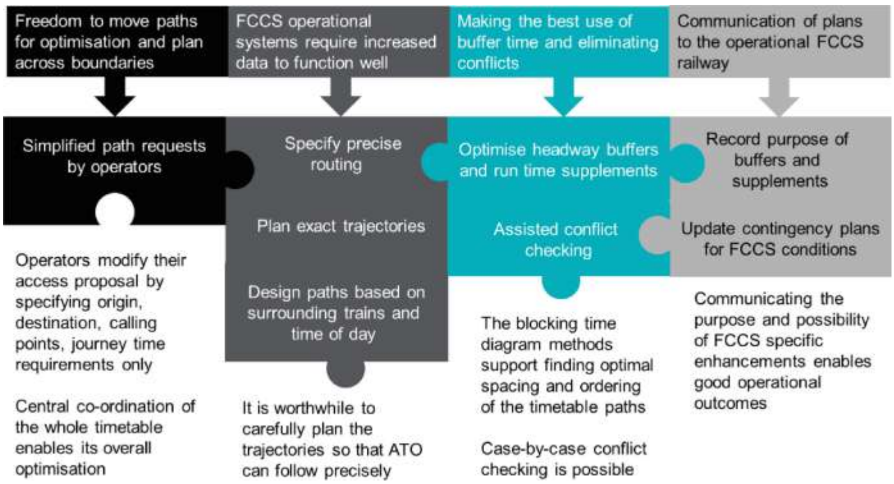

Fig. 5. Making effective use of FCCS data for train planning

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.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 27–33, 2026.
https://doi.org/10.1007/978-3-032-06763-0_4

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)

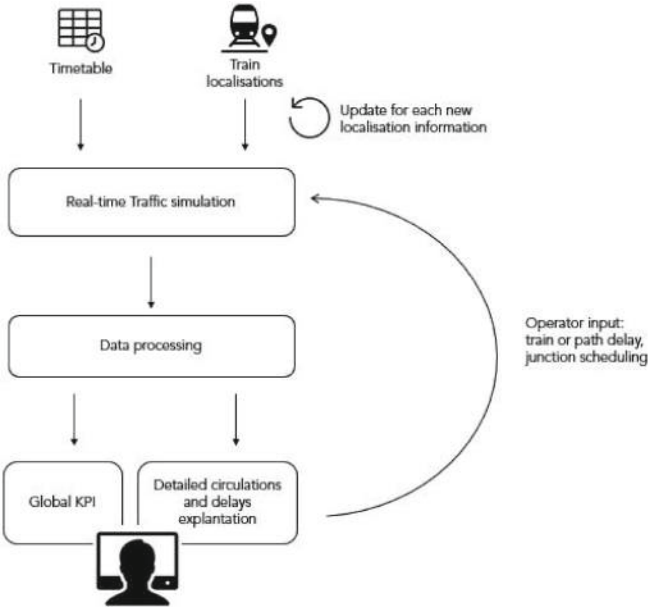

Fig. 1. Software architecture

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

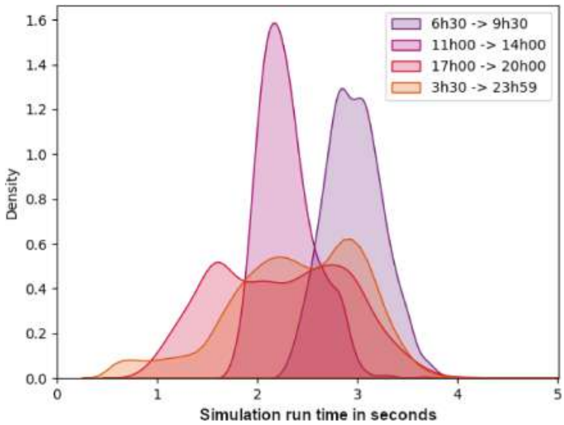

Fig. 2. Computation times of Allié Supervision on the COS SE perimeter by specific hour ranges

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.

Acknowledgements. This project was co-financed by SNCF DTIPG and TGV-Intercités. The authors thank the TGV agents at COS Est and COS Sud-Est for their time and constructive feedback on the prototype.

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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.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 34–40, 2026.
https://doi.org/10.1007/978-3-032-06763-0_5

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

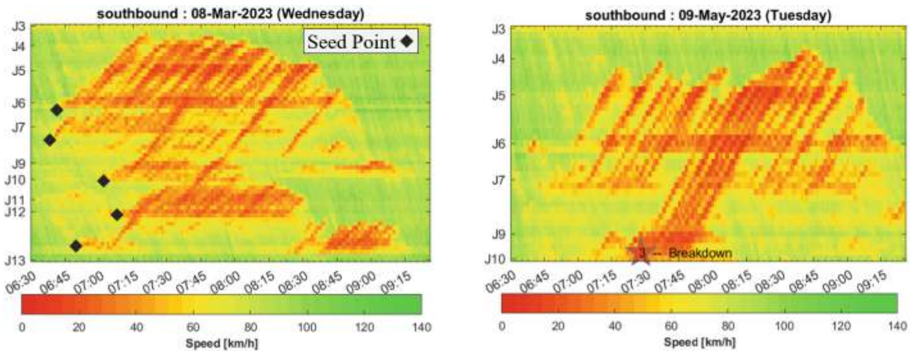
2.1 Overview of Measured Data Sources

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.



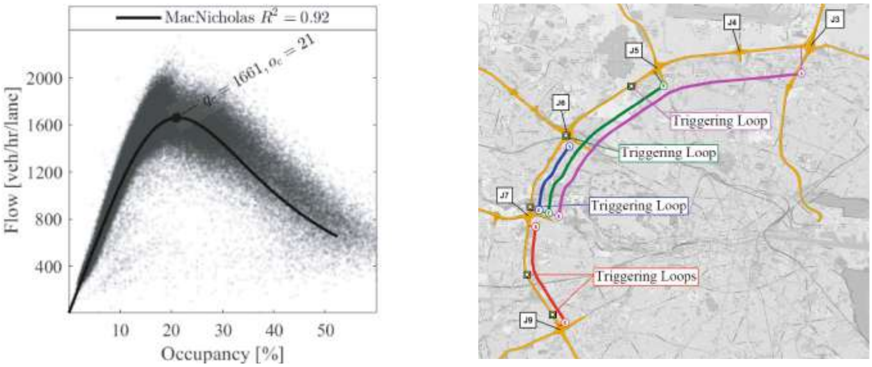
(a) (b)

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].



(a) (b)

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.

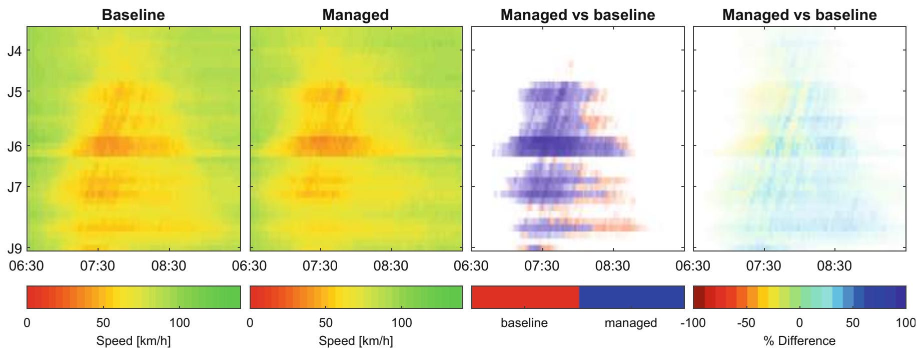


Fig. 4. Heatmaps showing changes in congestion patterns when proactive speed management plans ('Managed') were active compared to 'Baseline' traffic conditions. Image produced using MATLAB [6].

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 Green Deal and the Vision Zero. Hence, acknowledging both past and present R&I activities is key for the development of new technologies and strategies.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 41–46, 2026.
https://doi.org/10.1007/978-3-032-06763-0_6

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.

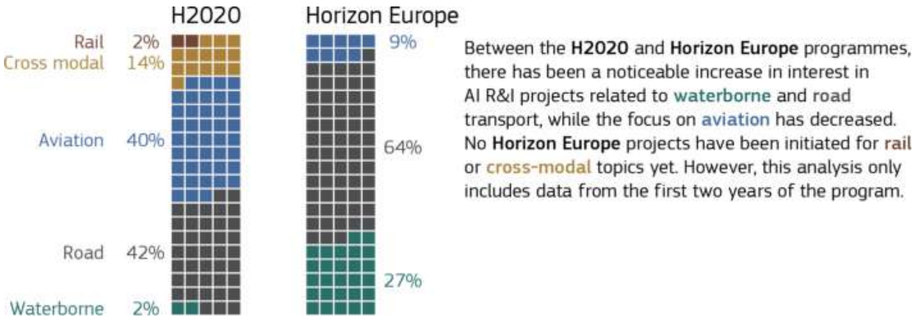

Fig. 1. R&I projects implementing AI in modes of transport in H2020 and HE

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 47–53, 2026.
https://doi.org/10.1007/978-3-032-06763-0_7

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.

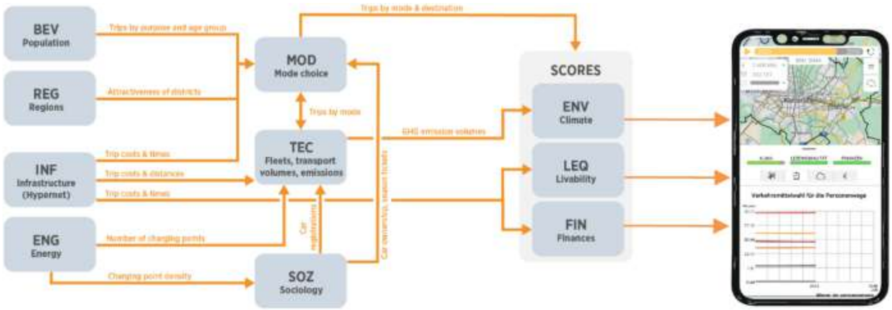

Fig. 1. MobileCity module and data structure

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

Module	Output unit	Scoring principle	Sub-indicators
ENV	t CO_2e 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.

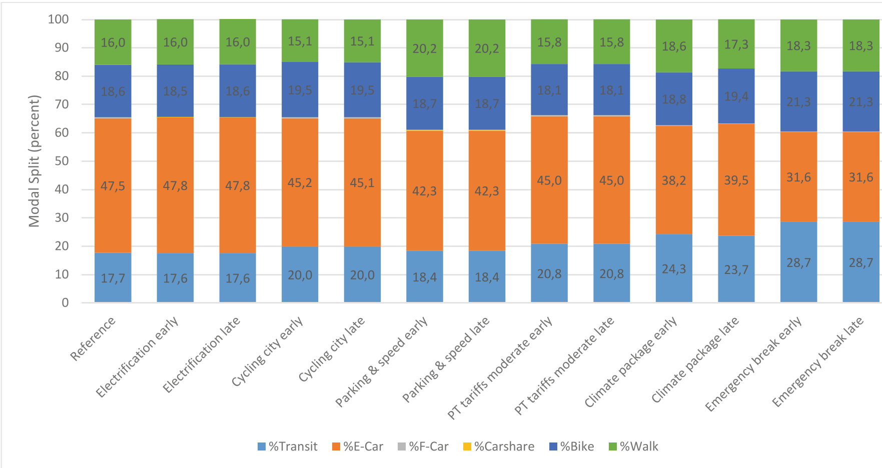

Fig. 2. Modal shares at trips 2050 by bundle

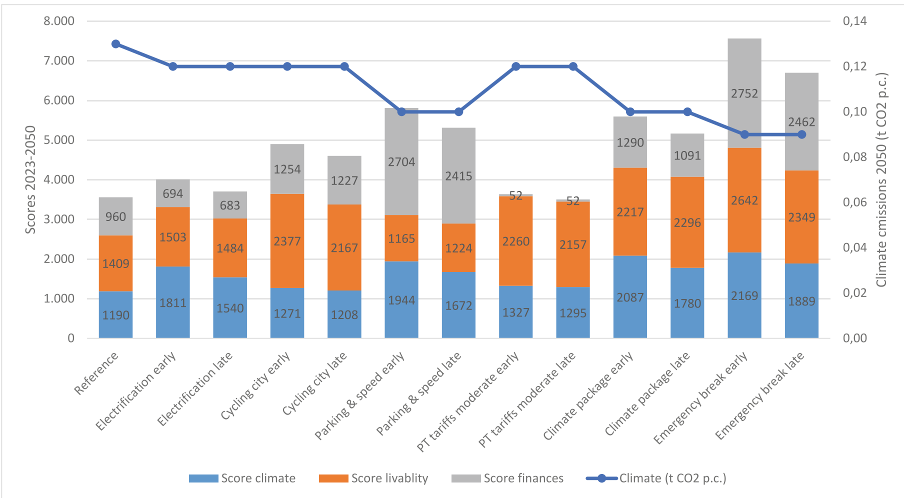

Fig. 3. A Scores 2023–2050 and climate emissions 2050 by bundle

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,

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 54–60, 2026.
https://doi.org/10.1007/978-3-032-06763-0_8

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.

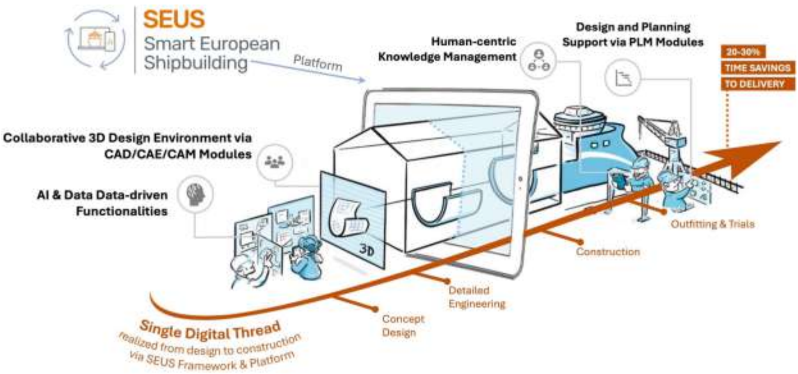

Fig. 1. Potential for lead time reduction in the upstream maritime value chain. Collage produced using Microsoft PowerPoint based on an illustration by Scribey Sense.

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.

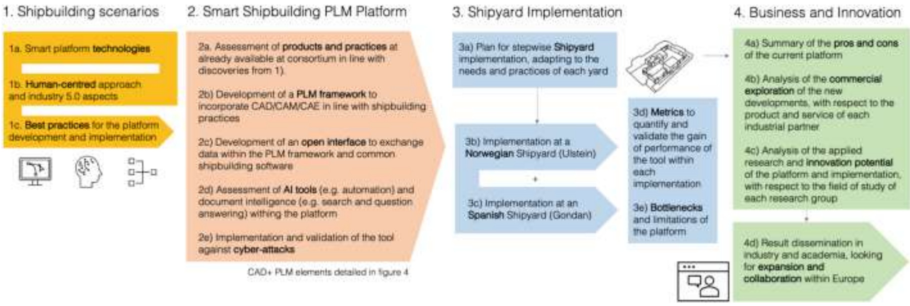

Fig. 2. SEUS methodology overview.

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.

Acknowledgments. An earlier version of this article has been presented at the 22nd Conference on Computer and IT Applications in the Maritime Industries (COMPIT'23), Drübeck, 2023. The

SEUS project has received funding from the Horizon Europe Framework Programme (HORIZON) under grant agreement No 101096224. Info is updated at http://seus-project.eu/.

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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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 61–67, 2026.
https://doi.org/10.1007/978-3-032-06763-0_9

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.

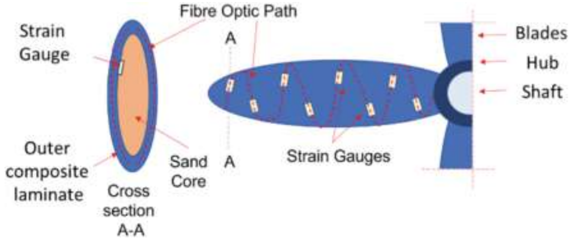


Fig. 1. Schematic of propeller blade construction and sensors (exact installation locations/topology is not final)

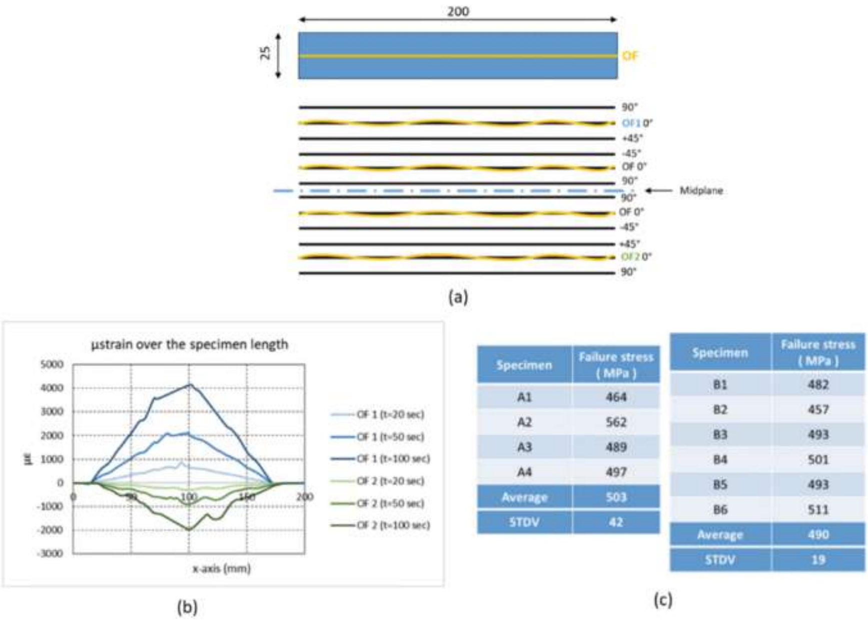
2.1 Fiber Optics Sensor (FOS) System for Strain Sensing

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]

$$\Delta_{\nu} = \mathrm{C}_{\varepsilon} \cdot \Delta_{\varepsilon}, \tag{1}$$

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).

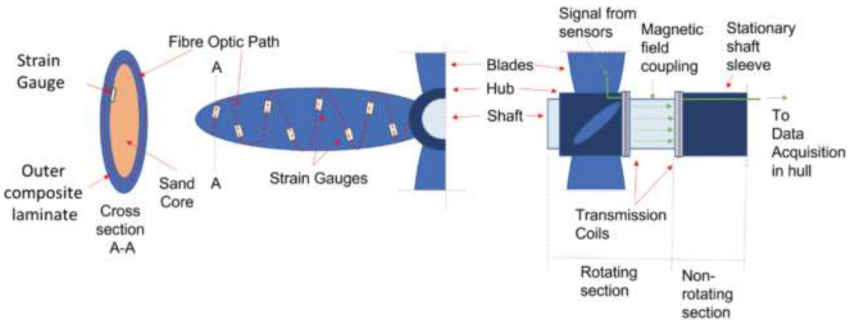


Fig. 3. Schematic of wireless strain gauge system

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.

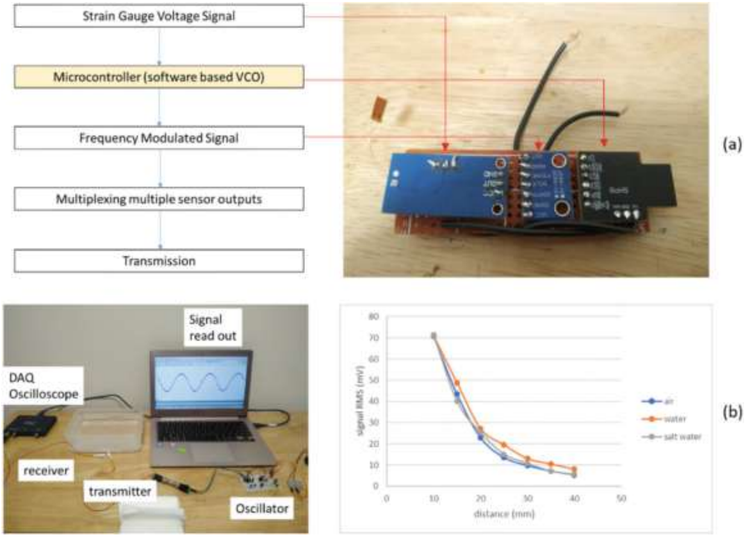


Fig. 4. Wireless strain gauge system: (a) prototype frequency modulation system and (b) preliminary transmission tests in different media

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).

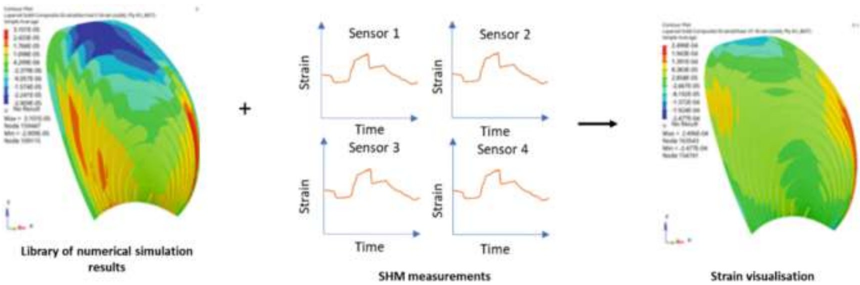


Fig. 5. Concept schematic of multifidelity approach for data visualisation

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 68–74, 2026.
https://doi.org/10.1007/978-3-032-06763-0_10

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 (α_{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

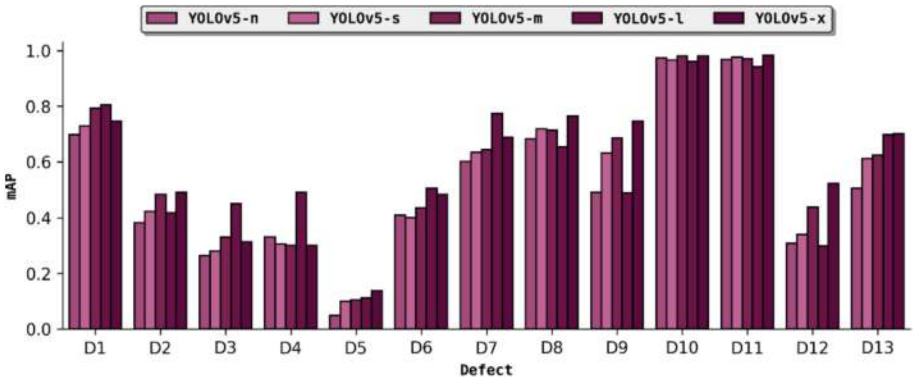

Fig. 1. mAP by road distress type for the different YOLOv5 sub-models.

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.

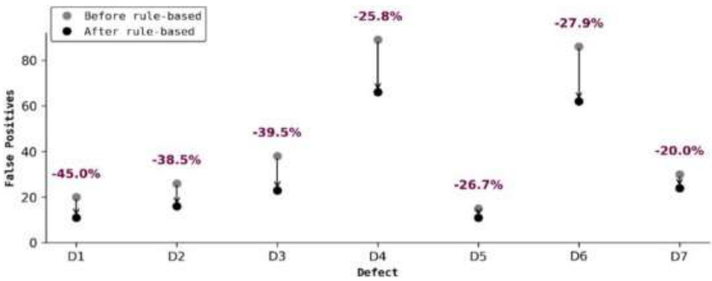

Fig. 2. False positives of YOLOv5-l after and before applying the rule-based filtering.

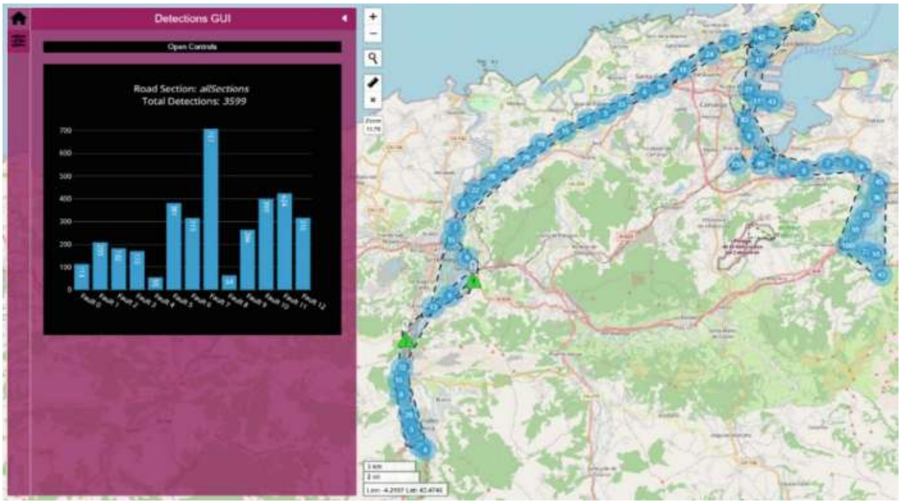

Fig. 3. Distribution of detections by category of defect for the case study and geospatial representation. Image produced using Leaflet.js (JavaScript), an open source software.

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 75–81, 2026.
https://doi.org/10.1007/978-3-032-06763-0_11

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].

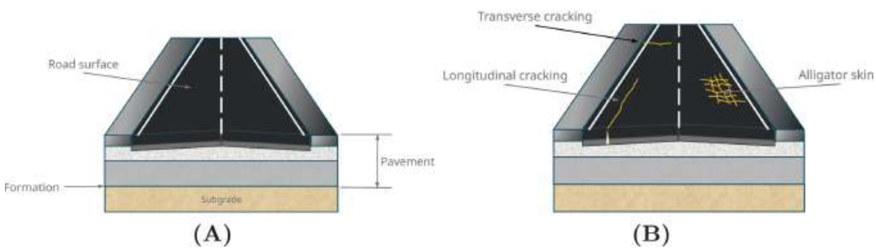

Fig. 1. (A) Schematic of the typical structure of road pavements and (B) different types of cracks. Both images produced using Libreoffice, an open source software.

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.

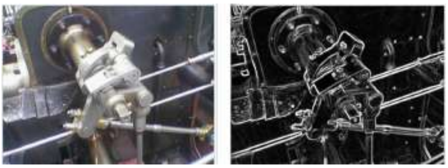

Fig. 2. Example of applying the *Sobel* filter in GIMP—Simpsons contributor, CC BY-SA 3.0, via Wikimedia Commons, 2025 (Valve original (1) & Valve sobel (3)).

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

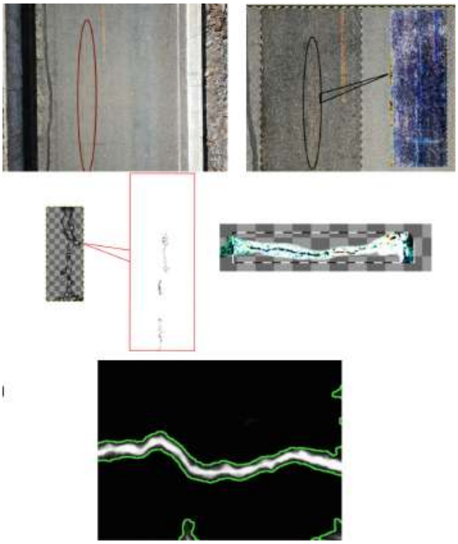

Fig. 3. Results obtained. The first is the crack identified on red, followed by the second imagem on the right, that was obtained by using the filters described above. On the third and fourth image is presented two isolated cracks. Finally the last imagem is the result obtained by using the VGG-16 and 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.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 82–88, 2026.
https://doi.org/10.1007/978-3-032-06763-0_12

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.

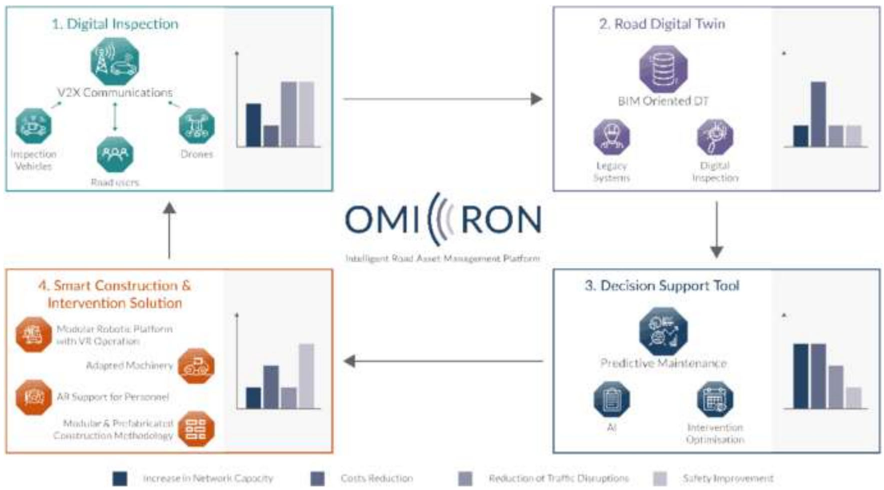

Fig. 1. OMICRON project concept covering modular construction, digital inspection, predictive maintenance and smart maintenance execution. Reproduced with permission from the OMICRON consortium, copyright OMICRON, 2024.

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.

Funding. *This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°955269.*

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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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 89–95, 2026.
https://doi.org/10.1007/978-3-032-06763-0_13

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 96–101, 2026.
https://doi.org/10.1007/978-3-032-06763-0_14

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.

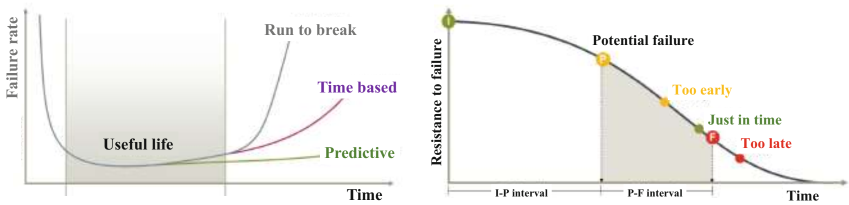

Fig. 1. Maintenance mode and failure rates (left). P-F curve with the PM objective (right).

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

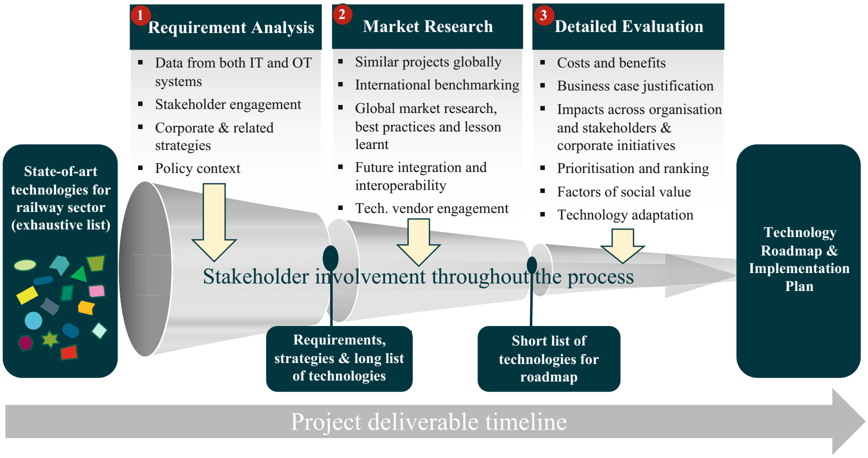

Fig. 2. A general framework for the execution of digital projects

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].

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 102–108, 2026.
https://doi.org/10.1007/978-3-032-06763-0_15

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.

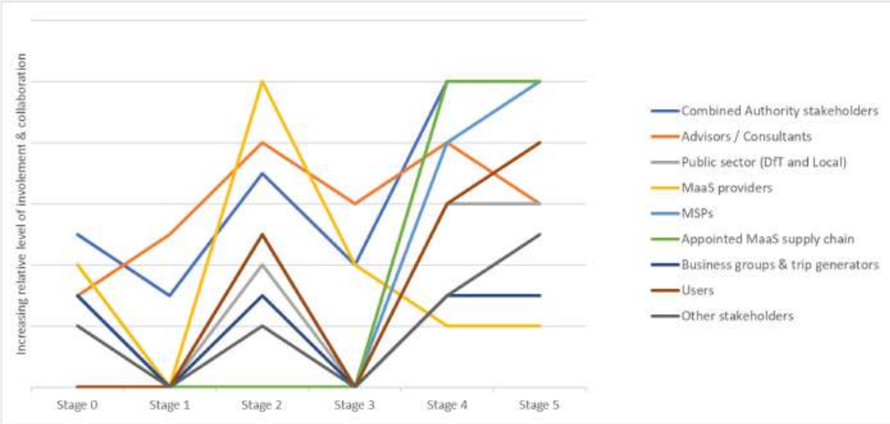

Fig. 1. Level of collaboration with stakeholders throughout the project stages

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.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 109–115, 2026.
https://doi.org/10.1007/978-3-032-06763-0_16

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.

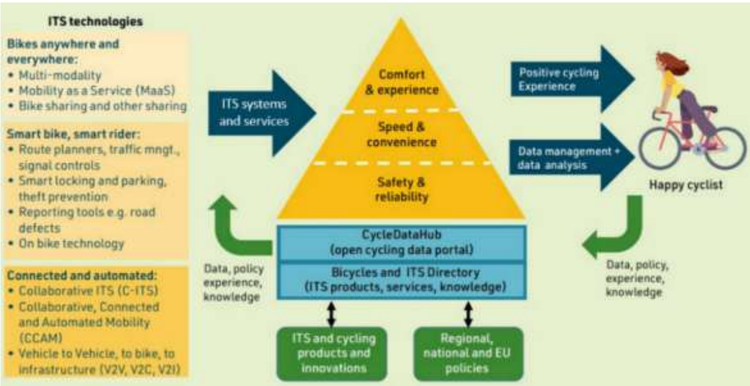

Fig. 1. ITS systems and services in relation to the cycling pyramid (source: MegaBITS project).

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) • Reducing cycling speed with dynamic signs (Amsterdam) • Analysis of 3D camera images of near accidents (Bornem/Antwerp) • Dynamic lighting at cycle lane (Zwolle, Aarhus)	• Projects have resulted in safer roads, less near accidents and lower speeds • Installation of road safety systems often is more cumbersome than anticipated (digging, connection to electricity, privacy issues) • Busy and complex traffic situations might not be suitable for additional dynamic signage • 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) • Bike sharing for tourists and citizens (Overijssel) • Bike sharing for students (Zwolle)	• Each situation requires clear goals and a clear bike sharing concept tailored to the goal • 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) • Bike parking guidance system (Zwolle)	• Signs should be placed at strategic and visible locations • Safe bike parking highly valued by cyclists (more expensive e-bikes, cargo bikes, fat bikes, etc.) • 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) • Extended green going downhill (Aarhus) • Faster green for groups of cyclists (Overijssel)	• Requires so-called ‘smart traffic lights’ • Faster green highly appreciated by cyclists • Smart traffic lights give additional benefits with collection of cycling data (e.g. counting, green time) • 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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 116–122, 2026.
https://doi.org/10.1007/978-3-032-06763-0_17

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.

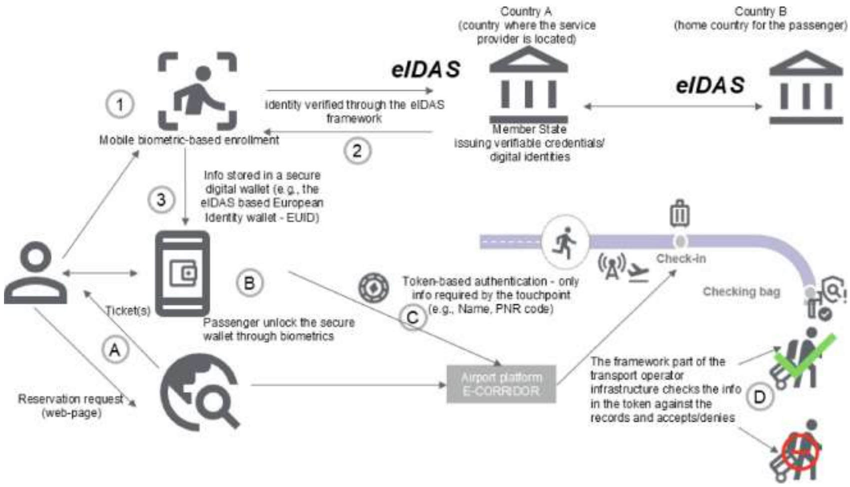

Fig. 1. Mobile enrollment for the transport sector based on eIDAS verifiable credentials. *Icons from* https://fonts.google.com/icons *Apache License Version 2.0.*

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.

Acknowledgments. Authors thank Olivier Mercier (Groupe ADP, Aéroports de Paris) for helping in the use case definition, and Tony Chapman (Collins Aerospace) for supporting the design of the mobile enrollment solution. Research partially supported by EU through the Horizon 2020 research and innovation program E-CORRIDOR (grant agreement No. 883135). The content of the paper does not necessarily reflect the position or the policy of the funding parties.

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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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 123–129, 2026.
https://doi.org/10.1007/978-3-032-06763-0_18

(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)

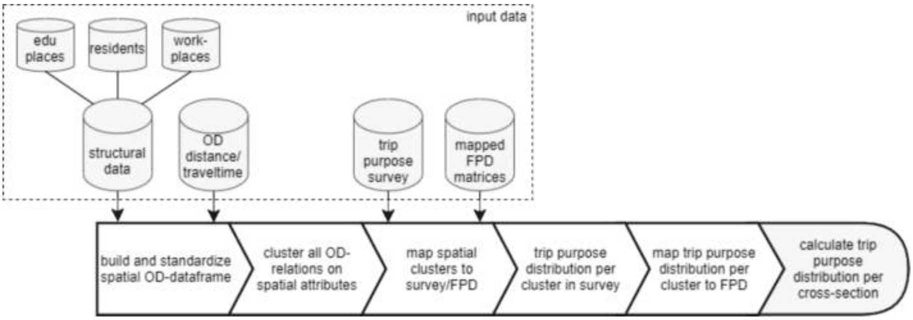

Fig. 2. Overview of the developed methodology.

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

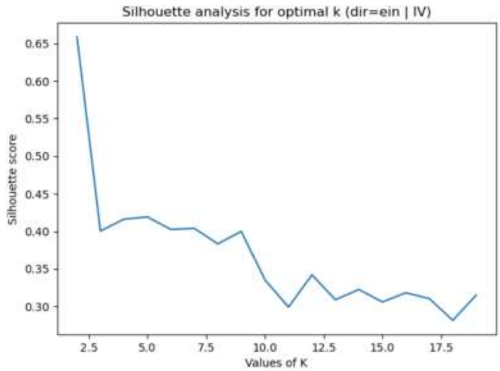

Fig. 3. Silhouette analysis for optimal number of clusters.

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.

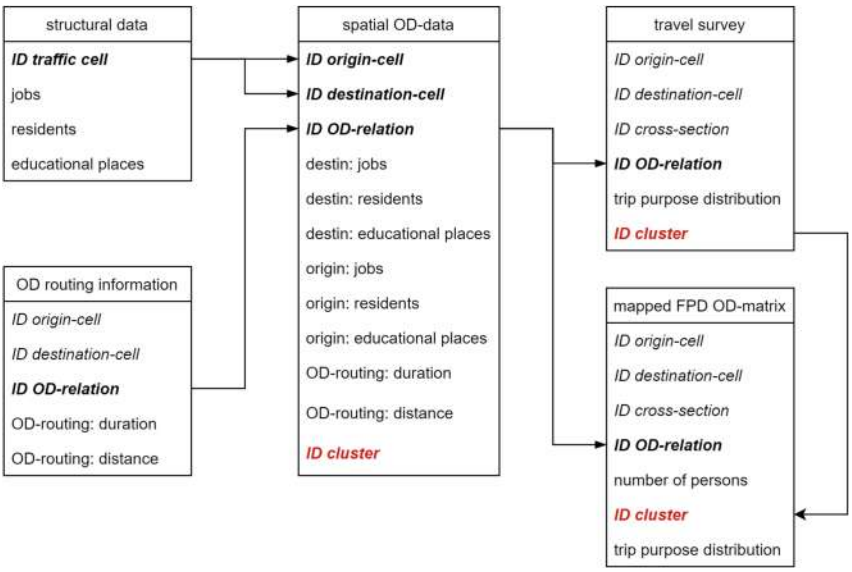

Fig. 4. Data structure and dependencies.

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 130–136, 2026.
https://doi.org/10.1007/978-3-032-06763-0_19

[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).

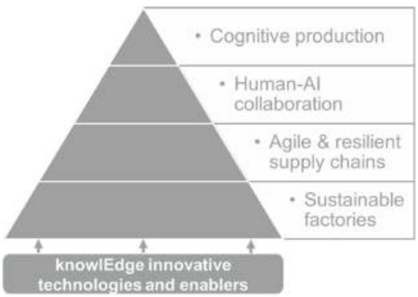

Fig. 1. knowlEdge response to the needs of industrial supply chains

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

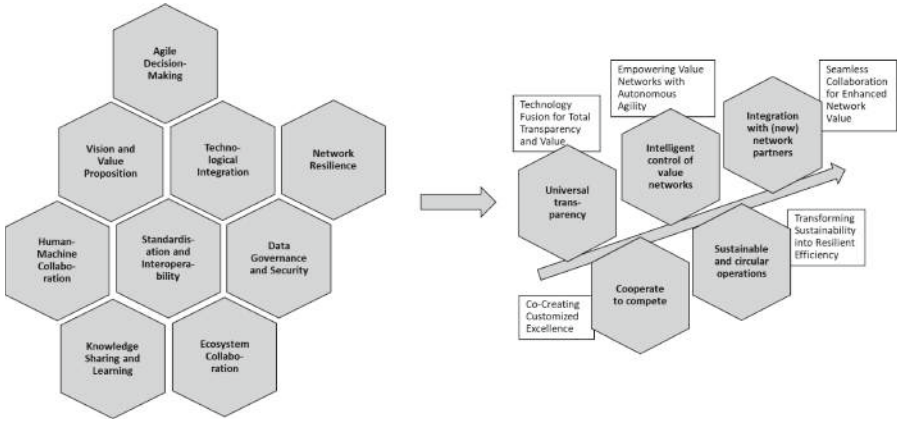

Fig. 2. Specifications forming the roadmap building blocks

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.

Acknowledgements. This research has received funding from Horizon 2020 under grant no. 957331.

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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.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 137–143, 2026.
https://doi.org/10.1007/978-3-032-06763-0_20

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.

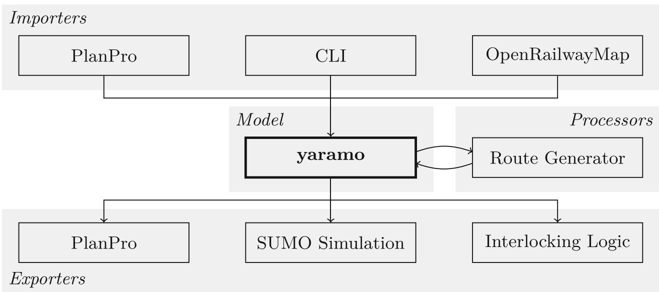

Fig. 1. The yaramo environment. It consists of the yaramo model and three tool chain layers: importers, processors, and exporters.

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.

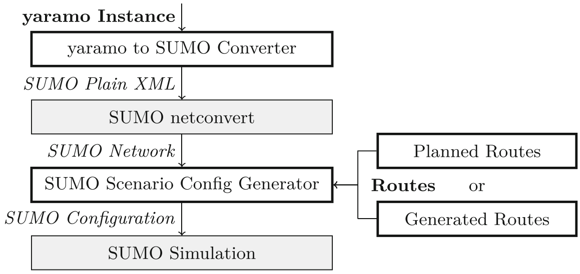

Fig. 2. The pipeline to convert yaramo instances to SUMO simulations. The grey boxes are provided by the SUMO tool chain, the bold boxes were developed as the exporter.

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.

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 144–149, 2026.
https://doi.org/10.1007/978-3-032-06763-0_21

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.

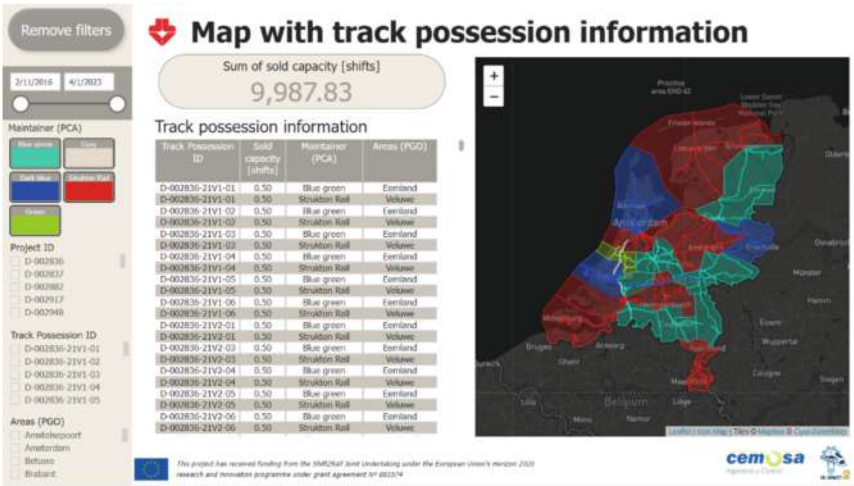

Fig. 1. Visualization of map with track possession information page. Generated with *Microsoft Corporation. Microsoft Power BI [Software]. Retrieved from* https://powerbi.microsoft.com.

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 150–155, 2026.
https://doi.org/10.1007/978-3-032-06763-0_22

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 156–162, 2026.
https://doi.org/10.1007/978-3-032-06763-0_23

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)

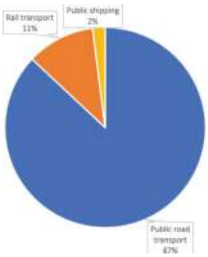

Fig. 1. Modal split of different modes of transport in France [10]

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.

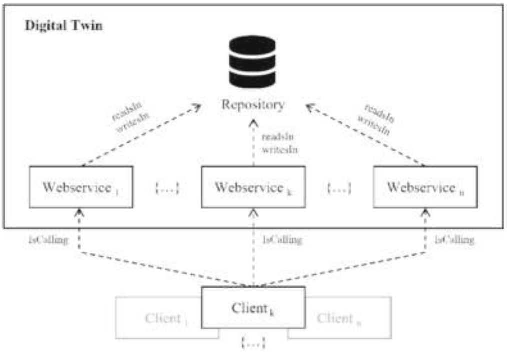

Fig. 2. Diagram of the technical architecture of the railway system DT at SNCF Reseau.

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).

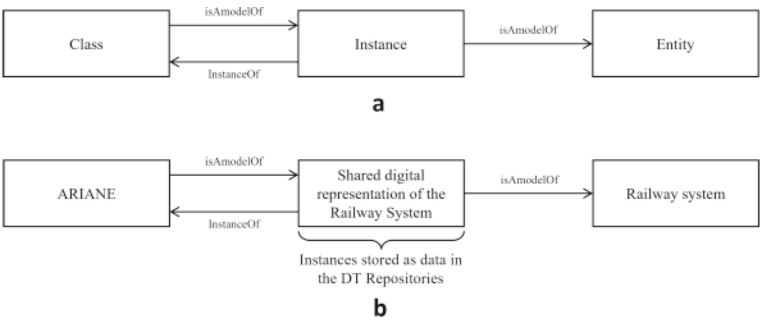

Fig. 3. a)Metamodel representing the instantiation/representation relationships between the different concepts that we use to handle the actual railway system along with related models. b) Shared digital representation of the railway system, produced with ARIANE, in conformity to the upper metamodel

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).

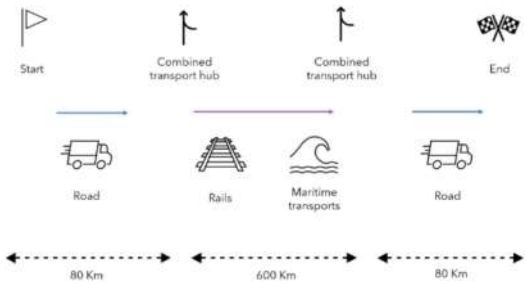

Fig. 4. Example of combined transport involving rail, maritime, road modes [13]

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 163–168, 2026.
https://doi.org/10.1007/978-3-032-06763-0_24

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.

Acknowledgements. The financial support of the Austrian Federal Ministry for Digital and Economic Affairs, the National Foundation for Research, Technology and Development, and the Christian Doppler Research Association to the CD-Laboratory for Sustainable Product Management, the financial support of the Austrian Research Promotion Agency FFG for the project CE-PASS and the financial support by the European Union for the project FREE4LIB under GA No. 101069890 are gratefully acknowledged.

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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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 169–175, 2026.
https://doi.org/10.1007/978-3-032-06763-0_25

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.

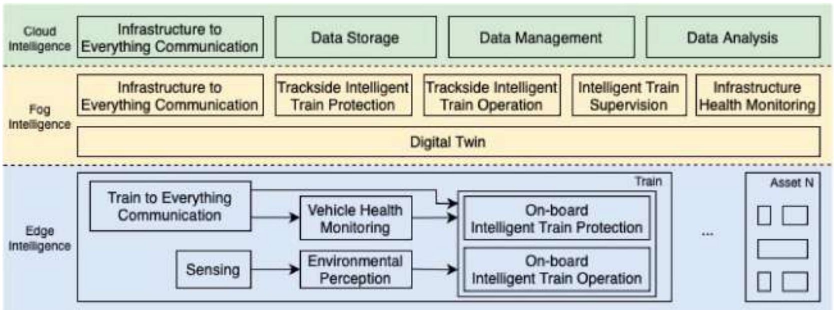

Fig. 1. Example Architecture for GoI4 Railway Lines.

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 176–182, 2026.
https://doi.org/10.1007/978-3-032-06763-0_26

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.):

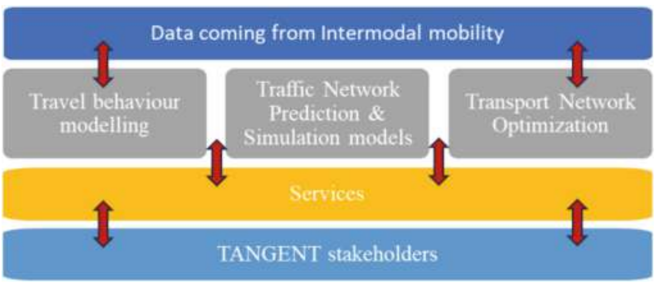

Fig. 1. TANGENT conceptual diagram.

- 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

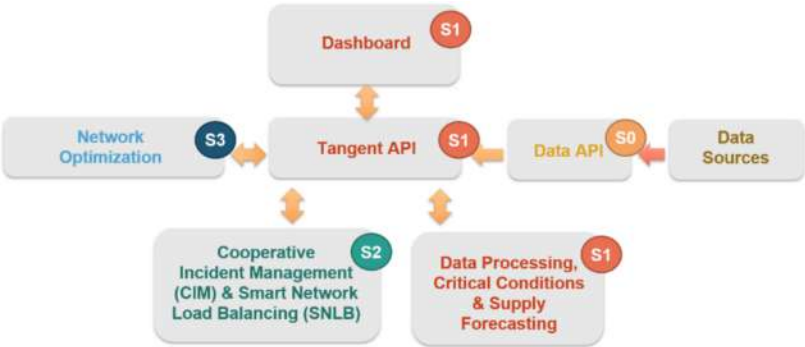

Fig. 2. Top-level technical architecture

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.

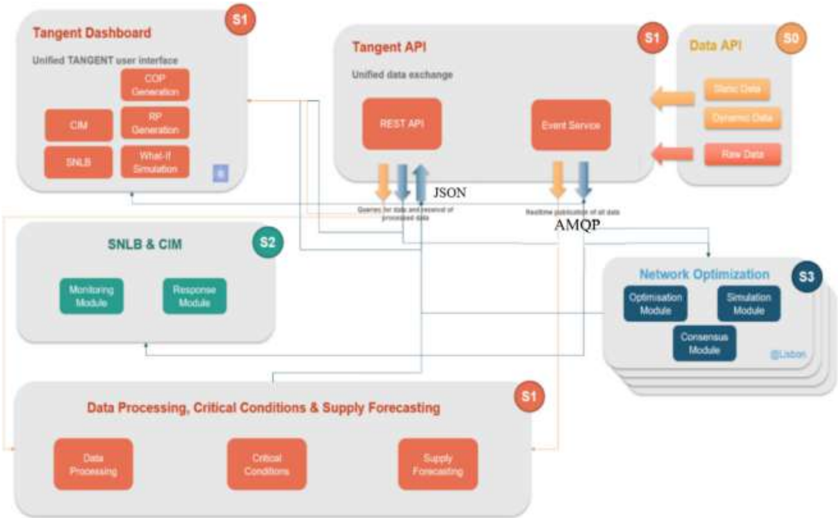

Fig. 3. TANGENT Detailed Technical architecture.

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

TANGENT project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 955273. TANGENT partners are DEUSTO (coordinator) AIMSUN, NTUA, IMEC, CEFRIEL, Rupprecht, ID4CAR, Rennes, A-to-Be, Carris, TfGM, Panteia and Polis.

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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].

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 183–189, 2026.
https://doi.org/10.1007/978-3-032-06763-0_27

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.

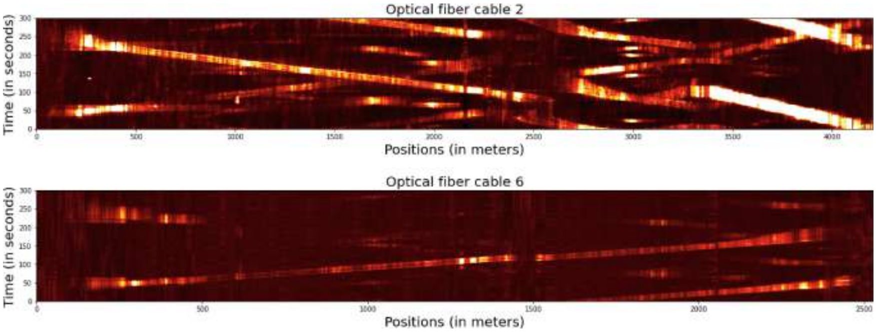

Fig. 1. A 5-min waterfall for two optical fiber cables in the study site showing vibrations induced by moving trains. Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

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.

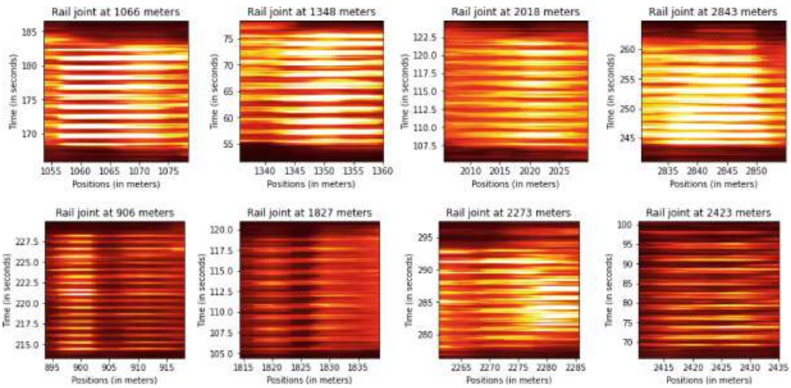

Fig. 2. Rail joint vibrations on different rail joints along the tracks. Data from the first row comes from cable 2, while the second row comes from cable 6. Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

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

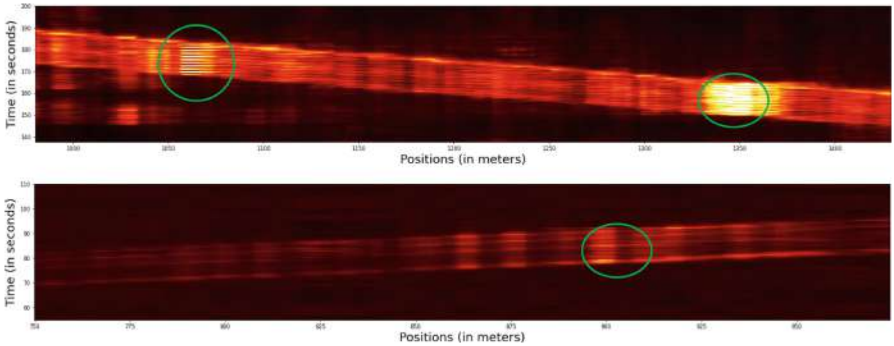

Fig. 3. Zoom on rail joint vibrations observed as a train travels along a track section (first row: data from cable 2, second row: data from cable 6). Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

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.

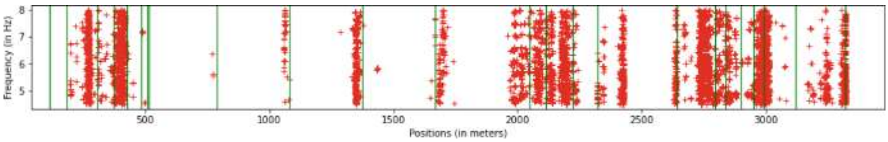

Fig. 4. Distribution of frequency peaks in the signal from cable 2 (range [4.5 Hz – 8.0 Hz]).

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 ± 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.

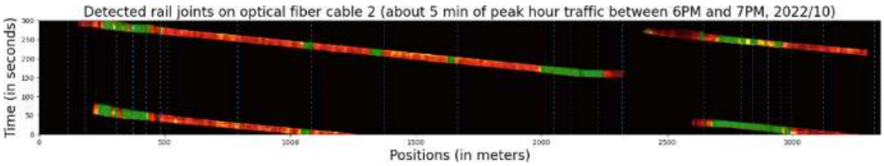

Fig. 5. Detected rail joints on 5 min of peak hour traffic (XGBoost, cable 2). Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

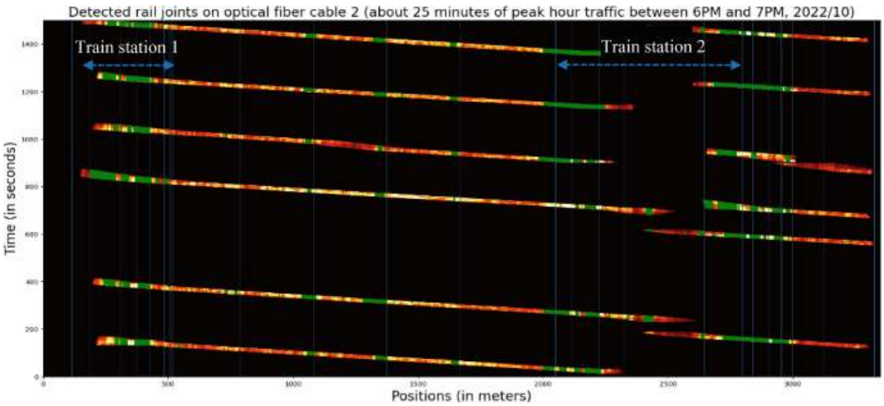

Fig. 6. Detected rail joints on 25 min of peak hour traffic (XGBoost, cable 2). Reproduced with permission from SNCF Réseau, copyright SNCF Réseau, 2024

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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 190–196, 2026.
https://doi.org/10.1007/978-3-032-06763-0_28

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.

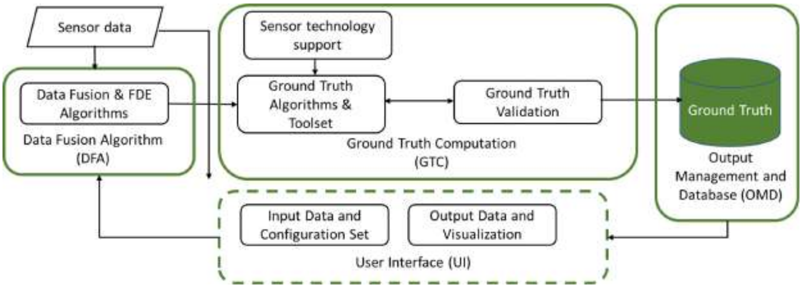

Fig. 1. Functional architecture of the Ground Truth

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.

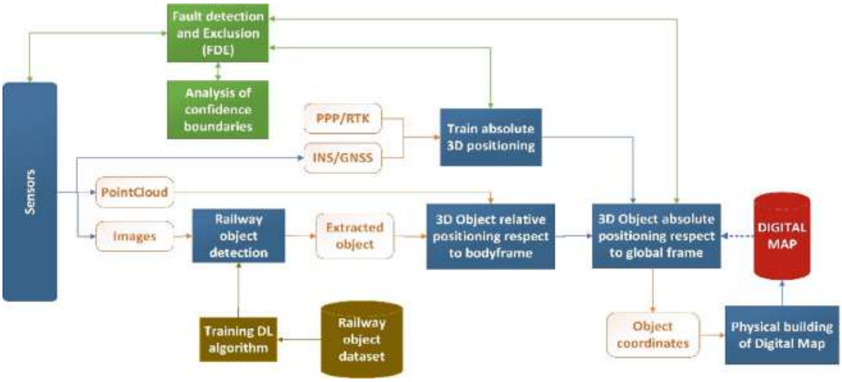

Fig. 2. TDM Functional Block Operational Workflow

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.

Acknowledgements. The RAILGAP project is funded by the H2020 EUSPA with GA N. 101004129.

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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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 197–203, 2026.
https://doi.org/10.1007/978-3-032-06763-0_29

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).

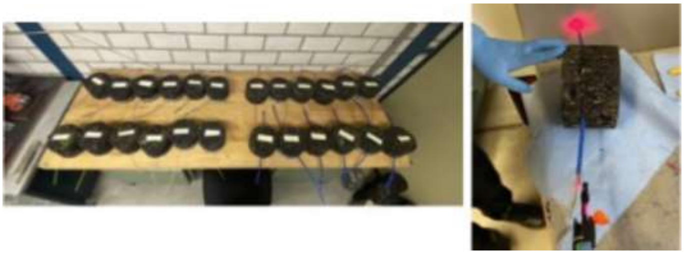

Fig. 1. On the left - samples realized for the experimental campaign; on the right - one of the performed tests.

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

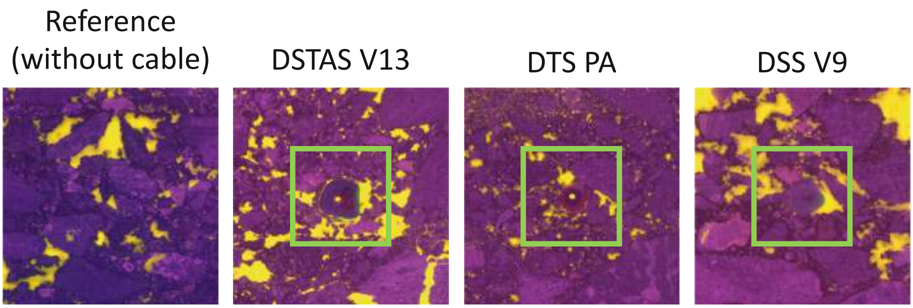

Fig. 2. Asphalt petrological sections of the three FOS samples (DSTAS V13, DTS PA, DSS V9)

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.

Acknowledgment. This paper was carried out in the framework of the InfraROB project (Maintaining integrity, performance and safety of the road infrastructure through autonomous robotized solutions and modularization), which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 955337. It reflects only the author's view. Neither the European Climate, Infrastructure and Environment Executive Agency (CINEA) nor the European Commission is in any way responsible for any use that may be made of the information it contains.

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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

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 204–211, 2026.
https://doi.org/10.1007/978-3-032-06763-0_30

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).

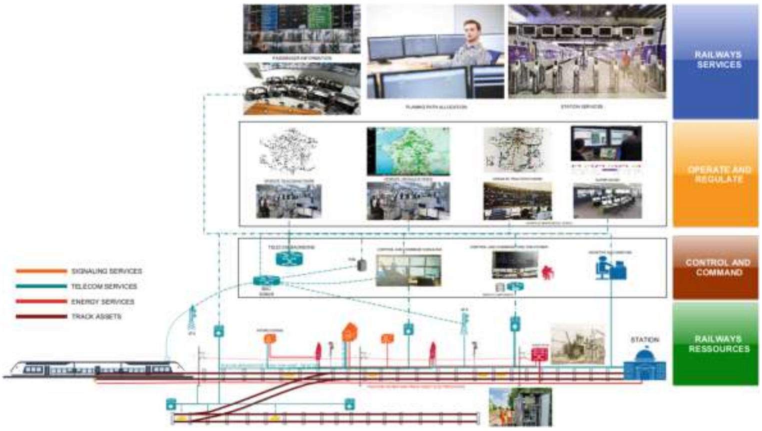

Fig. 1. Illustration overall railways architecture, designed within the framework of Horizon 2020 – Shift2Rail projet Linx4Rail, Grant agreement ID: 881826

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.

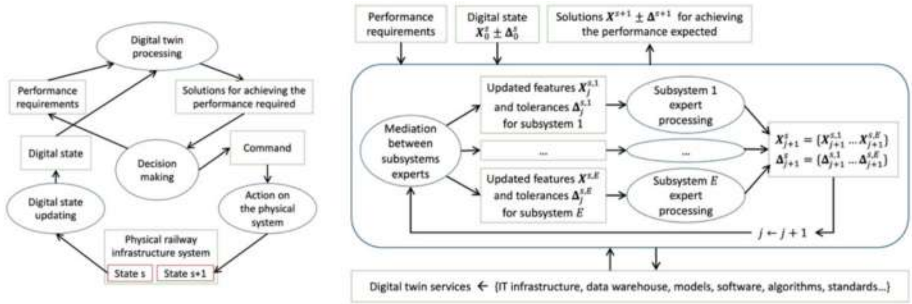

Fig. 2. DT concept for designing and building railway systems at the organizational level. [Left] Railway manager perspective where the outputs of the DT processing are used for aiding decision. [Right] The proposed DT concept integrates the engineering practice with an iterative process organized by 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).

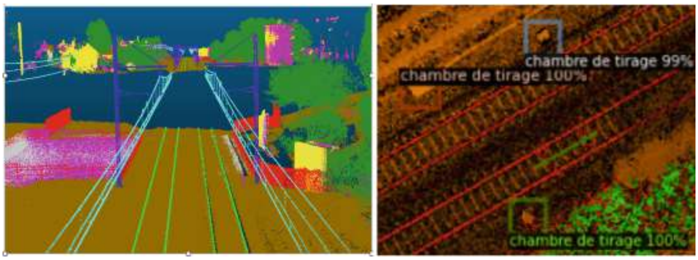

Fig. 3. Illustration of track (a) and telecom equipment (b) detection in a point cloud data, 3D point clouds of the French railway network processed with SNCF Reseau proprietary softwares.

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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