Proceedings of the 6th SmartRaCon Scientific Seminar

SRC6SS

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Dokumenteigenschaften

Titel	[Titel]
Betreff	SRC6SS – Europe's Rail research
Institut	Transportation Systems
Erstellt von	SmartRaCon
Beteiligte	-
Geprüft von	-
Freigabe von	-
Zugänglichkeit	■ Stufe 1: Allgemein zugänglich (in elib ohne Zugangsbeschränkung)
	☐ Stufe 2: DLR intern zugänglich (in elib mit Beschränkung „nur DLR-intern zugänglich“)
Datum	13.10.2024
Version	1.0
Datei Info	SRC6SS_Proceedings v1.0

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Keynote

1. SmartRaCon Introduction

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1.1. Smart Rail Control Systems – SmartRaCon background at Shift2Rail

During European H2020 programme, railway related research and innovation was carried out at European level within the framework of the Shift2Rail Joint Undertaking. Among the different topic covered, the work related to control, command and signalling for automation and safety purposes was carried out in the projects X2Rail-1 to X2Rail-5, among others. In addition to partners from industry and railways, the partners of the consortium "Smart Rail Control - SmartRaCon" Railenium (FR), GMV-NSL (UK), CEIT (ES) and DLR (DE) were active in these projects. Together as an associate member of Shift2Rail, they set themselves the goal of hosting an annual scientific seminar on one of the X2Rail projects. After the first one in 2019 in Villeneuve d'Ascq was hosted as a face-to-face event by Railenium, the second one in 2020 could be executed very successfully as a digital event by CEIT as well as the third in 2021 by DLR. In 2022, the fourth edition followed, as hybrid event in San Sebastian hosted by CEIT. In 2023, the fifth edition was hosted by GMV and DLR together as hybrid event in Berlin-Adlershof, where the focus will be on the X2RAIL-5 and TAURUS projects.

Figure 1.1 Logo of SmartRaCon

Once the European H2020 programme came to the end, in the frame of the European Horizon Europe programme and the SmartRaCon members have been updated in the frame of Europe's Rail. Six partners from six different European countries compose SmartRacon: CEIT (ES), DLR (GE), RISE (SE), SINTEF (NO), University Gustave Eiffel – UGE (FR) and Road and Bridge Research Institute- IBDiM(PL). After 5 editions of SmartRaCon Scientific Seminar in the frame of Shift2Rail Join Undertaking, the current SmartRaCon partners, together organise the 6th edition of the SmartRacon Scientific Seminar, in the frame of Europe's Rail Joint Undertaking, that will take place the 23rd and 24th October 2024 in San Sebastian hosted by CEIT.

1.2. Europe's Rail

Europe's Rail Joint Undertaking (Europe's Rail JU) is a public-private partnership under the European Union's Horizon Europe research and innovation program, aimed at driving the transformation of Europe's rail system. It focuses on enhancing the efficiency, competitiveness, and sustainability of rail transport in Europe by fostering research, innovation, and the deployment of advanced rail technologies.

- **Enhanced Capacity and Efficiency**: By addressing specific challenges through the FAs, Europe's Rail JU aims to significantly increase the capacity and efficiency of Europe's rail system.
- **Sustainability Goals**: Contributing to the EU's climate and environmental objectives by promoting greener and more sustainable rail solutions, as well as inclusiveness of various stakeholder groups.
- **Improved Passenger and Freight Services**: Through the deployment of innovative technologies and services, Europe's Rail JU seeks to make rail a more attractive option for both passenger and freight transport, boosting its market share.

Europe’s Rail shall accelerate research and development in innovative technologies and operational solutions for railways. This will support the fulfilment of European Union policies and objectives relevant for the railway sector and the competitiveness of the European rail sector and supply industry. In this way, Europe’s Rail will accelerate the penetration of integrated, interoperable and standardised technological innovations necessary to support the Single European Railway Area (SERA).
Europe’s Rail presents a structure of Flagship Areas ensuring a comprehensive and targeted approach to addressing the diverse needs of Europe’s rail system, aligning with broader EU policies and the vision for a connected, competitive, and sustainable rail network [1]

- Flagship Area 1: Network management planning and control & Mobility Management in a multimodal environment
- Flagship Area 2: Digital & Automated up to Autonomous Train Operations
- Flagship Area 3: Intelligent & Integrated asset management
- Flagship Area 4: A sustainable and green rail system
- Flagship Area 5: Sustainable Competitive Digital Green Rail Freight Services
- Flagship Area 6: Regional rail services / Innovative rail services to revitalise capillary lines
- Flagship Area 7: Innovation on new approaches for guided transport modes
- Transversal Topic: Digital Enablers

1.3. Partnership in the frame of international collaboration

The six partners CEIT, DLR, RISE, SINTEF, UGE and IBDiM are cooperating in SmartRaCon to accelerate the introduction and implementation of innovation in the railway sector. This gives the opportunity to validate if the approaches developed over several European and non-European countries.

- The **Centro de Estudios e Investigaciones Técnicas (CEIT)** i. CEIT is a non-profit technology center, created on the initiative of the University of Navarra in 1982, and whose main task is to carry out industrial research projects in close collaboration with the R&D departments of the companies. CEIT researches for the railway sector since its creation in different research lines. CEIT is a multidisciplinary research centre with the unique capability to bring technology to market. During the last 20 years, CEIT has created 18 spin-offs; some of them have been acquired by international companies present in the NASDAQ (IXYS), PAR (ERASTEEL), NYSE (PRAXAIR) & IBEX (CAF), among the spin offs- 3 are targeting directly the railway sector.
- The **German Aerospace Centre (Deutsches Zentrum für Luft-und Raumfahrt e.V – DLR)** brings large experience from the domains of aviation, automotive, robotics, space and energy, especially in the field of control command & human factors. DLR has a wide ranging experience in the field of human factors. Based on a long history of human factors research in the aeronautics area, DLR continuously broadened this field of research to the automotive and rail traffic domain. Especially with the experience of research in the field of air traffic management, transdisciplinary synergies are used to analyse and improve traffic management systems in the railway sector.
- **RISE** is Sweden’s research institute and innovation partner. Through our international collaboration programmes with industry, academia and the public sector, we ensure the competitiveness of the Swedish business community on an international level and contribute to a sustainable society. Our almost 3300 employees engage in and support all types of innovation processes. RISE is an independent, state-owned research institute, which offers unique expertise and over 130 testbeds and demonstration environments for future-proof technologies, products and services.
- **Road and Bridge Research Institute (IBDiM) (with association of PKP – Polish State Railways):** The Road and Bridge Research Institute is the leading scientific research institute in Poland dealing with issues of transport infrastructure. The Institute's activities are focused on the development of science and practical applications of research results. The research and development work performed concern the construction and maintenance of transport facilities, especially roads and road bridges, railroad engineering facilities and underground structures. The Institute's research activities include material,

technological, economic and ecological issues. Main lines of business: design, construction and maintenance of road infrastructure, testing of materials and products used in transport infrastructure construction, assessment of the technical condition of roads and engineering structures, geotechnics, traffic engineering and safety, road management systems, traffic telematics, road and engineering structure databases.

- **SINTEF:** SINTEF is one of Europe's largest independent research organizations, based in Norway. It focuses on applied research and development across various fields, including technology, natural sciences, health, and social sciences. SINTEF collaborates with industries, universities, and public organizations to promote innovation and sustainability. With a strong emphasis on practical solutions, its projects often address pressing societal challenges, making significant contributions to sectors like energy, materials, and digitalization. The organization is committed to bridging the gap between research and practical application, fostering technological advancements that benefit society.
- **University Gustave Eiffel (UGE):** Gustave Eiffel University is the only multi-disciplinary institution in France to combine the missions and skills of a university, a research organization, a school of architecture (ENSA Paris-Est) and three engineering schools (EIVP, ENSG and ESIEE Paris), with the common aim of being at the heart of the issues facing tomorrow's cities and regions.

1.4. Europe's rail participation

In the next table the participation of the SmartRaCon partners into the different FAs of the first wave of Europe's Rail is shown.

Participation of the SmartRaCon partners into the Europe's Rail FAs

Name	FA1	FA2	FA3	FA4	FA5	FA6	FA7	TT
ceit	X	X	X	X	X	X		X
DLR	X	X	X	X	X	X	X	X
RI. SE	X	X		X	X	X		
SINTEF	X		X		X			
Université Gustave Eiffel		X	X	X			X	
Instytut Badawczy Dróg i Mostów / Road and Bridge Research Institute						x		

Table 1.1 Participation of the SmartRaCon partners into the Europe's Rail FAs

To disseminate the results of the scientific work done in the frame of Europe's Rail, the SmartRaCon partners organize Scientific Seminars to present and discuss their results on a high scientific level. The the 6th edition of the SmartRaCon Scientific Seminar, in the frame of Europe's Rail Joint Undertaking, that will take place the 23rd and 24th October 2024 in San Sebastian hosted by CEIT.

1.5. Research Infrastructures and Simulators

The SmartRaCon partners are developing and operating a large number of simulators and research infrastructures which are used to validate the approaches for new systems. Among them are:

- Railway operation simulators like the TMS simulation or the OVM tool
- Test laboratories like the ETCS On-Board lab or the RailSiTe®
- Test vehicles like the RailDriVE®
- Aerodynamics FR8-Lab onsite testing laboratory
- Measurement labs like the Electrical mechanical, EMC test or EMC interference detection
- GNSS equipment like DETECTOR or the GNSS equipment at the ERTMS national integration facility – ENIF
- Communications laboratories
- Additive manufacturing and robotics laboratories
- And many more, at the locations shown at the next figure.

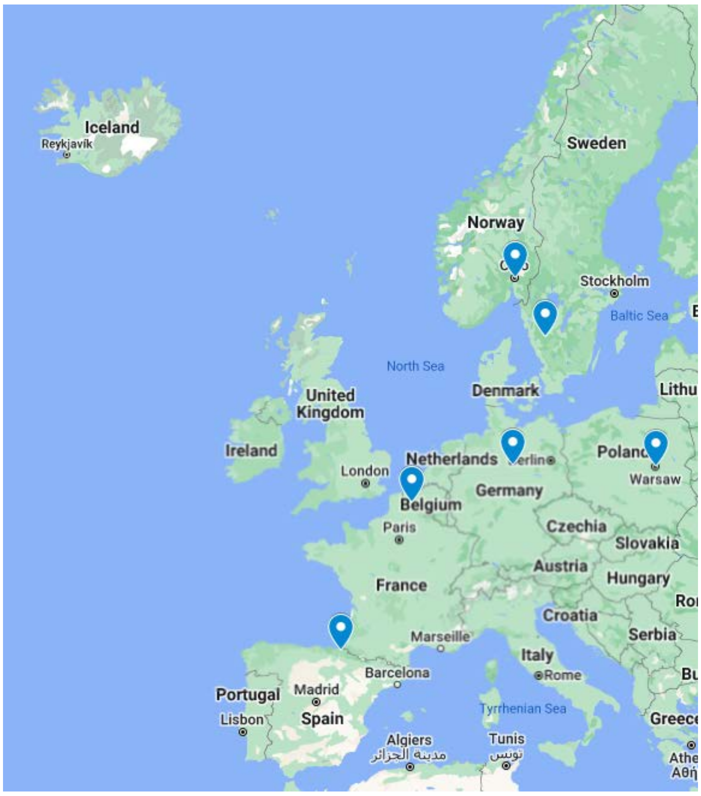

Figure 1-2 Selected Research Infrastructures and Simulators SmartRaCon

1.6. SmartRaCon Scientific Seminar

After 5 editions of SmartRaCon Scientific Seminar in the frame of Shift2Rail Join Undertaking, the SmartRaCon members have been updated in the frame of Europe's Rail. Six partners from six European countries compose SmartRaCon: CEIT (ES), DLR (GE), RISE (SE), SINTEF (NO), UGE (FR), and IBDiM (PL). They all together organise the 6th edition of the SmartRaCon Scientific Seminar, in the frame of Europe's Rail Joint Undertaking, that will take place the 23rd and 24th October 2024 in San Sebastian hosted by CEIT. After that, the event will be hosted in other European countries where the SmartRaCon members are located.

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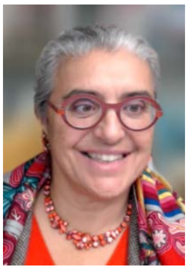

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Funded by the European Union

The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

2. Europe’s Rail Flagship Project 1 - Mobility management multimodal environment and digital enablers

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2.1. Introduction

The Flagship Project 1 "MOTIONAL", under the Europe’s Rail initiative and led by Hacon and Trafikverket with 89 partners, aims to transform the European Capacity Planning and Traffic Management Systems through digitalisation, automation, connectivity, and multimodal integration. Supported by Europe’s Rail’s initiative, this project aims to create a resilient, interoperable, and efficiently integrated future European railway system, facilitating last-mile operations. The methodology includes the definition of use cases, functional requirements, and specifications coordinated with the project partners, industry stakeholders and in collaboration with the EU-Rail System Pillar. Key advancements include also the development of digital enablers like digital twin technology, federated dataspaces and conceptual data models. The overarching goal is to position rail as the backbone of a multimodal transport system for both passengers and freight, aiming towards a Single European Rail Area.
This abstract will present the four different workstreams of the "MOTIONAL" project, enhancing railway planning and capacity management systems (CMS), modernizing traffic management systems (TMS), integrating multimodal transport, and leveraging digital enablers.

2.2. Planning and Capacity Management System

The railway planning and capacity management systems objective is to enhance both strategic and tactical network planning using optimization and simulation, addressing short-term adjustments and long-term planning. This involves developing new processes for European-wide capacity allocation and connecting planning with operational traffic. Key focus areas include:

- **Cross-border Planning:** Enhancing planning between national and international borders to ensure seamless operations. This involves creating harmonized scheduling processes that accommodate varying national regulations and infrastructure capabilities. By facilitating smoother international rail services, cross-border planning aims to reduce delays and improve the reliability of international journeys.
- **Advanced Algorithms:** Developing sophisticated decision support systems for timetable planners and capacity management operators. These algorithms will provide real-time data analysis and predictive capabilities to optimize timetables, allocate resources efficiently, and manage disruptions more effectively. By incorporating machine learning and artificial intelligence, these algorithms can adapt to changing conditions and enhance the accuracy and reliability of scheduling.
- **Simulation and Operational Feedback:** Creating advanced simulation methods to improve capacity planning and assess the impact of new technologies such as Digital Automated Train Operations (DATO) and the European Train Control System (ETCS). These simulations will enable planners to model different scenarios, evaluate potential outcomes, and make informed decisions based on data-driven insights. Feedback loops between simulation results and actual operations will help in continuously refining the planning processes.

2.3. Operations - modernizing traffic management systems

Currently, rail traffic is managed by Infrastructure Managers (IMs) at national or regional levels, often using outdated systems with low digitalisation and poor integration. By leveraging digitalisation, the "MOTIONAL" project aims to implement the future European Rail Traffic Management System. Key activities include:

- **Integration of TMSs and Processes:** Developing processes and interfaces for higher integration of Traffic Management System (TMS) functions and decision processes. This involves creating unified platforms that enable seamless communication and coordination between various TMS components across different regions and countries. By standardizing protocols and data exchange formats, the project will break down silos and facilitate more cohesive and efficient traffic management.
- **Improved Resilience and Efficiency:** Creating modules for cooperative multi-actor optimization and decision support to enhance disruption management. These modules will enable real-time collaboration between multiple stakeholders, including infrastructure managers, train operators, and emergency services. By integrating advanced analytics and predictive modelling, these tools will help in quickly identifying potential disruptions, assessing their impact, and coordinating effective responses to minimize delays and maintain service continuity.
- **Linking TMS to ATO/C-DAS:** Testing integration between TMS and Automatic Train Operation (ATO)/Connected Driver Advisory System (C-DAS) to increase network capacity, timetable robustness, energy efficiency, and punctuality. This integration will enable more precise and adaptive control of train operations, allowing for smoother acceleration and braking, optimized speed profiles, and better adherence to schedules. The project will conduct extensive testing and validation to ensure that these systems work harmoniously and deliver the intended benefits.
- **Automated Decisions for Optimization:** Developing algorithms and modules for future TMSs to provide decision support and automate decisions for traffic management. These algorithms will leverage machine learning and artificial intelligence to analyze vast amounts of operational data, identify patterns, and make informed decisions in real-time. Automation will reduce the reliance on manual intervention, leading to faster and more accurate traffic management decisions, improved capacity utilization, and enhanced overall network performance.

2.4. Multimodal Integration

"MOTIONAL" aims to make rail the backbone of multimodal transport by integrating with other modes to deliver door-to-door mobility. This is supported by three pillars:

- **B2B Integration:** Enhancing cooperation between Mobility Providers through improved B2B platforms and services in sales, distribution, financial services, and traffic information. This pillar focuses on fostering robust partnerships and interoperability among various transport operators. Key aspects include:
    - **Support for Cross-Operator and Cross-Mobility Functions:** Developing systems that enable seamless integration and coordination between different transport modes and operators. This will facilitate smoother transitions between rail, bus, tram, and other transport services, creating a unified travel experience.
    - **Enhancement of Standards:** Improving and standardizing protocols such as Open Journey Planning (OJP), Open Sales and Distribution Model (OSDM), Service Interface for Real-Time Information (SIRI), and Network Timetable Exchange (NETEX). These standards will ensure that data and services are interoperable, reliable, and consistent across different providers and platforms.
- **Inclusive Mobility:** Services focused on enhancing the environment in railway hubs to provide a seamless and user-friendly experience for all passengers. This includes the implementation of hands-free user experiences, such as touchless ticketing and boarding processes, to improve accessibility and convenience. Indoor navigation systems will guide passengers through complex station layouts, ensuring they can easily find their way to platforms, exits, and amenities. Interactive digital travel assistance will offer real-time information and support, helping travellers make informed decisions and adapt to any changes in their journey.
- **Anticipate Demand:** Designing solutions to anticipate and adapt to passenger demand, improving traveller satisfaction and optimizing provider operations. This involves:

- **Short-Term and Long-Time Demand Forecasting:** Utilizing advanced analytics and machine learning to predict travel patterns and demand trends. This will enable transport providers to plan capacity, allocate resources, and schedule services more effectively.
- **Simulation of Demand Using Digital Twins:** Creating digital replicas of the transport network to simulate various scenarios and assess the impact of different factors on passenger demand. This will help in identifying potential bottlenecks, optimizing routes, and enhancing service reliability.
- **Managing Disruptions Across Multiple Transport Modes:** Developing strategies and tools to handle disruptions in a coordinated manner. This includes real-time communication with passengers, dynamic re-routing, and collaboration between different transport operators to minimize the impact of disruptions and maintain service continuity.

2.5. Digital Enablers for the European Rail System

Digitalisation is a transformative process for the European Rail System, affecting all domains from passenger services to maintenance, engineering, construction, energy management, traffic management, train operations, and more. The "MOTIONAL" project identifies and develops a set of common digital enablers to provide foundational capabilities across specialized fields of application.

- **Rail Federated Dataspace:** Developing a cybersecure, reliable, scalable, and interoperable mechanism for data sharing across an ecosystem of autonomous business entities and heterogeneous systems. The "Rail Dataspace" aims to facilitate seamless data exchange while ensuring data privacy and security. This digital infrastructure will support digitalized trust, governance policy enforcement, and data provision contract negotiation, aligning with the European Data Strategy and leveraging open-source software. By implementing robust cybersecurity measures and standardizing data sharing protocols, the Rail Federated Dataspace will enable various stakeholders to collaborate effectively, share valuable insights, and drive innovation across the rail industry.
- **Conceptual Data Model:** Creating machine-readable and processable descriptions of data contents to enable communication of meaning and intent between heterogeneous and autonomous entities. This involves developing a unified data ontology and standardized data formats to ensure that information can be easily understood and utilized by different systems and organizations. The combination of common conceptual data models and data sharing mechanisms ensures full interoperability, reducing the risk of data silos and enhancing data accessibility. This approach will streamline data integration processes, facilitate more accurate data analysis, and support decision-making across various operational domains.
- **Digital Twins Development and Execution:** Providing common architectural guidelines, modelling languages, and tools for the development of interoperable digital twins. Digital twins are virtual representations of physical assets, processes, or systems that allow for real-time monitoring, simulation, and optimization. By establishing a standardized framework for digital twins, the project will enable the creation of complex simulation applications involving interactions between multiple cyber-physical systems, developed independently by multiple organizations. This will support a wide range of applications, from predictive maintenance and asset management to operational efficiency and scenario planning. The use of digital twins will enable rail operators to simulate different scenarios, assess the impact of various factors, and make data-driven decisions to enhance performance and safety.

2.6. Conclusion

The "MOTIONAL" project represents a significant leap forward in advancing the state-of-the-art in European railway systems. By focusing on digitalization, automation, connectivity, and multimodal integration, it aims to create a seamless, resilient, and efficient rail network that can serve as the backbone of a multimodal transport system. The project's contributions to planning, operations, and multimodal integration, supported by robust digital enablers, position it as a cornerstone in achieving the vision of a Single European Rail Area.

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His expertise extends to consulting on railway operations, intermodal transport, and logistics concepts, with a focus on multimodal transport planning and monitoring software. He has managed large-scale research and demonstration projects, successfully leading proposals for co-funded projects under FP6, FP7, H2020 and national funded projects. Lars specializes in leading interdisciplinary teams and leveraging advanced IT systems to drive innovation and efficiency in international rail transport.
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Funded by the European Union

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This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement n°101101973. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

3. Maglev Derived Systems for Rail

Michael Meyer zu Hörste, DLR; Giuseppe Carcasi, FSI

3.1. Introduction

Rail system using Maglev Levitation called “maglev” have been developed since more than half of century. Centers for those “pure” maglev systems are in Germany with the Transrapid and TSB, Japan with JR-Maglev and China. A few of those systems have been in use or are still in daily operation, which shows the maturity of the technology. But the economic environment seems to be challenging. Consequently, the concept of the “Maglev-Derived Systems” in short “MDS” was the focus of the project short-named “MaDe4Rail” for “Maglev-Derived Systems for (4) Rail” with the grant agreement no 101121851. The aim is to find the best of both worlds by combining conventional rail systems with magnetic and air levitation technologies.

The MaDe4Rail project aims to explore non-traditional and emerging maglev-derived systems (MDS) and to evaluate the technical feasibility and effectiveness to introduce MDS in Europe under safety aspects and technical-economic performance.

Figure 3.1 MaDe4Rail Logo

Identification and benchmarking of the different maglev-derived technologies for transportation systems and their state of development, definition of a common architecture and specification of the subsystems and technologies needed for its commercialization are expected in the MaDe4Rail Project. Moreover, a risk analysis and identification of needs for standardization on safety and security in operations of MDS will be performed. Also, the assessment of the technical and economic feasibility to introduce these systems into the common European mobility network will be implemented as well as the development of a European roadmap for the possible future implementation of MDS. Lastly, the design of the concept for an MDS vehicle subsystem and a prototype of a sample vehicle for a European use case are foreseen in this project.

The MaDe4Rail project is expected to have significant impacts such as contributing to the development of MDS, promoting more sustainable passenger and freight transport and initiating a path towards the reinforcement of railway as the backbone of a multimodal, sustainable and efficient mobility network by possibly, upgrading the existing railway lines/facilities through the adoption of a maglev-derived technology. Moreover, the project fosters information exchange and growth and diffusion of knowledge.

MaDe4Rail brings together a multidisciplinary group of experts from diverse backgrounds with a wide range of competences and expertise that would contribute to the success of the project such as Infrastructure Managers, Transport Authorities, Engineering and Consultancy Companies, Technological Developers and Research Centers and Universities.

3.1.1. Project Objectives

MaDe4Rail project aims to evaluate the technical feasibility and effectiveness to introduce MDS in Europe from the perspective of safety, economic and technical performance. As the scope of the Flagship Area 7 is to explore non-traditional and disruptive guided transportation systems that are based on new technologies, MaDe4Rail aims to contribute to the development of MDS. Quantitative KPIs are not formulated in this project, as its goal is to build a common knowledge, define the technological concept and the specifications of maglev-derived transportation systems to understand the potential of introducing such system – or their subsystems – into the European transportation network and to foster development towards its commercial maturity.

3.1.2. Project Structure

The overall methodology of the FA7: Maglev-derived systems will be subdivided into two major workstreams (WS): WS1 – Technical definitions and WS2 – Development of business case analysis, including feasibility studies and use cases. Each WS is divided into WPs that organize different activities in homogeneous tasks and gather the right competences.

3.1.3. Consortium

The consortium is composed of 16 organisations – 5 Founding Members, 4 Affiliated Entities and 7 External Partners – from different sectors such as research centres, universities, technological developers, SMEs, Infrastructure Managers (IM), and transport authorities. These organisations come from Switzerland and from 7 European Member States – France, Germany, Italy, Netherlands, Poland, Spain, and Sweden cf. Figure 3.2

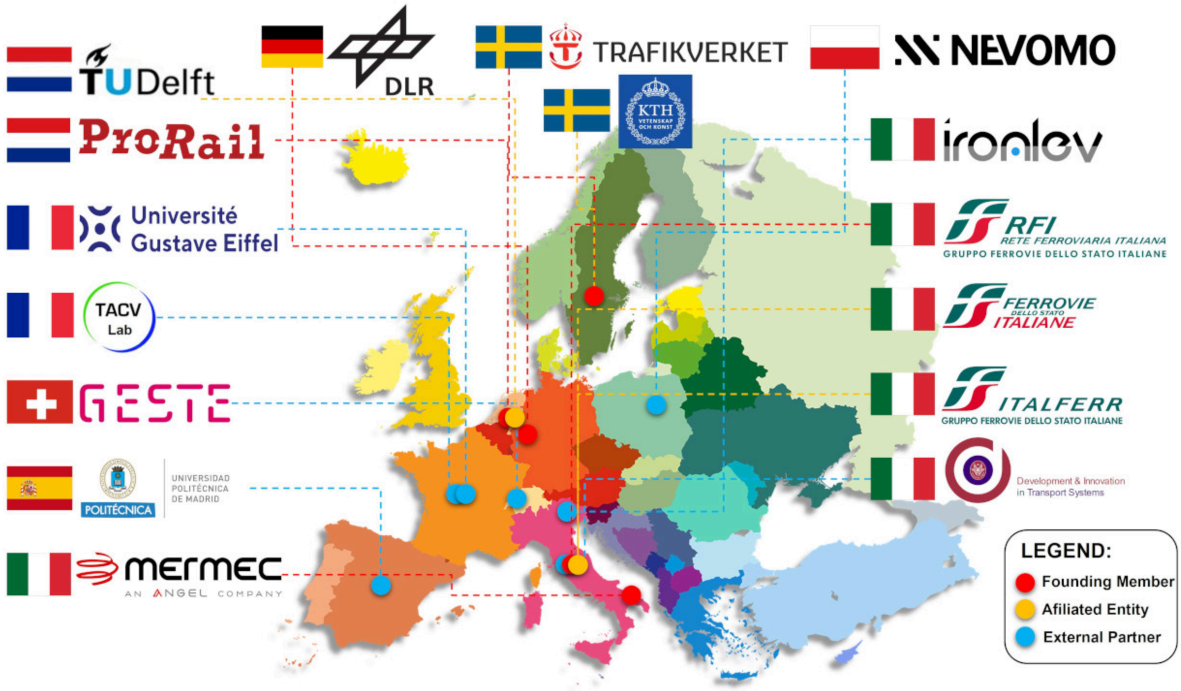

Figure 3.2 MaDe4Rail Consortium and geographical distribution

Facts & Figures	
Total Project Cost:	2,56 Mio€
EU-Rail JU Funding	1,5 Mio€
Duration	15 Months
Project Start Date	01/07/2023
Project End Date	30/09/2024
Partners	16 Partners from 8 Countries
Project Coordinator	Rete Ferroviaria Italiana S.P.A.
Grant Agreement No.	101121851

Table 3.1 Facts & Figures of MaDe4Rail

3.2. Approach and method

3.2.1. Technology Readiness Assessment for the technologies involved in MDS

The first step has been to develop a complete evaluation of the technical maturity of the technologies involved in the MDS was first carried out, based on a Technology Readiness Assessment (TRA) which is a formal, metrics-based process and accompanying report that assesses the maturity of the technologies that are to be used in the systems. This TRA has been used to propose which of them best fits the different MDS, as well as to evaluate the overall TRL of each MDS.

The TRA concluded with the findings and comparison of the different systems, considering the four main subsystems of an MDS: vehicle, infrastructure, energy system and TMS. As a result, this TRA has completed a technology analysis by comparing the different systems and identifying and exploring significant development gaps. The complete results of this TRA can be found in reference [2]. Figure 3 shows the critical technologies that have been identified for the TRA for the for the Vehicle subsystem and components.

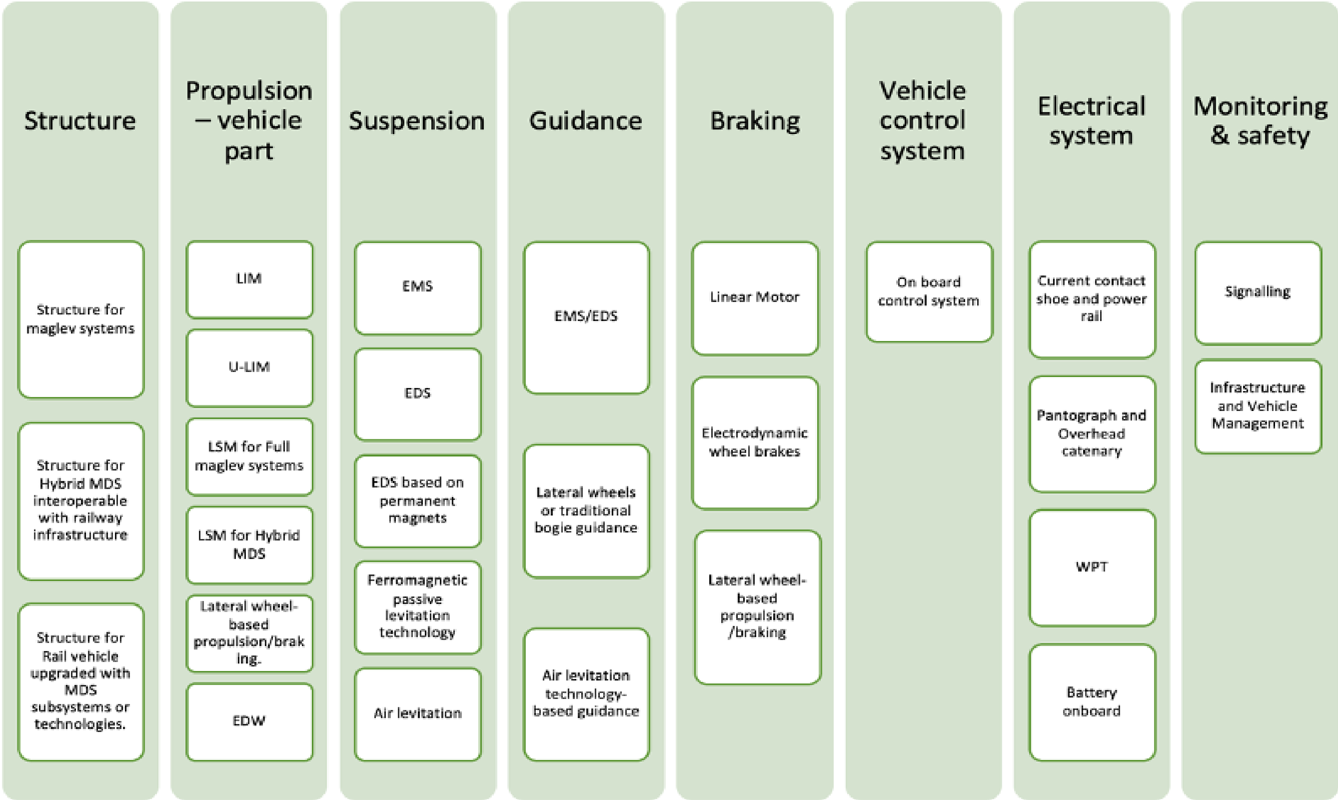

Figure 3.3 Critical technologies identified for the Vehicle subsystem and components

3.2.2. Definition of Use Cases and methodology of the MCA

The second step was to analyse different use cases for the different technologies and to identify and propose a set of use cases to be evaluated in further work packages.

For this purpose, a Multi-Criteria Analysis (MCA) was carried out to select the different MDS use cases that would be most appropriate to consider in further work packages for use on existing railway lines [2]. Several criteria were used, considering aspects such as TRA, scalability, adaptability, type of vehicle, system configuration, impact on existing infrastructure and the possibility of installation on existing railways. For the selection of the possible use cases to be considered in the following steps, a multi-criteria analysis has been carried out using the Promethee method [3]. Figure 4 shows the criteria used for the MCA.

CRITERIA		SUB-CRITERION				System configuration			
Definition	Weight (%)		Definition	Unit of measurement	Weight (%)	Pure Maglev	Hybrid Air-levitation	Hybrid Mag levitation	Rail vehicle upgraded
TECHNOLOGY	40,00	1.1	Technical Complexity	Range [1(Low)-5(High)]	10,00	5	4	4	3
		1.2	Technical Feasibility	Range [1(Low)-5(High)]	30,00	5	2	4	4
		1.3	Impact on the existing infrastructure	Range [1(Low)-5(High)]	30,00	5	2	2	2
		1.4	Scalability or Adaptability	Range [1(Low)-5(High)]	10,00	1	4	4	5
		1.5	Possibility of installing on existing railways	Range [1 (Yes) or 0 (No)]	20,00	No	Yes	Yes	Yes
INTEROPERABILITY	20,00	2.1	Interoperable with existing Service	Range [1 (Yes) or 0 (No)]	90,00	No	Yes	Yes	Yes
		2.2	Interoperability with future hyperloop	Range [1 (Yes) or 0 (No)]	10,00	Yes	No	Yes	No
TYPE OF SERVICE	30,00	3.1	Passengers: Urban services	Range [1 (Yes) or 0 (No)]	16,67	Yes	Yes	Yes	Yes
		3.2	Passengers: Conventional services	Range [1 (Yes) or 0 (No)]	16,67	Yes	Yes	Yes	Yes
		3.3	Passengers: High speed services	Range [1 (Yes) or 0 (No)]	16,67	Yes	Yes	Yes	Yes
		3.4	Freight: Conventional services	Range [1 (Yes) or 0 (No)]	16,67	No	No	Yes	Yes
		3.5	Freight: Local applications	Range [1 (Yes) or 0 (No)]	16,67	No	Yes	Yes	Yes
		3.6	Both passengers and freight traffic	Range [1 (Yes) or 0 (No)]	16,67	No	Yes	Yes	Yes
TYPE OF VEHICLE	10,00	4.1	Fixed trainsets	Range [1 (Yes) or 0 (No)]	50,00	Yes	Yes	Yes	Yes
		4.2	Pods	Range [1 (Yes) or 0 (No)]	50,00	Yes	Yes	Yes	No

Figure 3.4 Criteria and data used for the MCA

3.2.3. Application of the MCA

With the selected criteria and their weights, the results presented in Figures 1-5 and 1-6 were obtained.

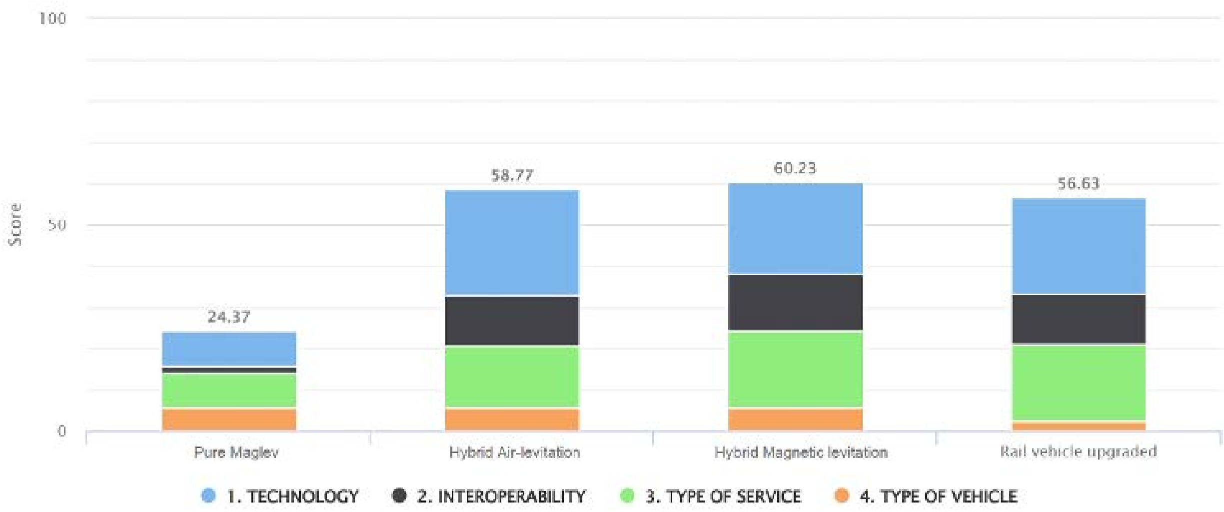

Figure 3.5 Criteria contribution in the MCA

CRITERIA Definition		Definition	Pure Maglev	Hybrid Air-levitation	Hybrid Mag levitation	Rail vehicle upgraded
3. TYPE OF SERVICE	3.1	Passengers: Urban services	Yes	Yes[1]	Yes[1]	Yes
	3.2	Passengers: Conventional services	Yes	Yes	Yes	Yes
	3.3	Passengers: High speed services	Yes	Yes	Yes	Yes
	3.4	Freight: Conventional services	No	No	Yes	Yes
	3.5	Freight: Local applications	No	Yes[1]	Yes[1]	Yes
	3.6	Both passengers and freight traffic	No	Yes	Yes	Yes
4. TYPE OF VEHICLE	4.1	Fixed trainsets	Yes	Yes	Yes	Yes
	4.2	Pods	Yes	Yes	Yes	No

(The columns Pure Maglev to Rail vehicle upgraded are under the spanning header "System Configuration".)

Figure 3.6 Criteria for selection of possible use cases

From this analysis, it appears that the MDS configurations with the greatest potential for use in today's rail infrastructure are the hybrid magnetic levitation and the air levitation MDS, closely followed by the rail upgraded vehicles. In contrast, the systems that are the most challenging to use on the current infrastructure are the existing pure maglev systems.

3.2.4. Selection of three MDS configurations

After the selection of the three MDS configurations through the MCA and the analysis of the possible use cases where they could be applied, an early selection of the most interesting use cases was made in terms of applicability of the MDS technology to the specific use case, considering the actual existing needs for transport infrastructures or services across Europe.

This primary selection was composed of six use cases where, in order to cover a wide range of possibilities, it considered the inclusion of the three MDS configurations that emerged from MCA analysis and the three different time horizons defined for the analysis (short, medium and long term). These possible use cases are shown in Figure 3.7.

	Freight application	Passenger application
Hybrid MDS based on air levitation	Local freight applications (Medium-term)	Conventional passenger services (Long-term)
Hybrid MDS based on magnetic levitation	Conventional freight services (Long-term)	High speed passenger services (Long-term)
Rail vehicle upgraded	Local freight applications (Short-term)	Conventional passenger services (Medium-term)

Figure 3.7 Selection of possible use cases for MDS applications.

3.2.4.1 Rail vehicle upgraded MDS

The “Incline Pusher” use case was selected by the MCA as one of the most interesting cases, with high scores in the two criteria with the higher weight: "Environmental Sustainability" & "Implementation and Economics". The incline pusher can directly provide additional tractive force which is not dependent on conventional powered vehicles and rail/wheel adhesion. There are two different case applications:

In the first case, the windings are built on the track with high gradient and permanent magnets are installed under some freight wagons, so the incline pusher can provide additional tractive force. This improves the performance of freight vehicles on challenging infrastructures with high gradients (to avoid the use of additional locomotives and to increase the operational speed). Short but steep inclines affect the maximum load of a freight composition, which can result in reduced trains loads or additional locomotives, which causes additional operational costs. This application of the incline pusher can help to reduce the operational costs of using additional locomotives and increase line capacity by increasing the operational speed of the freight trains.

The second case uses the incline pusher to negotiate a much higher gradient than the original designed gradient. Therefore, the allowable maximum track gradient in design becomes possible, which is less limited by traction and adhesion. This achieves a reduction in construction costs on lines planned at the design stage by allowing for higher track gradients in design and construction. This use case is applied to passenger dedicated lines. Upgraded conventional railway vehicles and tracks allow much more freedom when it comes to the orography where the line is to be built, so that a much less costly infrastructure is projected, with reduced earthworks and less tunnel or bridge sections to be built. Meanwhile, it is possible to achieve a high acceleration and retardation to reduce travelling time and increase line capacity.

3.2.4.2 Hybrid MDS based on air levitation

A hybrid MDS system based on air levitation generally refers to a transportation system that relies both on wheel-based suspension and air levitation suspension in combination or during different operative conditions. An air-cushion vehicle, also named as airlev vehicle for the purposes of the project, is an important alternative for hybrid MDS development. Integrating airlev trains into existing railway systems as well as possible new railway infrastructures is the main idea behind the concept of hybrid MDS based on air levitation.

The principle behind air cushion suspension is rooted in creating a pressure differential between the air inside and outside an air chamber. This generates enough mechanical force to lift an object, such as a vehicle, a few millimetres off the ground [4]. This technology will utilize a cushion of air to lift the vehicle, envisioned to further eliminate friction, reduce energy consumption, and enable even higher speeds similar to maglev trains but with much lower costs.

Instead of using wheels in direct contact with rails, airlev trains use powerful fans to create a cushion of air underneath them, effectively levitating the vehicle above the track. This not only decreases friction but also reduces wear and tear on both the vehicle and the infrastructure, promising greater longevity and lower maintenance costs.

3.2.4.3 Hybrid MDS based magnetic levitation

A hybrid MDS system based on magnetic levitation generally refers to a transportation system that relies both on wheel-based suspension and magnetic levitation suspension in combination or during different operative conditions. As an example, the vehicle can operate on wheels during switch crossing or platform approaching and on magnetic levitation systems on dedicated maglev corridors.

The propulsion can be wheel-based during wheeled operation while different technologies can be adopted during maglev operations. A proper choice of the propulsion technology must be done based on a compatibility study and an economic evaluation. The vehicle shall be designed to ensure the compatibility with the existing or upgraded railway infrastructure as well as the interoperability of the transportation system.

3.3. Conclusion and Perspective

In conclusion, while MDS technologies offer some advantages, particularly in localized power boosts and potentially lower track maintenance, the overall commercial benefits compared to conventional technologies are nuanced and require further technological development and evaluation.

The MCA shows in detail that all the three approaches have significant benefits. The “conventional railway upgraded” is well-suited as an overlay on a regular rail system to solve local issues and helps to increase performance and sustainability. This approach keeps the interoperability with the existing rail system and most probably allow mixed operation. The two further use cases are delivering performance benefits and are better suited for specific pod-systems.

In the next steps is planned to have some of the technologies implemented in real scale and tested in a realistic environment.

Zoom Authors

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Funded by the European Union

This project is under the scope of the Europe’s Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101121851. The project is supported by the Europe’s Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe’s Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

PhD

4. New Generation Train Communication Network

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4.1. Introduction

Train services are mainly composed of two main areas namely Train Control and Monitoring System (TCMS) and On-board Multimedia and Telematics (OMTS). TCMS is responsible of the integration of train functionalities such as braking, commands and others. Whereas OMTS conveys operator and customer information. Telecommunication infrastructure used by Train Communication Network (TCN) to convey the train traffic is currently very simple and based on a wired system. Due to cables maintenance and diagnosis cost, the efficiency of this system should be greatly improved to enhance the functionality of both TCMS and OMTS domains. Hence, the New Generation Train Communication Network (NG-TCN) has emerged as a major innovation introducing a wireless architecture as an enabler to enhanced automation, flexible train management and increased railway capacity, by exploiting the virtual coupling concept. Our contribution in the IAM4RAIL project focus on the design and evaluation of safe, secure, resilient solution for the wireless train-to-train communications (inter consist and inter carriage) as illustrated on Figure 4.1. Different complementary existing wireless technologies will be investigated in laboratory and with simulations, namely: ITS-G5, UWB, LTE and 5GNR including millimetric Waves.

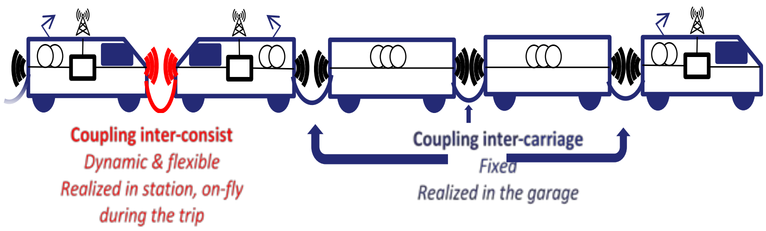

Figure 4.1 Wireless onboard telecommunication network

Virtual coupling [1], is based on mutual information exchange between trains regarding velocity, position, braking characteristics. It allows trains to move at a closer distance than the traditional distance allowed by the conventional Absolute Braking Distance Supervision (ABDS) concept. Two types of coupling are considered in this project namely mechanical and virtual coupling. In the conventional coupling mode and for safety reasons, it is recommended to keep safety TCMS services on wired based communication, while transmitting the other domains wirelessly. As a result, the new generation system should be capable of considering all coupling modes (virtual and mechanical). In addition, the proposed system should consider the data overhead resulting from the virtual coupling from transmitting additional information such as braking curve, speed and positions of the consists.

4.2. Related works

Many European projects and research activities have emerged to address the application of the NG-TCN in the future railway systems, among which we can cite Connecta-1-2-3 [3], Safe4Rail-2 [4] and Roll2Rail-2 [5]. Connecta projects investigated the candidate wireless technologies that could meet TCMS and OMTS domains requirements for both Wireless Train Backbone (WLTB) and Wireless Consist Network (WLCN). Connecta concluded that none of the existing radio technologies satisfy completely the TCMS domain. On the contrary, the requirements of OMTS

domain may be satisfied in theory by IEEE 802.11s Technology. Connecta refers to the New Radio V2X (NR-V2X) technology as the solution that seems to be the most appropriate technology to satisfy the WLTB requirements. Roll2Rail project investigated the technologies and the architectures to allow the development of NG-TCN based on wireless transmission with the goal to use them in TCMS, as well as other on-board systems. Roll2Rail specifies the requirements of the NG-TCN system with particular focus on the communication systems at both WLCN and WLTB levels, including train to train communication. Safe4Rail project proposed a demonstrator prototype for WLTB based on LTE-V2X with an additional overlay module to handle the missing features (service discovery, group communication and mesh networking). The project also investigated NR-V2X from a theoretical point of view, as a potential wireless solution.
The authors in [6] investigated the applicability of the NR-V2X at WLTB communications. The results indicate that NR-V2X technology is suitable for WLTB, but in order to cover a large number of consists either high-end 5G configurations need to be used (such as 4x4 MIMO and beamforming in millimeter waves) or the requirements for the WLTB need to be scaled down. In [7], an LTE-based WLTB system is tested in metro environments. Results illustrate that the system can transfer data at 3.2Mbps with acceptable Frame Error Rate (FER). The authors in [8] investigated various available and future wireless technologies matching the requirements at both train backbone and consist levels. It was concluded that there is not a single wireless technology alone that is capable of matching all the NG-TCMS requirements.
Hence, the problematic of emerging towards NG-TCN has not been yet fully answered and further research activities are needed to find the suitable technology or technologies that might answer NG-TCN needs.

4.3. Requirements and User Needs

The requirements are mainly stemming from the different train types, various environments, coupling modes, Interference resilience, and security as illustrated in Figure 4.2 Following the publication of subset 147, very precise temporal alignment or time sensitive function (TSN) is excluded. Hence the technologies relying on TSN will not be considered.

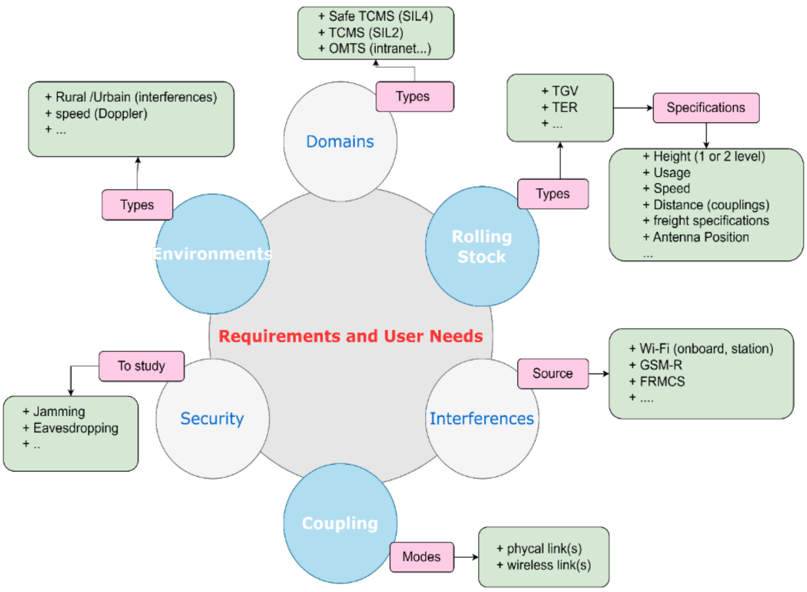

Figure 4.2 User needs and requirements

There are three different types of service domains namely safe-TCMS, non-safe TCMS and OMTS. According to its functionality, each of these domains has different requirements in terms of data rate and latency. Hence, the new proposed wireless system should be capable of providing adequate resources to each domain to meet the

requirements imposed by each domain and for different rolling stocks and environment types with taking into account the different type of coupling (virtual and physical).
One of the major challenges to the NG-TCN is the interference of other coexisting wireless systems in the railway environment such as the FRMCS, GSM-R and the Wi-Fi onboard and at the stations. Therefore, the proposed system should adopt interference mitigation techniques or consider new frequency bands to operate on to avoid any potential interference with the existing/installed wireless systems.

4.4. Train services

Train services can be classified in the following three function domains: Train Control and Management System (TCMS), Operator Oriented Services (OOS) and Customer Oriented Services (COS) as illustrated in 3. Normally in the railway activities, those three domains can be grouped into two areas TCMS and On-board Multimedia and Telematics (OMTS), with OMTS that includes both OOS and COS domains. The TCMS area can be divided into two subareas, safe TCMS and non-safe TCMS. The safe notion comes from the SIL (Safety Integrity Level) associated with each service. Generally, in the TCMS, there are 3 SIL granularities: SIL4, SIL2, SIL0.

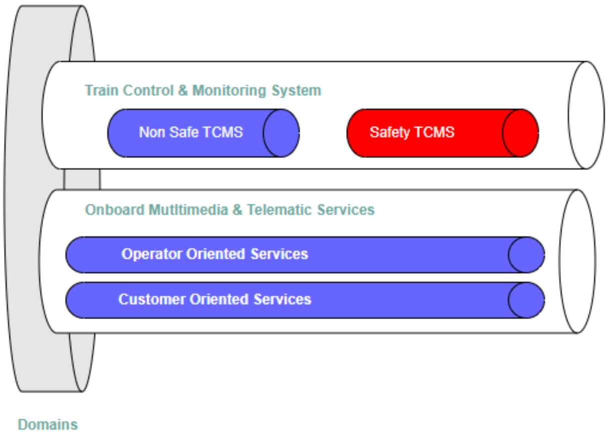

Figure 4.3 Train services domains

4.5. Scenarios and Use Cases

The train communication network consists of two sub networks namely intra-consist and inter-consist. **Intra-consist** network is composed of intra-carriage and inter-carriage networks. **Intra-carriage** consists of End Devices (ED) or/and Wireless End Devices (WED) that communicate with each other at carriage level using a switch or Wireless Access Point (WAP) respectively. **The inter-carriage** network secures the communication among the carriages in wired manner by using a consist switch (CS) establishing what is referred to as Ethernet Consist Network (ECN), or in wireless manner using WAP forming a wireless consist network (WLCN). **Inter-consist** network acts at train backbone level, it performs inter-consist communication either wirelessly using Wireless Train Backbone Nodes (WLTBN), or via Ethernet Train Backbone Nodes (ETBN). The current train network is based on Ethernet at both intra-consist and inter-consist levels, to carry out the communications among coupled train units and carriages as illustrated in Figure 4.4.

Figure 4.4 Current TCN usage case

We propose four different scenarios and use cases described here after.

1. **Ethernet Intra Consist-Hybrid Inter Consist**: In this approach we maintain the consist network based on the ethernet (ECN) at the intra-consist level for both safe and non-safe domains. At the inter-consist level and for safety reasons, safe TCMS is kept connected via the Ethernet Train Backbone (ETB), while a wireless train backbone (WLTB) is used to carry out wireless communication for non-safe TCMS and OMTS. This scheme the physical coupling.
2. **Hybrid Intra Consist-Hybrid Inter Consist**: Similarly, Scenario 2 maintains the safe-TCMS domain ethernet-based at both intra and inter-consist levels. Whereas wireless communication will be adopted for non-safe TCMS and OMTS domains at inter and intra consist communication using wireless access points (WAP) and wireless train backbone nodes (WLTBN) respectively. Wherein the end devices (ED) are replaced (when possible) with Wireless End Devices (WED), and those wireless end devices are connected to a WAP to carry out the intra-consist communication in a wireless manner. Like the scenario 1, this scheme requires the physical coupling.
3. **Ethernet Intra Consist -Wireless Inter Consist**: This approach maintains the structure of the ECN at the intra-consist level, but it uses wireless backbones for inter-consist communication for all domains (safe TCMS, non-safe TCSM and OMTS). It is worth mentioning that this approach can be applied in both mechanical and virtual coupling modes.
4. **Hybrid Intra Consist-Wireless Inter Consist**: In this approach all end devices (that can be replaced), switches and wired backbone nodes are replaced by WED, WAP and WLTBN respectively for all domains at intra-consist and inter-consist levels. While keeping the end devices that cannot be replaced by wireless devices connected via switch, and the latest is connected to the WAP. This scenario can be applied in both modes of coupling mechanical and virtual.

4.6. TCMS and OMTS Requirements

Table 4.1 provides the expected network performance identified by Roll2Rail project for the WLTB based on the current network uses, as well as the network performance expected by the NG-TCN. Roll2Rail project defines the requirements needed by both TCMS and OMTS domains in term of data rate, latency and jitter. From Table 4.1, it can be deduced that the radio technology to be adopted for the TCMS domain must provide a data rate of 43Mbps (30Mbps 70%) with minimum cycle times of 20ms, and minimum latencies equal to 60ms. Regarding the current use OMTS domain, it has a minimum data rate requirement of 50Mbps (35.2Mbps 70%) with minimum latencies of 100ms.

SCOPE	DATA CLASS		DATA SIZE (octets)	DATA RATE NEED		CYCLE TIME		LATENCY [1]		JITTER	
				Current Use [2]	NG-TCN	Current Use [2]	NG-TCN	Current Use [2]	NG-TCN	Current Use [2]	NG-TCN
TCMS	Process Data	time sensitive	≤ 1432 [acc. IEC61375-2-3]	N/A	≤ 100Mbit/s	N/A	≥ 1 ms	N/A	$T_L = \sum T_{Sn}$ (Example: n=128 → T_L = 15.92ms)	N/A	± 1%
		normal	≤ 1432 [acc. IEC61375-2-3]	10Mbit/s	≤ 100Mbit/s	20ms	≥ 10 ms	Between 3CycleTime and 7CycleTime	$T_L = 2 * \sum T_{Sn}$	N/A	± 50%
	Message Data		≤ 65388 [acc. IEC61375-2-3]	10Mbit/s	≤ 10Mbit/s	N/A	N/A	250ms	≤ 500 ms	N/A	Not relevant
	Supervisory Data		Not relevant	10 Mbit/s	≤ 10Mbit/s	Not relevant	50ms	250ms	$T_L = 2 * \sum T_{Sn}$	N/A	Like process data (normal)
OMTS	Streaming Data	Audio	N/A	≤ 3.2 Mbit/s (100 Kbit/s audio channel, one per consist)		N/A	N/A	≤ 100 ms		N/A	For synchronized A/V Stream: ≤ 80ms difference (lipsynch); minimal jitter
		Video	N/A	≤ 32 Mbit/s 1 Mbit/s video stream [no needs for HD]	≤ 256 Mbit/s (one stream rear-/side-/internal view per consist 8Mbit/s video stream [HD])	N/A	N/A	≤ 500 ms	≤ 100 ms		
	BestEffort Data		≤ 4 GB	Not relevant	≥ 10Mbit/s	N/A	N/A	Not relevant		Not relevant	Not relevant

Table 4.1 Train Domains requirements (Roll2Rail Project)

4.7. Candidate Wireless Technologies

This section investigates the potential wireless technology (technologies) that might meet the requirements of NG-TCN in terms of data rate, latency, interference immunity and network dimension.

4.7.1. LTE-V2X

LTE-Advanced allows obtaining wider transmission bandwidths (up to 100 MHz) and higher data rates compared to previous generation by exploiting carrier aggression approach. LTE-V2X is an LTE based technology that permits user devices to communicate between each other in vehicular scenario without eNodeB intervention using the Side Link (SL) concept introduced by LTE Proximity Services (ProSe) in 3GPP Release 12. LTE Release 14 defined two operation modes namely mode 3 and mode 4. The maximum data rate of the LTE-V2X technology is 27Mbps in mode 4. The end-to-end latency in LTE-V2X is mainly determined by the scheduling process that includes the process of Window Sensing and Selecting that requires between 20 to 100ms. Hence the estimated latency of the LTE-V2X is estimated between 20 to 100ms. Regarding interference resilience, LTE-V2X implements Self-Optimization Network (SON) technique defined in LTE-Advanced Release 10 and beyond. As for the network dimension, LTE supports up to 200 users/nodes per network with maximum communication distance of 387m [4]. LTE-V2X technology allows up to 27Mbps data rate and 50-100ms latency, therefore it does not fulfil the requirements for the TCMS domains, neither for OMTS domain. By contrary, it fulfils the transmission range requirements and the possibility of working in mode 3 and mode 4 allows its use in busy scenarios, i.e., busy junctions, train stations or depots, with a radio scheduling provided by the LTE network and therefore having a collision-free deterministic performance.

4.7.2. Ultra-Wide Band

Ultra-Wide Band (UWB) technology uses low transmit power to transmit short duration pulses of the degree of 1ns in time domain, consequently the UWB signal occupies large bandwidth in the frequency domain. UWB provides a maximum data rate of 27.24Mbps, with non-deterministic medium access where no latency range has been identified in the literature. UWB is immune against multi-path and fading as due to short duration of the signal. Furthermore, as the UWB spreads under the noise floor, the interferences with other coexisting wireless systems are reduced. UWB uses ALOHA as the medium access technique. Regarding network dimensions, the maximum distance for UWB communication is 100m. This communication distance has been calculated using typical transmitter power and receiver sensitivity values . From the discussion above the UWB does not respond to the requirements of both the TCMS and OMTS domains in term of data rate and latency.

4.7.3. Wi-Fi

The theoretical data rate of the Wi-Fi versions varies between 2Mbps to 4.8Gbps. Device-to-device (D2D) communication is provided in 802.11s which modifies the Medium Access Control (MAC) layer in order to allow the devices to sense and access the carrier. Regarding latency, IEEE 802.11 implements Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) as medium access technique. CSMA/CA is non-deterministic technique, wherein latency cannot be predicted and therefore Wi-Fi does not support hard real time applications. However, the latency in Wi-Fi technology varies between 1 to 20ms. Regarding Interference immunity: Wi-Fi operates on the ISM unlicensed bands 2.4 and 5 GHz, hence it is prone to many interferences from other wireless signal operating on the same frequency. However, Dynamic Frequency Selection (DFS) technique was implemented in In IEEE 802.11h to avoid interferences. Wi-Fi network can support hundreds of nodes per network with maximum communication distance of 216m using typical transmitter power and receiver sensitivity values. From the above discussion, Wi-Fi can meet the requirements of TCMS and OMTS domains in term of data rate, however, its non-deterministic access behaviour makes Wi-Fi not suitable for the TCMS domain especially the safe domain.

4.7.4. ITS-G5

Intelligent Transport System G5 (ITS-G5) has been developed by ETSI as an equivalent to the American Dedicated Short-Range Communication (DSRC) technology. ITS-G5 implements LTE-V2X functionalities over Wi-Fi to enable device-to-device communications in transport domain. Wherein, ITS-G5 applies the LTE techniques at the physical layer, and the Wi-Fi MAC layer techniques to leverage the device-to-device communication. Similarly to LTE-V2X, ITS-G5 provides a maximum theoretical data rate of 27Mbps. Regarding time consideration, the latency of ITS_G5 varies from 1 to 20ms. However, unlike LTE-V2X, ITS-G5 does not provide any mode with radio scheduling that may allow deterministic behaviour. The maximum communication distance of ITS-G5 is 300m with up to 200 nodes/user per network. ITS-G5 doesn't fulfil the requirements of both TCMS and OMTS domains in terms of data rate and latency.

4.7.5. NR-V2X

New Radio (NR-V2X) technology has been identified in LTE Release 15/16 as an evolution of LTE-V2X technology in order to benefit from the 5G aspects of Ultra-Reliable Low-Latency Communication (URLLC), Enhanced Broadband (EBB) and Massive Machine Type Communication (MMTC). NR-V2X adopts OFDM-Cyclic Prefix (CP) as waveform for both Uplink and Downlink, whereas LTE only uses OFDM-CP for Downlink. Furthermore, contrary to LTE, 5G NR implements various subcarrier spacing and slot duration. 5G uses two Frequency Ranges (FR): FR1 from 450MHz up to 6GHz, and FR2 (or millimeter waves) from 24.5 GHz up to 52.6GHz, with 200MHz and 400MHz bandwidth respectively. NR-V2X can achieve a maximum data rate of 620Mbps in FR1 and up to 1Gbps in FR2. NR-V2X is expected to provide latencies between 1 to 20ms. Interference avoidance in 5G can be carried out via beamforming technique especially in millimeter waves. Regarding network dimension, NR-V2X can support 200 users per network and variant coverage depending on the adopted frequency. From the previous analysis it can be concluded that none of the existing radio technologies fully satisfies the TCMS domain requirements. By contrary, the requirements of OMTS domain may be satisfied in theory by Wi-Fi technology. NR-V2X seems to be the most appropriate technology to satisfy the NG-TCN requirements.

4.8. Conclusion

In this paper we have presented the work methodology to tackle the NG-TCN implantation, wherein both system requirements and possible implementation scenarios were introduced. User needs concerning different types of rolling stocks, environments and interference sources were considered. Four possible NG-TCN implementation scenarios based on consist and train backbone network types have also been presented. In addition to a state of the art of the previous European project approaches of NG-TCN emigration.
Furthermore, a survey of the possible wireless solutions such as LTE-V2X, ITS-G5 and 5G-V2X has been presented with their corresponding performance metrics. In the future work, we will focus on 5G NR performance evaluation in the context of NG-TCN development and requirements. The study will be based on numerical and in-lab simulations. We will consider the coexistence interference sources in the corresponding channel models. Furthermore, we will propose a versatile, adaptive and safe architecture of the future TCN telecommunication system.

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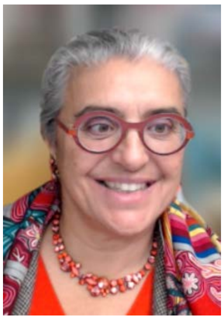

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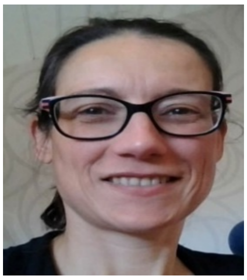

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº101101966. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

5. NG-TCN: Towards Network Slicing in on-board Wireless Train communication networks

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5.1. Introduction

The Train Communication Network (TCN) are typical wired on-board networks of the train defined by the standard IEC 61375 [1]. The TCN architecture is structured hierarchically with two main levels: the Train Backbone Network (TBN) and the Consist Network (CN) shown in figure 1. The CN is a communication network connecting devices within or among carriages that are inseparable during operation. This is referred as intra-Consist communication. The TBN facilitates inter-consist communications, enabling the exchange of data, such as control commands, diagnostics, and monitoring information, voice, video streams and message packets between different train units. The existing TCN infrastructure relies on a costly and maintenance-intensive wired system, highlighting the necessity for advanced wireless technologies and network virtualization to enhance efficiency and flexibility.
Therefore, European projects have advocated for the Next generation of TCN (NG-TCN) including a Wireless Train Backbone Network (WLTBN). Nevertheless, Railway Communication services are complex in the diversity of requirement as specified by the future railways communication User requirement specification by the UIC [2]. This complexity includes priority of service, security, reliability, throughput which could be amplified in a wireless context therefore posing a traffic orchestration problem [3]. Despite significant efforts made at the European level to explore wireless technologies that could meet the railways communication requirements, deeper investigations are needed to address the resource orchestration question in this wireless approach.
To deal with this resource and traffic orchestration problem, the advent of 5G is regarded as promising in the railway context [4]. Network Slicing (NS), which allows the segmentation of a single network into different virtual networks each with guaranteed Quality of Service (QoS) for connected devices on the same infrastructure, is a 5G feature with great potentials in this case. Despite this interesting potential, there is very limited research works focusing on Network Slicing within the WLTBN. This abstract describes how Network Slicing principles can be leveraged to enhance WLTBN. We analyze the wireless train backbone problem in the state of the art. We review related works to contextualize current research and identify gaps. We also highlight the main challenges and research directions in NS implementation in on-board railway networks, including spectral efficiency, intelligent resource management, and service reliability.

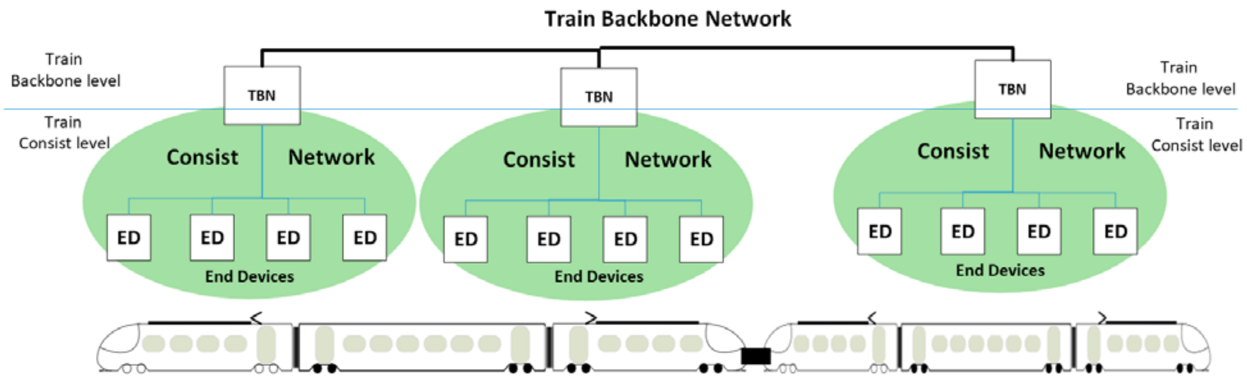

Figure 5.1 Wired TCN Architecture

5.2. Background

5.2.1. The Wireless Train Backbone Problem

The introduction of wireless technologies at both the backbone and consist levels aims to create solutions that increase flexibility, ease interoperability, and reduce the costs associated with wired solutions [3]. The WLTB is designed to connect different consists, or groups of vehicles, within a train as proposed by Roll2Rail project [5] shown in figure 2. Unlike a wired network, introducing wireless technology into the train backbone network brings inherent challenges, notably sensitivity to radio conditions such as signal propagation, interference, and loss.
European projects have significantly advanced the Wireless Train Backbone Network (WLTBN) in the NG-TCN context. The Roll2Rail project (2015-2017)[5] specified the requirements for the NG-TCN system, addressing both the Wireless Consist Network (WLCN) and WLTBN levels. As shown in figure 2, it implemented one ENodeB per train consist with UEs as Access Points for end devices and utilized RFID for train topology discovery. SAFE4RAIL 1[6] and 2 [7] (2018-2022) developed a WLTBN prototype based on LTE-V2X with additional modules for service discovery and mesh networking, and investigated NR-V2X. CONNECTA 1[8], 2[9], and 3[10] (2016-2023) concluded that no existing radio technology fully satisfies the Train Control and Management System (TCMS), and suggested combination of LTE-V2X and LTE-D2D functionalities for WLTBN. IAM4RAIL project [11] (ongoing) found Wi-Fi suitable for data rates but not for TCMS due to its non-deterministic access behaviour, and plans to study NR-V2X for NG-TCN requirements. A solution based on 5G-NR and a combination of technologies is studied in the framework of the project by SNCF [12].These projects collectively enhance wireless train communications by addressing key challenges and proposing innovative solutions. But the question of Network Slicing in NG-TCN has not received enough attention.
The problem is that the WLTBN serves multiple on-board end devices with diverse service requirements varying in priority, latency, and throughput. It is important to maintain the coexistence of heterogeneous requirements, which span sensitive data traffic, video streaming, voice communication, and low-latency periodic data. All train functions collected in CENELEC EN15380-4 standard[13] are categorized into three key domains: Train Control and Management System (TCMS), Operator Oriented Services (OOS), and Customer Oriented Services (COS). TCMS consists of on-board systems like propulsion and braking, requiring reliability, high security level and minimal latency. OOS supports operational services for scheduling and maintenance with throughput requirement performance like CCTV and Passenger Information System (PIS). COS enhances passenger experience with real-time information and entertainment, demanding high bandwidth and seamless connectivity. Addressing these complexities is essential to maintain operational efficiency and passenger satisfaction on trains.

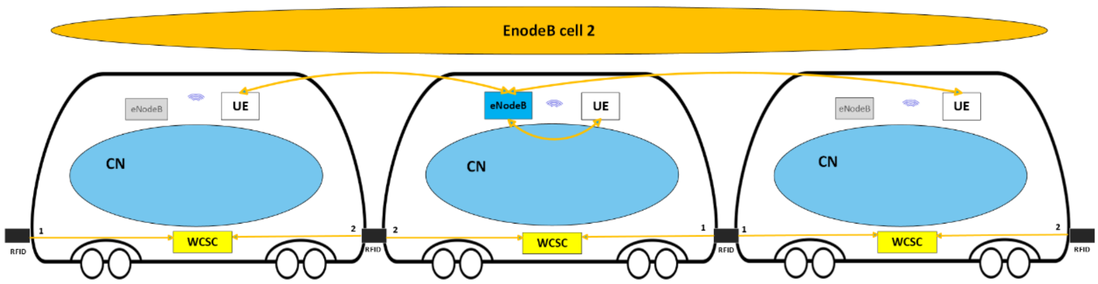

Figure 5.2: NG-TCN with wireless Train backbone Network using 4/5G [5]

5.2.2. The Network Slicing (NS) Principle

Network Slicing, a core feature developed in the 5G 3GPP standards since release 15 [14], involves partitioning network resources to create virtual, customizable networks for various services or user groups. This approach extends cellular networks beyond the traditional "individual mobile user" model to support new applications with diverse requirements [15]. By forming logical "network slices," multiple independent end-to-end (E2E) networks can coexist on the same physical infrastructure. Each slice is tailored to meet service requirements sensitive to performance metrics such as latency for Ultra-Reliable Low-Latency Communications (URLLC), throughput for Mobile Broadband (MBB), and reliability for Vehicle-to-Vehicle (V2V) or critical railway communications.

5.3. Related Works

In Section 2, we introduced the evolution of the WLTBN problem through various European projects, which serves as a starting point for our work. Our analysis of the state of the art in Network Slicing specifically dedicated to railway communication reveals a limited amount of research, highlighting that this concept is still in its early stages in railways, particularly in on-board railway networks.
Authors in [16] proposed Slicing model to enable coexistence of train control services (TCS) and Passenger Information Services (PIS). Considering slice attributes such as the number of terminals, latency for TCS, and throughput for PIS, channels are reserved for slices in advance. Authors considered a simplified service requirement assuming two types of services, while railway requirements have more varying characteristics as explained in Section 2.

5.4. Leveraging NS in WLTBN

5G-based Network Slicing is considered key for future railway operations [17]. Considering the varieties of service embedded on-bord the train, NS can be leveraged as an enabling factor for optimal resource utilization. Considering the above domains TCMS, OSS and COS, we defined three dedicated Network slices tailored to their specific needs respectively Critical, performance and business slice. The TCMS, categorized under “critical” Slice use cases, requires ultra-reliable low-latency communication (URLLC) for real-time monitoring and control of on-board systems. The OOS comes under the “Performance” slice use cases, where network slices are designed to optimize throughput and efficiency, supporting operational applications such as in-train communication between staff and passengers. The “Business” slice use cases is dedicated to COS prioritizing high bandwidth services for passenger. Using NS, various types of applications, such as low-latency remote driving applications and platooning applications, may be supported at the same time despite their different virtual network characteristics – e.g., different frequency bands, heterogeneous throughput requirements, different latency tolerances, and heterogeneous security requirements [18].
As shown in Figure 3, our proposal presents the implementation of network slicing within the WLTBN. Building on the NG-TCN architecture, which was enhanced by previous European projects, certain components of the WLTBN have been retained. The train topology discovery principle uses RFID, and the eNB has been replaced by a gNB (5G). A train is composed of a gNB, with each consist represented by a UE, which acts as a gateway between the intra-consist and inter-consist level network. We introduce the concept of network slicing in the RAN, ensuring the allocation of radio resources for different types of traffic, particularly in 3 slices namely critical, performance, and business slice. Our proposal focuses on on-board traffic scenarios with abstraction of gateway points that could lead to external networks.

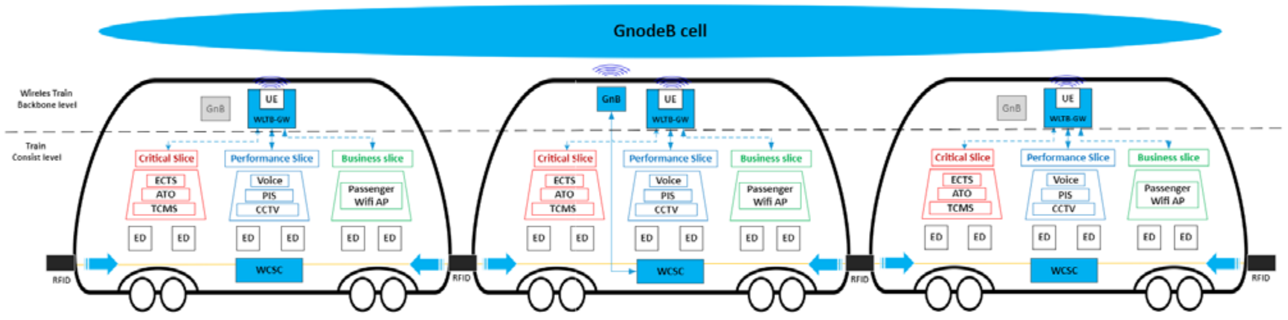

Figure 2.3: 5G Network Slicing in wireless Train backbone Network

5.5. Challenges and Research Directions

We identified major challenges and emerging research directions in network slicing for railway communications. These are centred around enhancing spectral efficiency, advancing intelligent resource management, and ensuring service reliability.

5.5.1. Spectral Efficiency

Spectral efficiency remains a challenge due to the need for a harmonized railway bands across Europe and the limited availability of frequency bands. Consequently, there is a need to adapt resource allocation in the Radio Access Network (RAN) for future railway mobile radio[19]. The Future research should focus on advanced modulation and coding schemes, spectrum sharing techniques, and dynamic spectrum access methods to improve spectral efficiency. Additionally, exploring the use of higher frequency bands (millimetre wave) and integrating multiple-input multiple-output (4x4 MIMO) technology as suggested in [20], could further enhance data throughput. The implementation of Reconfigurable Intelligent Surfaces (RIS) on the train explored in [21] can be considered as intelligent mirrors along with beamforming techniques to direct signals more efficiently, thereby significantly improving spectral efficiency and coverage [22].

5.5.2. Intelligent Resource Management

Managing computing and radio resources in a dynamic train environment is highly complex because it involves various interdependent variables and constraints. With NS these interdependencies can quickly result in a combinatorial explosion of possible solutions, categorizing the problem as NP-hard. In computational complexity theory, NP-hard problems are those for which no polynomial-time algorithm is known to exist that can solve all instances optimally. This complexity underscores the need for sophisticated algorithms to handle resource orchestration. As surveyed in [23], Machine learning, particularly Deep Reinforcement Learning (DRL) in [24], offers promising solutions with the potential to predict network conditions [25], optimize resource allocation [26], and ensure quality of service (QoS) for various applications [27]. Future research should investigate the development of ML-based algorithms for real-time resource management, and adaptive Network Slicing.

5.5.3. Service Reliability

Ensuring uninterrupted service delivery, even during events like train carriage (consist network) coupling, is critical for the WLTBN. Particular attention should be drawn on redundancy mechanisms, fault-tolerant network designs, and robust handover protocols to maintain continuous service. Leveraging edge computing for local data processing can enhance reliability by reducing dependency on central servers, thereby minimizing latency, and improving the responsiveness of on-board systems for real-time applications and critical operations. Authors in [28] showed the benefits of on-board content caching in optimizing content retrieval. Additionally, implementing stringent security measures is crucial to protect against cyber threats and maintain service integrity.

5.6. Conclusion

In this abstract we explored the potential of leveraging 5G Network Slicing to enhance the Wireless Train Backbone Network (WLTBN). The current limitations of the Train Communication Network (TCN), including high costs, maintenance challenges, and inflexibility, made the need for advanced wireless technologies and network virtualization becomes evident. The transition to WLTBN presents inherent challenges, particularly sensitivity to radio conditions such as signal propagation, interference, and attenuation. These points are analysed within the IAM4RAIL project as mentioned previously. The traffic orchestration problem arises from the complexity involving service prioritization, security, reliability, and throughput, which can be amplified in a wireless context. Network

Slicing with 5G offers promising potential to ensure the coexistence of complex and heterogeneous service requirements, catering to diverse communication requirements and ensuring high performance for various train subsystems. We demonstrated that designing intelligent, relevant, and secure slice orchestration algorithms is crucial for leveraging Network Slicing in the context of railways. We identified Key challenges including spectral efficiency, intelligent resource management, and service reliability. Future research should investigate these areas for seamless integration of wireless technologies in railways, enhancing passenger and freight services and paving the way for innovative railway operations.[29]

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Funded by the European Union

This project is under the scope of the Europe’s Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº101101966. The project is supported by the Europe’s Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe’s Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

6. Rail Fasteners Looseness Detection by Analysing Real and Synthetic Axle-Box Acceleration Data: A Dual Approach

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6.1. Introduction

Rail fasteners are a key component of railway infrastructure, as they connect the rail to the ground along the entire length of the track and thus prevent dimensional deviations in the track geometry. Checking the condition of these fasteners, which is essential for railway safety, is still based on visual inspections that are carried out manually. Although progress has been made in detection by on board vision systems on inspection vehicles, these vehicles do not have frequent access to the track and the system itself is subject to ideal environmental conditions. For this reason, it seems clear that analysing the vehicle's reaction to passing over areas with damaged fasteners (due to loss of torque or missing fastener clip) is the future of detecting this type of defect. Appropriate processing of acceleration signals in the axle-box of a vehicle (inspection and passenger vehicles) is the way forward, both for the detection of loose fasteners and for the further development of predictive maintenance of the railway infrastructure.

As mentioned by Baniček et al. [1], any defect or damage in any of the fastening system components can lead to a change in track geometry, wear of the rail, and loosening or failure of the rail fastening point. For this reason, the continuous acquisition of track condition data using ABA (Axle-Box Accelerations) and its subsequent analysis is a key factor in maintenance decision making by asset and maintenance managers.

6.2. Methodology

On-board systems are commonly used to monitor any section of the track [2]. They are primarily based on the acquisition of acceleration data from accelerometers installed in the axle-boxes of in-service rail vehicles [3], [4], although these devices can also be installed in the bogies or body of the vehicles.

According to the type of track defects or problems to be detected and the main types of sensors used, different signal filtering techniques and algorithms may be implemented to analyse the recorded signals. In this research, we will use ABA data to assess the condition of rail fasteners [5], investigating the related impact on the condition of track geometry (e.g. misalignments) and the apparition of other defects in the rail (e.g. corrugation).

To do so, the work will be developed in four steps:

1. Carry out a field test by striking the rail head with an excitation hammer and varying the tightening torque of a fastening element. The aim is to evaluate the reaction of the rail to different torque situations.
2. Analyse the real acceleration signals of a section of track where loosened fasteners have been detected using a vision device. This data comes from the axle box accelerometers and the optical camera system installed in the Leonardo inspection vehicle.
3. Create a virtual model of the track and the vehicle to reproduce the reaction of the loosened fasteners and analyse the acceleration data provided by a virtual sensor.
4. Develop different algorithms to detect loosened fasteners and compare the results with both real and synthetic data.

6.2.1. Rail response under an impact excitation

Among other applications, modal analysis ([6], [7]) is heavily used to analyse any critical structure that is exposed to forces that might induce harmful or even destructive resonant frequencies with little damping, and can give an overview of the natural frequencies, damping parameters, and structural mode shapes [8].

Modal test and analysis typically involve:

- One or more exciters (modal shaker or impact hammer)
- Force transducers to acquire the input excitation signals
- Accelerometers to acquire the output response signals
- A data acquisition device to display and record the test
- A modal test and analysis software application

The field test will follow the methodology described in previous papers related to the study and detection of failed fasteners [9], [10] and damaged railways [11], based on the idea that a damage in the fastener will change system's stiffness, inertia, or energy dissipation properties, and therefore, the measured dynamic response of the system. In the first research study, a power spectrum entropy method based on entropy theory and power spectrum analysis was presented, and fastener looseness was identified by analysing the frequency change of vibrations when the rail was hit with a hammer. In the second study, a hammer test was conducted to analyse the vibration signal excited by an impulse. It was considered that the amplitude of the rail vibration is small, and the damping speed is fast when the fasteners are properly tightened, while the amplitude of the rail vibration increases and the damping attenuation speed decreases when the fasteners are loose. In the third study, the feasibility of the FRF-based statistical method in combination with non-destructive hammer test measurements (*see* Figure 6.1) was investigated, and it was found that it can be used to identify the characteristic frequencies of damaged railway rails.

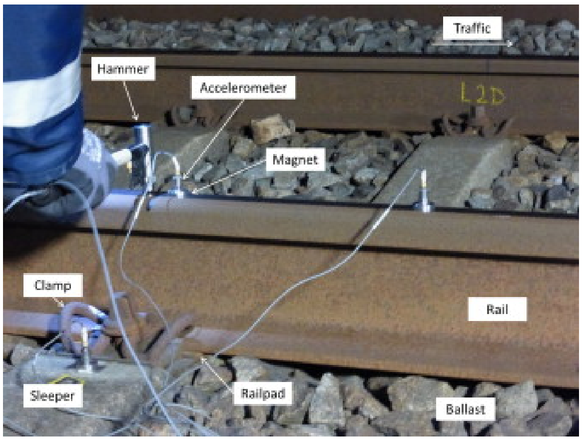

Figure 6.1 Layout of Impact Hammer Test used by Oregui et al. [11]

The experiment will be conducted by applying different torque conditions in one of the fasteners. By applying the operating conditions criteria defined by Wei et al. [12] to our real case, the following Table 6.1 has been defined:

Excitation Number	1	2	3	4	5
Tightening torque (N·m)	220	165	110	55	0
Damage severity (%)	0	25	50	75	100

Table 6.1 Torque looseness conditions on target fastener

Other authors [9] have stated similar tightening conditions for the test, so that when the looseness is 0%, it means the bolt or screw is completely fastened and the corresponding torque is 220 N·m, and if the looseness or damage severity is 100%, the corresponding torque will be 0 N·m.
The desired layout of the hammer test will follow the following configuration (*see* Figure 6.2), with an excitation and vertical and lateral measurements.

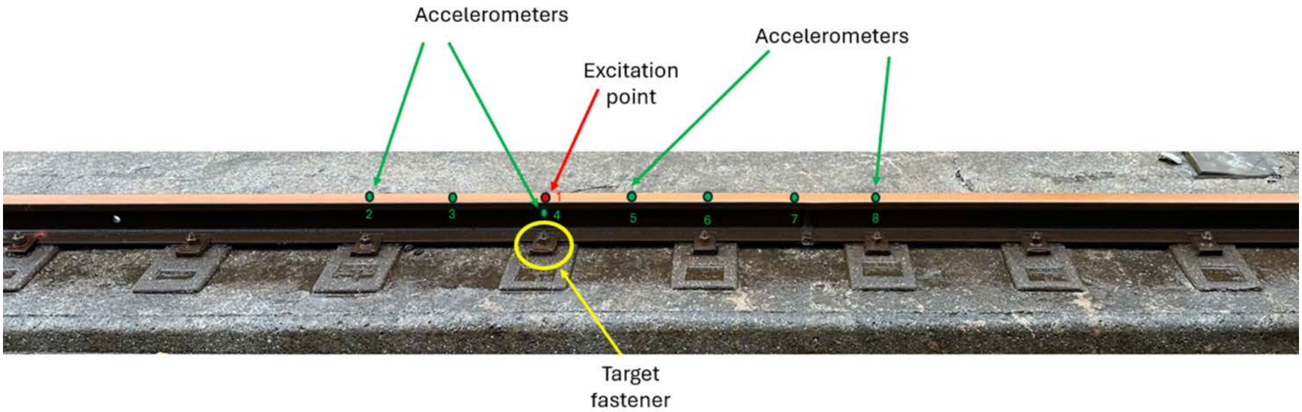

Figure 6.2 Designed hammer test layout to be applied

6.2.2. Real acceleration data. Selection and analysis of rail segments with loosen fasteners

Within the European IAM4RAIL Project [13], the company Strukton Rail, owner of the Leonardo inspection vehicle (*see* Figure 6.3), is providing different datasets with acceleration values collected in the vehicle's axle-box, as well as different track inspection data, both geometric and visual, in different track segments.

The following data are available:

- ABA acceleration data (two tri-axial accelerometers on one axis)
- Trackscan data with track geometry
- GPR (Ground Penetrating Radar) ground data
- Tagged images of defects/situations detected

The geographical information of the track is available, so it is possible to locate the area where something is happening, so that the acceleration data can be aligned with the Trackscan data to analyse those sections of ABA data where the defects to be analysed are known to be.

Figure 6.3 Leonardo inspection vehicle (Strukton Rail NV)

In the case study, the geolocation of the sleepers is available with the tag "defective", which is applied to moved or broken clips (loosened fasteners) and the tag "missing", applied to clips that have disappeared.

With this information we can select a specific track segment with the desired loosened fasteners. Three example images can be seen below, where the yellow circles indicate defective fasteners and the red ones missing fasteners (*see* Figure 6.4).

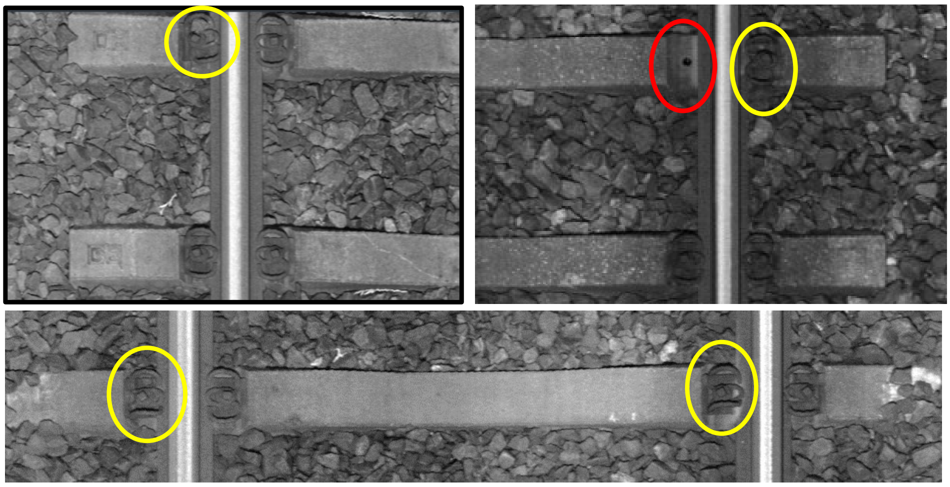

Figure 6.4 Example of loosen fasteners detected by Leonardo (Strukton Rail)

Once we have selected the appropriate segments, and knowing the modal behaviour of the track, we will be able to apply different signal denoising and analysing algorithms.

This will be one of the parallel lines of work for the comparison between the real acceleration data and the results that will be obtained in the simulation [14].

6.2.3. Virtual model creation and synthetic data generation

After collecting the information from track and vehicle we can create a virtual model to generate synthetic acceleration data that will be processed and compared with the real data.

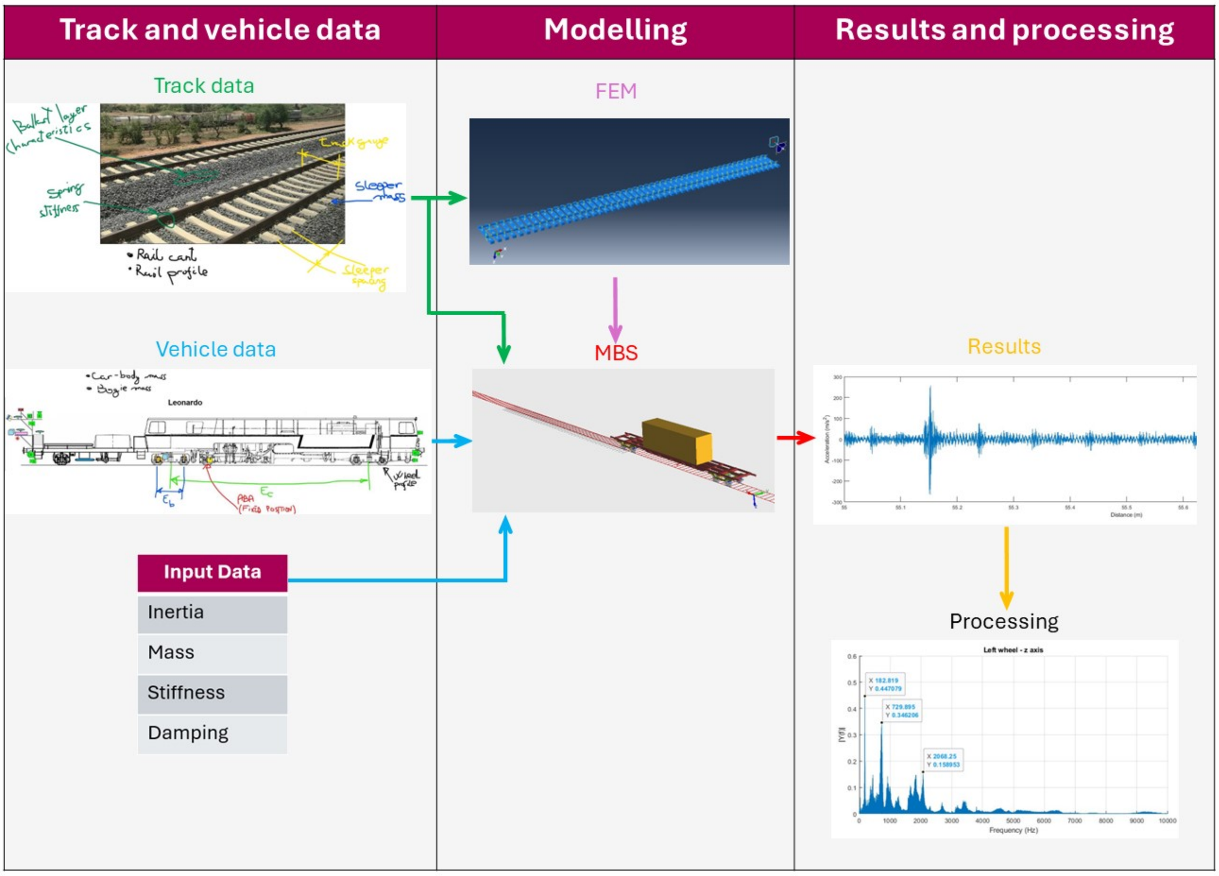

Figure 6.5 Workflow of the virtual model creation

As it can be seen in the workflow (*see* Figure 6.5), the first step has been the generation of a virtual model of the track using the FEM software Abaqus (*see* Figure 6.6). In this track model, defects must be introduced, which in the case of loosened fasteners consists of varying the equivalent stiffness and damping values in the desired fastener(s).

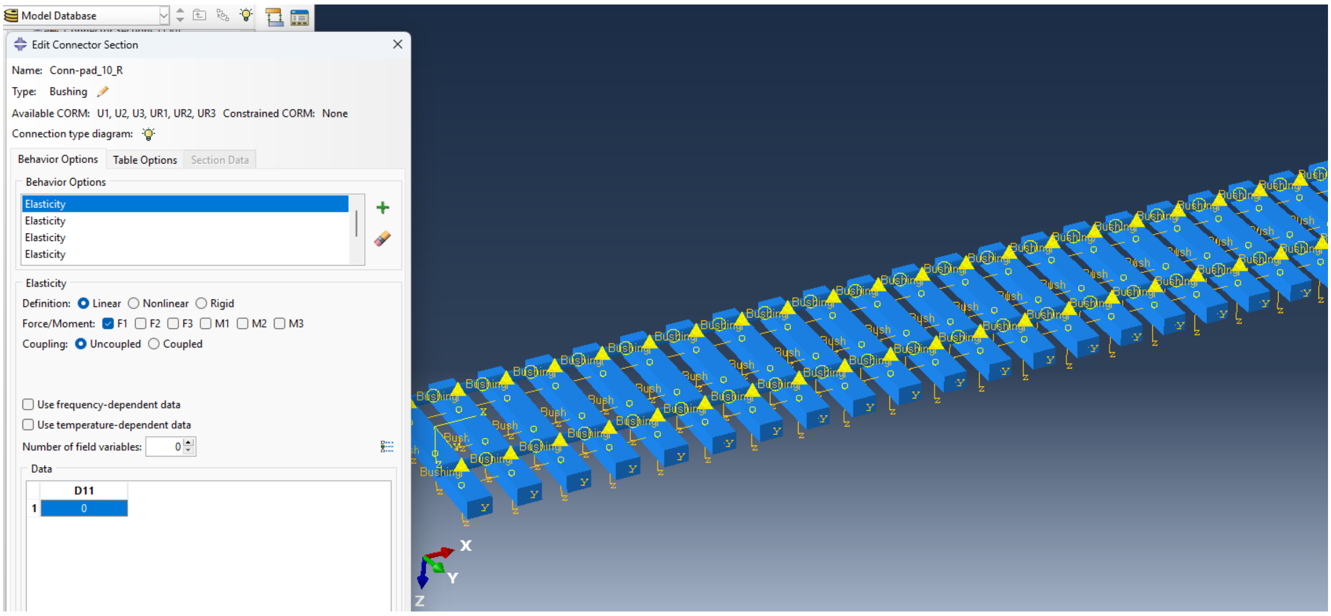

Figure 6.6 Track model in Abaqus (straight segment)

This model is then imported into the multibody simulation software (MBS) Simpack, where the model of the inspection vehicle has previously been created (*see* Figure 6.7).

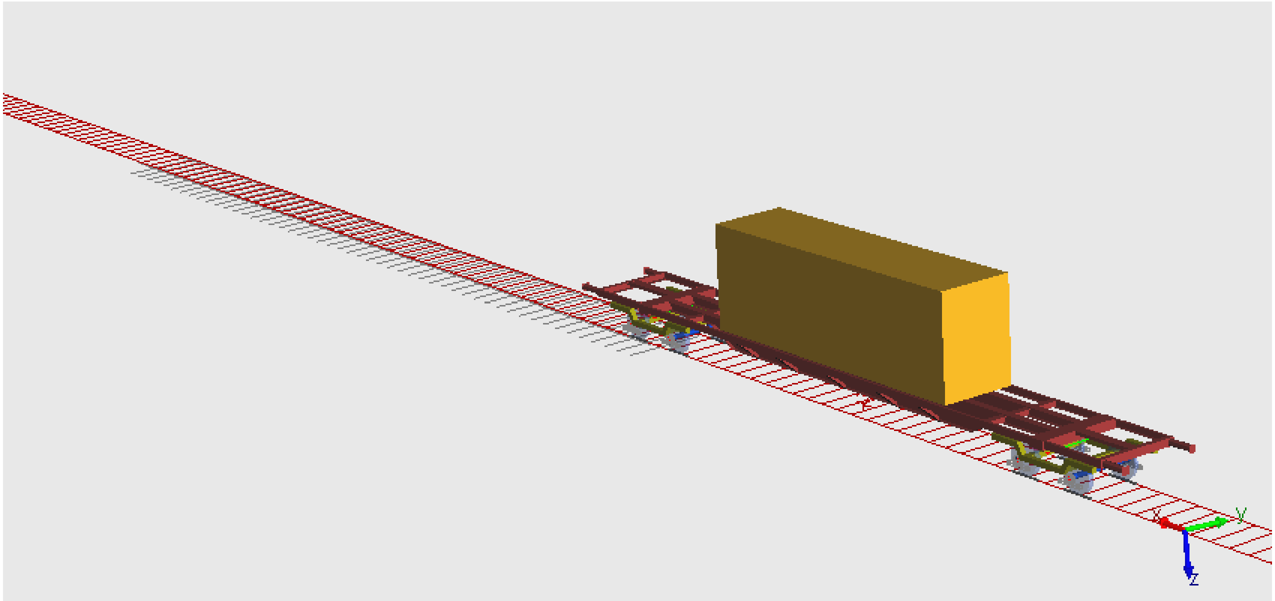

Figure 6.7 MBS model (track and vehicle)

Virtual sensors have been selected in the model to calculate axle-box accelerations (ABA). This information can be visualised in Simpack Post (*see* Figure 6.8) and exported for further analysis.

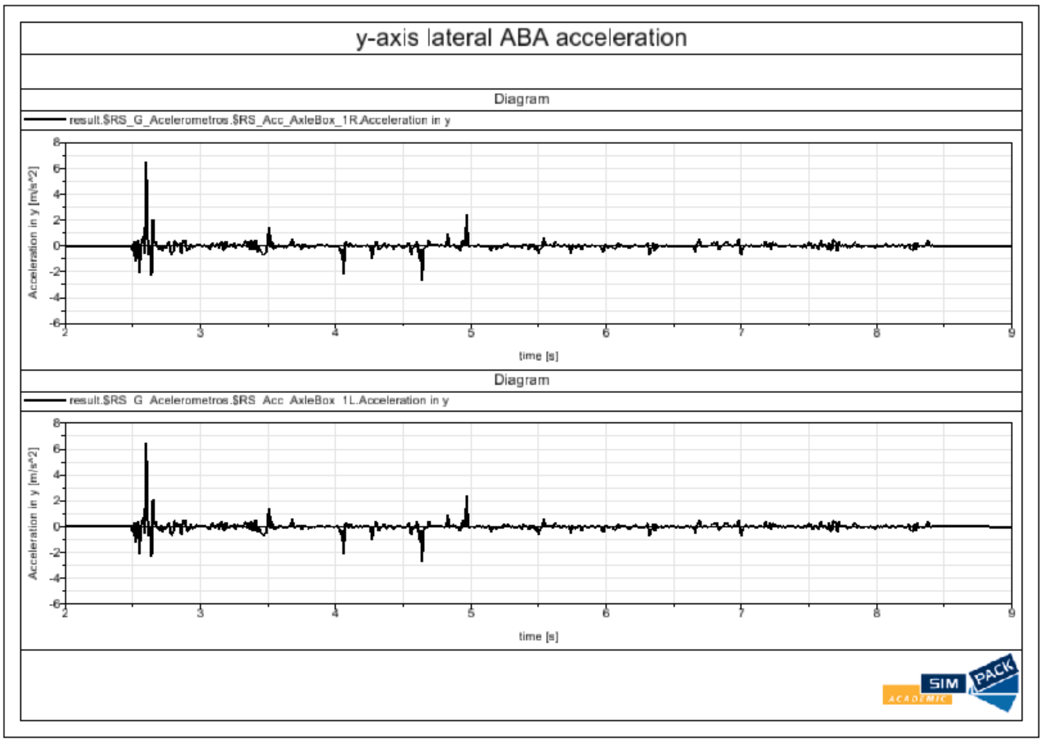

Figure 6.8 Simpack Post synthetic ABA data graph

6.2.4. Methodological summary

In a schematic way, the steps of the research would be as follows:

1. Modal analysis of the rail under different fastener torque conditions
2. Selection of a segment of the track inspected by the Leonardo vehicle for filtering and analysis of the axle-box acceleration signals. Experimental signal processing on selected segments with loose fasteners
3. Generation of a virtual model of track and vehicle.
   - Generation of the simplified track model with the main features of the real Dutch layout in the finite element software Abaqus
   - Compilation of inspection vehicle characteristics to create the model in the MBS Simpack software
   - Import of the track model into Simpack and its integration with the vehicle model
   - Creation of fastener failures in the virtual model and generation of acceleration data in the axle-box for further analysis
4. Comparison of results obtained after analysis of real and synthetic signals

First results and more details will be published within the next months under the work package 11 of the IAM4RAIL [13] project.

6.3. Conclusions

The project is still a long way from completion, but the detection of loosened fasteners by analysing the dynamic response of the vehicle is the way forward to rationalise the use of resources dedicated to the maintenance of rail fasteners.

To date, there is not much previous research specifically on the detection of problems with fasteners, but those that do exist lead the way in detecting loose fasteners by analysing acceleration signals using power spectrum [9] or by using wavelet analysis [12], for example.

Optimal acceleration signal selection and filtering will be one of the first milestones to be reached in the ongoing research on the analysis of acceleration signals for the identification of problems in rail fastenings.

The application of the developed detection methodology to the combination of real acceleration data captured from the Leonardo vehicle, together with synthetic data generated in the laboratory, should lead to a prompt validation of the generated algorithms, and the first results will soon be available.

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List of Abbreviations

ABA – Axle Box Acceleration
GPR – Ground Penetrating Radar

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº101101966. The project is supported by the Europe's Rail Joint Undertaking and its members.

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7. Health of railway infrastructure based on AI

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7.1. Introduction

Maintenance is one of the largest expenses in railway infrastructure. According to the European Commission, maintenance constituted nearly the 25% of total expenditure in railway infrastructure in the EU
(Eighth Monitoring Report on the Development of the Rail Market under Article 15(4) of Directive 2012/34/EU of the European Parliament and of the Council, 2023)
. Among the numerous elements that comprise this infrastructure, the tracks are among the most important, both in terms of cost and their relevance to the safety and comfort of passengers and transported goods.
Condition-based maintenance is a strategy that involves planning maintenance based on the current state of the track. This allows for maintenance tasks to be carried out at the optimal time, thus avoiding unnecessary expenses. To achieve this, periodic inspections of the tracks are necessary. Traditionally, measurements have been conducted using track geometry trolleys or instrumented trains equipped with various types of sensors, including lasers. However, these methods incur high operational costs and, in most cases, require the suspension of regular traffic on the tracks where they are operating, making frequent measurements not possible.
In recent years, the idea of employing accelerometers placed in different parts of trains in service has been explored to estimate the irregularities and defects of the tracks based on the movements these cause in the vehicle (Weston et al., 2015). This approach would allow for multiple measurements per day at a low cost and without disrupting the line's traffic, thus providing an almost real-time map of the railway tracks' condition.
Among the studies proposing track inspection through inertial measurements, two groups can be distinguished. On the one hand, some focus on measuring the state of specific elements such as crossings or detecting localised faults. In these cases, as the wavelength of the accelerations to be analysed is very short (<1 m), it is common to place the accelerometers in the axle box to avoid the filtering effect caused by the primary and secondary suspensions (Molodova et al., 2011). On the other hand, it has also been proposed to use accelerometers to provide a general assessment of the track condition over sections. The focus of this research will be in the estimation of track quality.
The European Standardization Committee defines various types of track geometry irregularities in the EN 13848 standard (EN13848, 2019): track gauge, longitudinal level, cross level, alignment, and twist irregularities. Figure 7.1 shows a diagram of the types of track irregularities. For each type of irregularity, the European standard establishes a classification of track quality at different levels based on the standard deviation measured in 200 m windows, taking into account the maximum allowed speed for that line. Additionally, it distinguishes different wavelength ranges for the thresholds of the different track irregularities, with the D1 range (between 3 and 25 m) receiving the most attention.

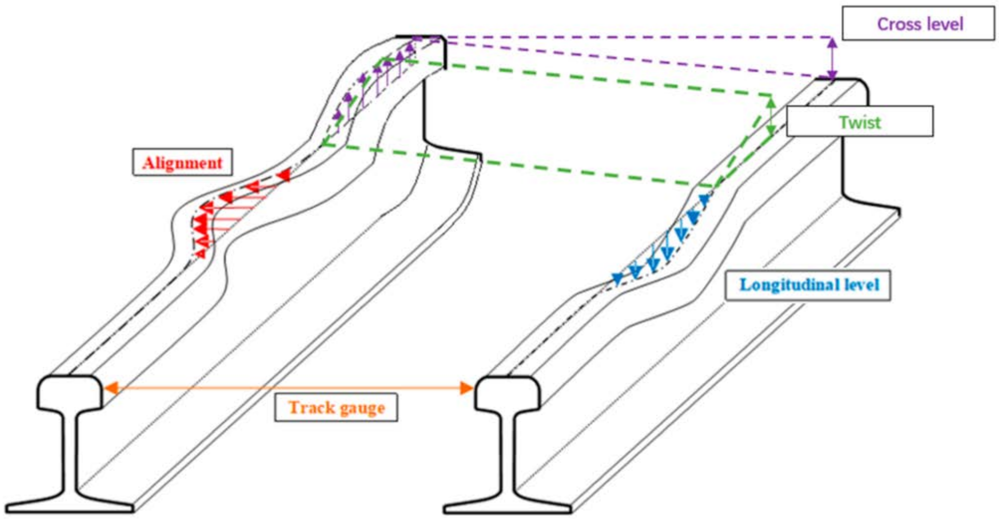

Figure 7.1 Diagram of track irregularities (Liao et al., 2022).

7.2. Review of the state of the art

The estimation of irregularities from inertial measurements has gained interest in recent years, particularly due to the improvement in computing power and the development of Artificial Intelligent (AI) techniques, such as Machine Learning (ML) (Hoelzl et al., 2022). These techniques are able to recognise and model complex systems so could be applied to the estimation of track quality based on the on-board inertial measurements. However, there is no clear consensus on the methodology to be applied, and various proposals have been made that differ in key points such as the position of the accelerometers, the source of the data, signal processing, statistical methods, and applied algorithms.

As previously mentioned, the position of the accelerometers partly depends on the wavelength range to be measured. To estimate track quality according to the EN 13848 standard, the D1 range is generally used, although some studies address a broader range between 1 and 100 metres. Broadly speaking, there are three possible positions: the axle box, the bogie frame, and the carbody of the train. The bogie is affected by the primary suspension, which filters out higher frequencies, and the carbody of the train also has the secondary suspension, increasing the filtering effect. Many of the reviewed articles place their accelerometers in one of the three positions for practical reasons, e.g., installation and maintenance of devices is easier in the train carbody (Tsunashima et al., 2014), or based on a dynamic analysis of the vehicle in relation to the accelerations to be measured (La Paglia et al., 2023). A few combine accelerometers in different positions to merge the measurements and improve precision (Jiang et al., 2016). However, there is a lack of previous studies aimed at finding the optimal combination of accelerometers and positions.

The data used can come from measurements on an actual train or from a simulation. The advantage of working with real measurements is that the method can be developed in the environment where it will be applied. However, in many cases, it is not possible to obtain these measurements, or they are limited to the characteristics of a specific train, line, and infrastructure conditions. Multibody simulations (MBS) provide an alternative that allows the design of different scenarios and the generation of a large amount of data.

Regarding data processing, filtering is performed to eliminate wavelengths outside the range of interest using band-pass filters. Feature extraction from the signal, which may be related to irregularities, is also carried out by calculating statistics in the spatial or temporal domain, such as the RMS of the accelerations or the peak-to-peak maximum, or in the frequency domain, such as the dominant frequency (Zhang et al., 2017). Kalman filters were the most commonly used method until a few years ago for estimating track geometry, along with double integration of the signal (Lee et al., 2012). However, there has been a clear trend in recent years towards the application of ML techniques, both classical and Deep Learning.

Classical ML has typically been used for estimating track quality indicators in windows based on statistical features of the signal (La Paglia et al., 2023) or for classification tasks (Tsunashima, 2019). Studies applying Deep Learning tend to focus more on the reconstruction of the track geometry itself from acceleration signals, taking advantage of the greater capacity and complexity of such models (Hao et al., 2023).

7.3. Methodology

Despite the number of studies and authors addressing the estimation of track quality by means of dynamic measurements and application of ML algorithms, several gaps remain open and can be identified:

While many studies focus on estimating vertical irregularities, the estimation of other types of irregularities, especially lateral ones, whose relationship with vehicle movements is more complex, is barely studied in the literature.

More attention must be paid to the location of the sensors to guarantee optimal data collection based on the irregularities studied.

The effectiveness of the proposed method in different scenarios must be analysed. The dynamic behaviour of the train can vary significantly depending on various variables such as speed, track layout, or load. Therefore, it is necessary to understand the limitations of the proposed methodologies.

To try to address these points, a large number of simulations in different scenarios and vehicle and track parameters will be generated in SIMPACK MBS software. A 3D model of a single train coach composed of a carbody, two bogie frames and four wheelsets connected by force elements is used. The acceleration data extracted from the simulations will be used to train ML models to estimate the standard deviation of irregularities. Hence, the workflow shown in Figure 7.2 will be followed iteratively, as the analysis of results can provide insights to redefine scenarios and/or decide for the best sensor layout definition. Once these aspects have been fixed, efforts will be focused on improving the performance of the ML models.

So, the first key step is to determine the scenarios to work with. The variables that define each simulation (excluding irregularities) are divided into two groups. On the one hand, the variables related to the model of the vehicle itself, such as different suspension parameters, lengths and weights, etc. In the other group, those related to the scenario in which the given vehicle is located, its speed, the load it carries, the layout, the coefficient of friction, etc. Due to the wide range of cases, the influence that each parameter has on the vehicle dynamics and the variability that they may have in the real world is previously analysed to select a subset of these to work with first and design the simulations according to this.

Second, with the aim of finding the optimal arrangement of accelerometers, in each simulation the acceleration is measured at different points of the train body, the bogies and in the eight axle boxes. Those acceleration measurements that provide the most information using a smaller number of sensors are selected.

Finally, the training of the ML models and the analysis of the results are carried out. The parameter to be estimated is the standard deviation of the irregularities every 200 meters in accordance with the provisions of the EN 13848 standard (EN13848, 2019). The trained models are validated in different scenarios to evaluate its robustness and scope.

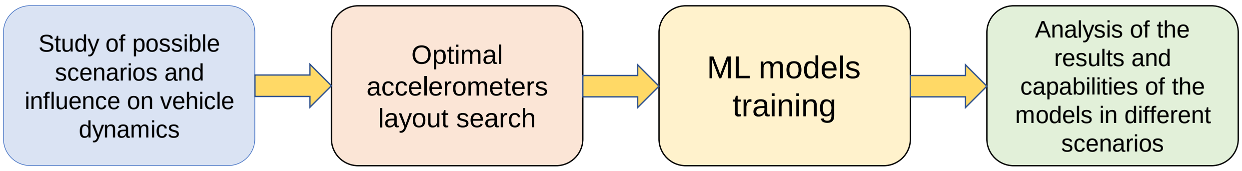

Figure 7.2 Work flow chart.

7.4. Preliminary results

During the first year of the PhD research, some preliminary results related to the first step shown in Figure 7.2 were obtained. To study how the different scenarios affect the accelerations measured for a given vehicle, simulations have been carried out varying the load condition, the speed (between 40 and 80 km/h), the layout (straight or with

different curves and slopes) and the friction coefficient for different levels of irregularities, generated from the Power Spectral Density (PSD).
From the results of these simulations, it has been observed that speed significantly affects the amplitude of accelerations in the axle box and bogie, with the accelerations measured being greater when the speed is higher. Accelerations measured in the body of the train also depend on speed, although there is no uniform trend due to the effects of secondary suspension. **¡Error! No se encuentra el origen de la referencia.** shows the dependence observed between accelerations and speed in the body and in the bogie for given track irregularities. The RMS of the accelerations has been calculated in 200 m windows along a 9500 m track. The line represents the average value across the entire track, while the shaded area indicates the interval in which 95% of the measurements lie. The coefficient of friction on the other hand, does not seem to have much effect within the usual range in dry conditions.

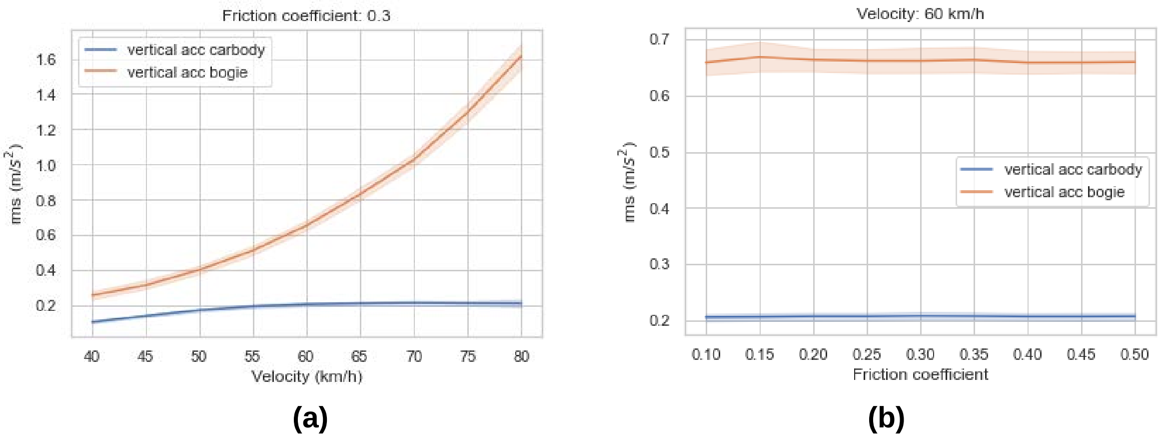

Figure 7.3: (a): Vertical acceleration measured in carbody and bogie frame for different running speeds. (b): Vertical acceleration in carbody and bogie frame for different friction coefficient values.

Curvature and camber are also variables to take into account. Curvature, and more specifically uncompensated acceleration, especially affects lateral accelerations, as shown in Figure 7.4.

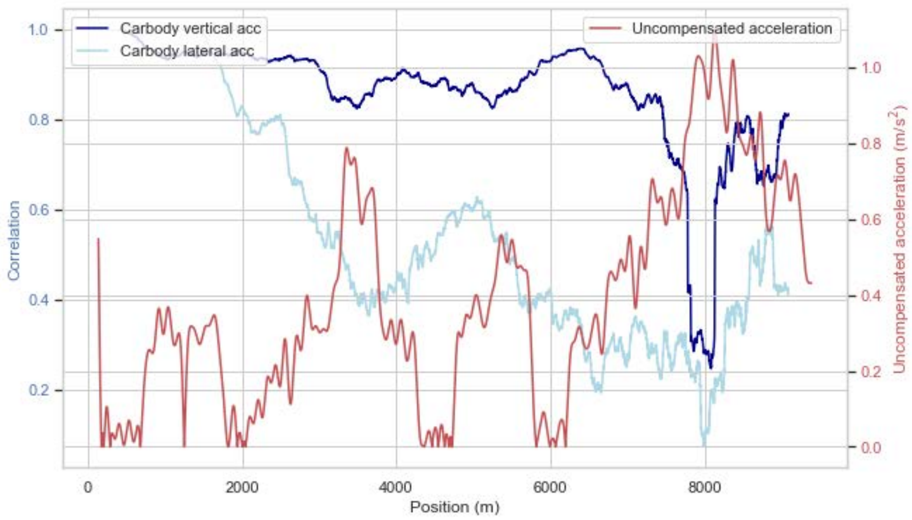

Figure 7.4 Correlation between acceleration measurements on straight and curved tracks obtained through simulation.

The analysis has included the training of preliminary ML models. As input, different statistics calculated from the accelerations divided into windows have been used. By analysing these models, it is possible to know their sensitivity to changes in the scenario or simulation parameters, as well as extract the importance of variables. For the models trained so far, the RMS of the vertical accelerations at different points of the train body is the most important variable to estimate the vertical irregularities, and the lateral accelerations, to estimate the lateral irregularities.

7.5. Future work

We will continue with the approach outlined in the Methodology section. The next step will be to identify the most appropriate accelerometer arrangement for estimating each type of irregularity by means of multibody simulations. This will involve evaluating the relevant and non-redundant information provided by each sensor, as well as the effectiveness of preliminary models trained with different sensor configurations. Subsequently, the focus will shift to the development of machine learning models, which includes generating the necessary dataset from simulations, training the models, and analysing the results. Finally, real measurements will be necessary to validate the system designed for track quality estimation.

7.6. Conclusions

The estimation of railway track quality through inertial measurements has garnered significant interest in recent years. A methodology has been proposed to address this objective. First, via simulations, the dependence on the operating condition of acceleration measured in various parts of a train have been analysed. The next steps will involve studying the optimal sensor placement and applying machine learning techniques to develop regression models capable of estimating track quality under different scenarios.

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This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement n°101101973 and nº101101966. The project is supported by the Europe's Rail Joint Undertaking and its members.
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

8. Map-matching for train localisation: from the digital map to the map-matching techniques

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8.1. Introduction

In the frame of Europe's Rail, Flagship Project 2: R2DATO - Rail to Digital automated up to autonomous train operation (*Eurail-Fp2*, n.d.) , WP21 and WP22 work packages are responsible for the Absolute Safe Train Positioning (ASTP). The first of which is centred around the operational needs, and the other is centred in the system architecture, design and RAMS. Main objectives of these work packages are: Identify common high-level user needs and system capabilities of ASTP, Analysis of required system performance for the ASTP system and the definition of a ASTP system architecture and its design.

The work done in X2Rail-5 (*X2RAIL-5*, n.d.) regarding the Safe Train Positioning System (FSTP), paved the way for the ASTP in the R2DATO framework. The ASTP works in R2DATO are a continuation of the work in X2Rail-5, with a particular focus on the relevance of localisation in different architectures. X2Rail-5 aims to develop a fail-safe, multi-sensor train positioning system applying Global Navigation Satellite Systems (GNSS) technology. This highlights the importance of ASTP as a crucial element in the system pillar of the European Rail Joint Undertaking (ERJU), with the aim of bringing the specification into the next Technical Specifications for Interoperability (TSI).

This article presents the current research in terms of train localisation in fusion with the concept of a digital map. It is organised as follows. The next section presents the state-of-the-art for train localisation, from the digital map to the main categories on the map-matching techniques. Following this, the current state of the research and the future steps are analysed and the last section wraps the article with the conclusions.

8.2. Train localisation

Current railway localisation technologies depend greatly on track-side equipment. The most popular used technology for train localisation is odometry in most of the cases complemented with balises, which are detected by the train when it passes by. The balises are numerous on every track and need maintenance work, which drastically increases the cost of this technology for localisation. On top of this, this localisation approach expenses increases with the reach of use.

Therefore, in recent years alternative methods have been studied for train localisation with just onboard sensors. These methods rely on sensors mounted in the train and do not need any track-side equipment. That requires more than just a GNSS (Global Navigation Satellite System) sensor; due its performance, precision and due to the harsh environments and signal outages that can be found in urban or indoor environments.

Railway localisation problem has an inherent property: train motion is constrained to the track, which means that trains can only move mounted on rails. This way, localisation of trains can be considered as a 1-D localisation problem, easing the localisation approach (Lavoie & Richard Forbes, 2021). In this context, estimating the train position on a map of the track is known as map-matching.

This section is divided in two subsections. The first one explores the concept of the digital map and the main digital map reconstruction methodologies starting from a set of points. The other subsection presents the main map-matching categories found in the state-of-the-art literature.

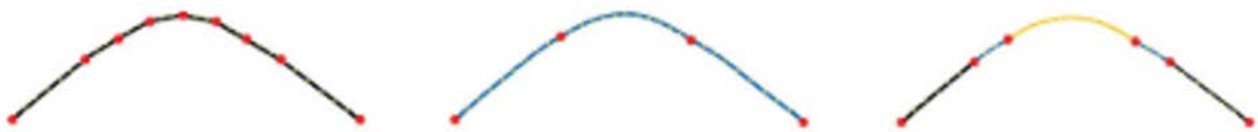
8.2.1. Digital map

Localisation with maps makes a great choice as the maps describe unambiguously train tracks, easing the train localisation and making it an effective choice. On top of that, train localisation with a map requires just onboard sensors and the railway digital map, making it a low-cost alternative to localisation with track-side equipment.

The digital map stores the topology and mileage of the railway network in absolute coordinates. This will need to fulfil the following: accuracy, storage efficiency and usability (Gwon et al., 2017).

Starting from a set of coordinates, the most common digital maps reconstructions are the three shown in Figure 8.1: interpolation, curve and geometric.

- - Interpolation: joins the adjacent coordinates with a straight line. Use case example: (Sessa et al., 2021).
- - Curve: Unified curve model, such as a spline curve. Use case example: [6].
- - Geometric: composed by three main elements: straight lines, curves and clothoids (or easement curves), also called traditional as it is based on the railway traditional design elements. Use case example: [7].



Interpolation Curve Geometric

Figure 8.1: Three main geometries for digital maps. Figure extracted from (Liu et al., 2021)**.**

8.2.2. Map-matching for train localisation

Even though map-matching for train localisation has been widely studied in the literature, there has not been a classification. The research has been centred on making a classification of the state-of-the-art map-matching algorithms for train localisation.

Three main categories have been identified in the literature for map-matching: geometric, similarity and hypothesis.

8.2.2.1 Geometric

The geometric one considers only geometric information in a naive approach (Garcia Crespillo, 2013). As the Figure 8.2 shows, having a GNSS measurement, the geometric map-matching algorithm will project that measurement onto the digital map to estimate the train position. Use case example: (Zheng & Cross, 2012).

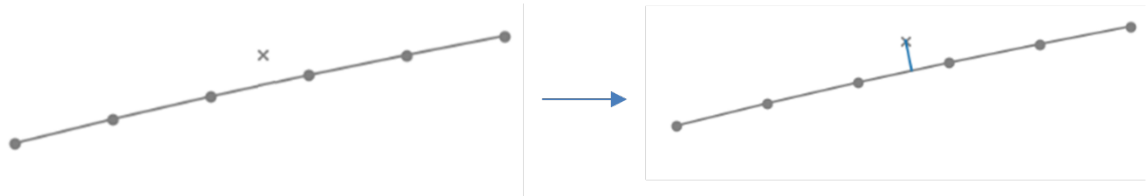


Figure 8.2: Geometric map-matching

8.2.2.2 Similarity
The similarity compares measurement from the sensors with location dependant data. As train localisation can be considered a 1-D problem, matching the measurement of a sensor to the location-dependant data can be used for localisation, as shown in Figure 8.3

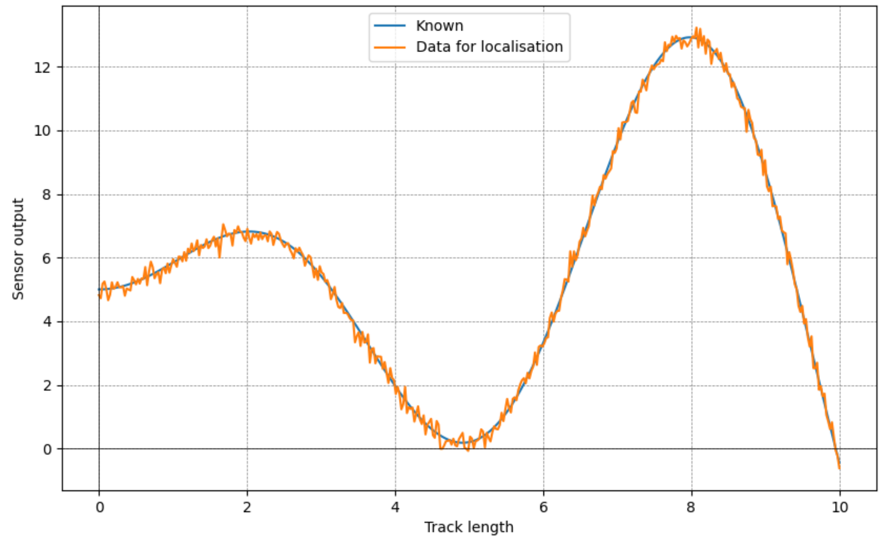


Figure 8.3: Similarity map-matching

This category is divided in two categories: topological (the known data is the digital map) and feature matching (the location dependant data needs to be recorded for the posterior localisation).

- - Topological: The location dependant-data is the digital map.
- - Feature matching: The known data needs to be recorded on the track, for the posterior localisation.

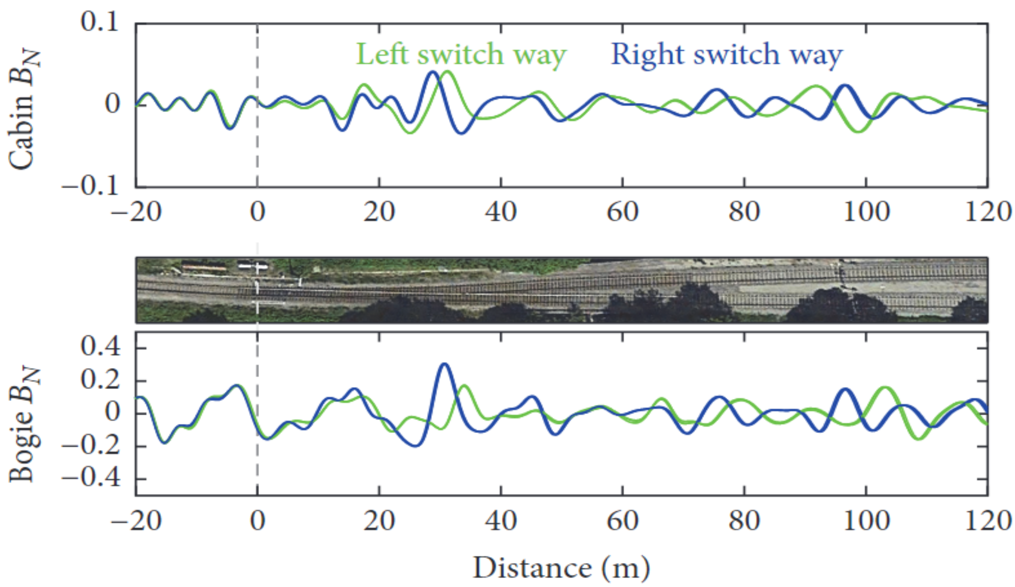


Figure 8.4: Feature matching with magnetic measurements. Figure extracted from (Heirich et al., 2017)

Figure 8.4 shows an example of feature matching with magnetic measurements. Each way is recorded three times, for the cabin and the bogie. Both blue and green measurements are the same before the switch, but once the switch is crossed, each way has a distinct magnetic measurement.

8.2.2.3 Hypothesis

This category exploits nonlinearity by considering positions on tracks as hypothesis. This is divided in two main techniques:

- - Particle Filter: Estimates a topological position directly in the track map, as the particles only exist on tracks. Use case example: (Heirich et al., 2013)
- - Multi-Hypothesis: Different hypotheses are examined, defined as possible vehicle positions within the rail network. Use case example: (Gerlach et al., 2009)

8.3. Current work and future work

Our current work is centred around building a digital map using OpenStreetMap (OSM) data, which will serve as a foundational element for enhancing train localization systems. The primary focus of this phase is the creation of a precise digital map of the railway tracks. By extracting and processing OSM data using custom Python scripts, we ensure that the digital map is both accurate and reliable for subsequent localization tasks.

The next step involves integrating this digital map into the train localization system. This will include developing algorithms to match the train's real-time location with the map data, thus enhancing the accuracy and reliability of train positioning.

8.4. Conclusions

Absolute safe train positioning is crucial for optimizing train operations, enhancing energy efficiency, and increasing train density while reducing the need for extensive trackside equipment. It also ensures high safety standards, lowers maintenance costs, and improves system availability across various railway applications.

Train localisation problems can benefit from its inherent track-constrained nature via map-matching. This paper presents an in-depth literature review of digital map generations and map-matching algorithms for train localisation. The results of this survey and classification offer valuable insights for practitioners in the field of map-matching for train localisation, paving the way for future research endeavours.

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Funded by the European Union

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This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102001. The project is supported by the Europe's Rail Joint Undertaking and its members.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

9. CEIT's Multi-connectivity Platform Development

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9.1. Introduction

During a typical journey, a train continuously exchanges information with the trackside infrastructure in order to meet some safety requirements. Along the last years, these requirements have been evolving to support the increasing number of trains and daily journeys. This evolution can be translated into more stringent signalling and control requirements that demand higher data reliability and data availability. Thus, more data to exchange per unit of time.

Nowadays, voice communication between trains and controllers, railway emergency calls, and Automatic Train Protection (ATP) data transfer [1] are some of the applications that most illustrate how train-trackside communications are essential for the proper functioning of a train trip. Application counterparts that aren't in the same location must exchange data and voice information, emerging the need to incorporate a communication system into the infrastructure, particularly a wireless system from which the train can establish a connection with the trackside infrastructure.

For a long time, the most popular of these communication systems has been Global System for Mobile Communications - Railways (GSM-R) [2]. The success of GSM-R, over a couple of decades, relies on its integration with the European Rail Traffic Management System (ERTMS) [3], being GSM-R the communication system which performs the functions of the control and signalling system.

While different technologies such as cellular technologies are constantly evolving giving more and more capabilities to the final users, railway communications are stacked in GSM-R. As GSM-R is a technology based on GSM, is becoming obsolete being its end of its lifecycle 2030 [4], [5]. Beyond this point, maintaining the same level of service quality for infrastructure managers will become progressively challenging and costly. Then, the adoption of new communication technologies, systems and standards is required.

In this context, the International Union of Railways (UIC) is working on the definition of the Future Railway Mobile Communication System (FRMCS) [6] in cooperation with the different stakeholders from the rail sector. The main targets of FRMCS are to be the successor of GSM-R and contribute to the digitalization of railway communications. For that goal, the FRMCS activity is organized into several working groups aiming to deliver a set of specifications for the sector. The principal FRMCS directives alongside the wide range of scenarios, in which services are desired to be provided, are being covered by different research projects such as 5GRAIL [7], 5GMED [8], X2RAIL-5 [9], or Europe's Rail FP2-R2DATO [10] to name a few.

In this regard, this abstract aims to provide a quick overview of the state of train-trackside communication systems and to contextualize CEIT's work in this area as part of Europe's Rail FP2-R2DATO project.

9.2. FRMCS and related research projects

In this section, a brief description of FRMCS is provided together with the main highlights of previous and current related research projects: 5GRAIL, 5GMED, X2RAIL-5, FP2-R2DATO.

9.2.1. FRMCS

As stated in the previous section, FRMCS has been designed by UIC as the evolution of communication system for the future of the railways with two main goals: on one hand, finding a successor to GSM-R due to its obsolescence and, on the other hand, enabling and supporting the digitalization of the railways, providing services such as the transmission and reception of increasing volumes of data.

As part of the European strategy to promote the use of trains over other modes of transportation, such as short flights, FRMCS is committed to enhancing the safety and comfort of travellers by employing applications of three

use categories [11]: (i) critical services to oversee and supervise train operations and ensure safety (incorporating mission-critical applications, not just those currently supported by GSM-R), (ii) performance services to enhance the efficiency of railway operations and (iii) business services enhance passenger comfort. Therefore, it is necessary to have a communication system in which applications of different levels of criticality coexist, each with an appropriate QoS.
FRMCS proposes a 5G dedicated network with an MCx server responsible for managing QoS. There are two main ways to access FRMCS services [12]: a Direct access mode, which essentially means access by a handheld device enabled to that in which the application is embedded, and the Gateway access mode, in which an application can access the FRMCS services through an On-Board/Trackside FRMCS gateway. The application communicates with the On-Board/Trackside FRMCS gateway via a local onboard/trackside transport network and the On-Board device manages the radio access and is responsible for supporting communication services for the On-Board applications. The design of these gateways, particularly the On-Board gateway, has received special attention in several research projects, as shown in the following subsections.

9.2.2. 5GRAIL

The primary goal of 5GRAIL is to validate the first set of FRMCS specifications, referred to as FRMCS V1, through the developing and testing of prototypes within the FRMCS ecosystem [13]. The project, closed in December 2023 [14], establishes functional tests and then proceed with the development and assessment of prototypes. This includes prototypes for both trackside infrastructure and On-Board systems and it is planned to use applications like ETCS, ATO, voice services, and TMCS.
5GRAIL seeks to decrease the costs associated with specific equipment and reduce the time required for installation engineering in the On-Board system. The project attempts to unify all train-trackside communications following the so-called Telecom On-Board Architecture (TOBA) [15].
This project followed a dedicated network model, mainly using a 5G standalone (5GSA) network for communications. The On-Board gateway is connected to different RAN and allows the communication of On-Board applications with their pair in the Trackside. This network follows and architecture shown in Figure 1, which is a simplification of the test scenario presented in [16].

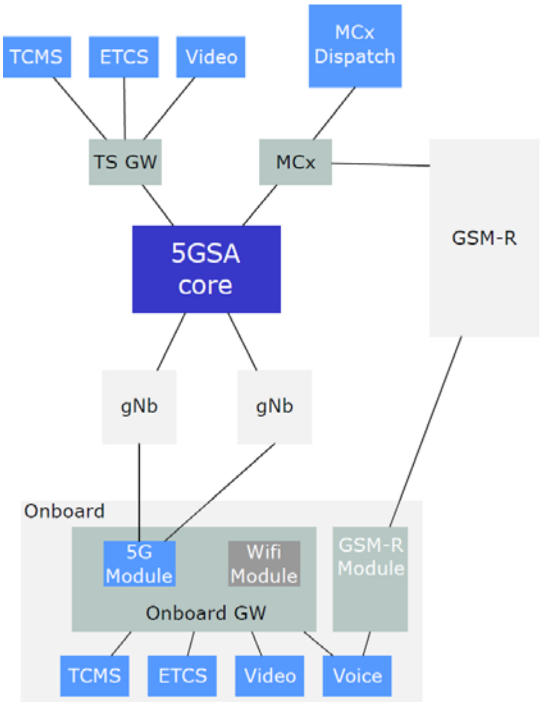

Figure 9.1: 5GRAIL lab test network configuration [16]

9.2.3. 5GMED

The 5GMED project uses the line between Figueras and Perpignan, in the Mediterranean corridor, which includes a cross border between Spain and France to join different actors of the railway sectors as Mobile Network Operators (MNOs), road and rail operators, and telecom neutral hosts to develop a communication system for non-critical applications and artificial intelligent functions [17]. This project was finished in August 2024 [18].
The 5GMED project leverages the proximity of the E-15 European route and the high-speed rail track within the selected cross-border section. In this scenario, the 5GMED Consortium attempts to showcase the potential of a proposal based on a multi-stakeholder 5G infrastructure featuring a variety of radio technologies, as shown in Figure 2 (a simplification of the 5GMED architecture presented [19]).

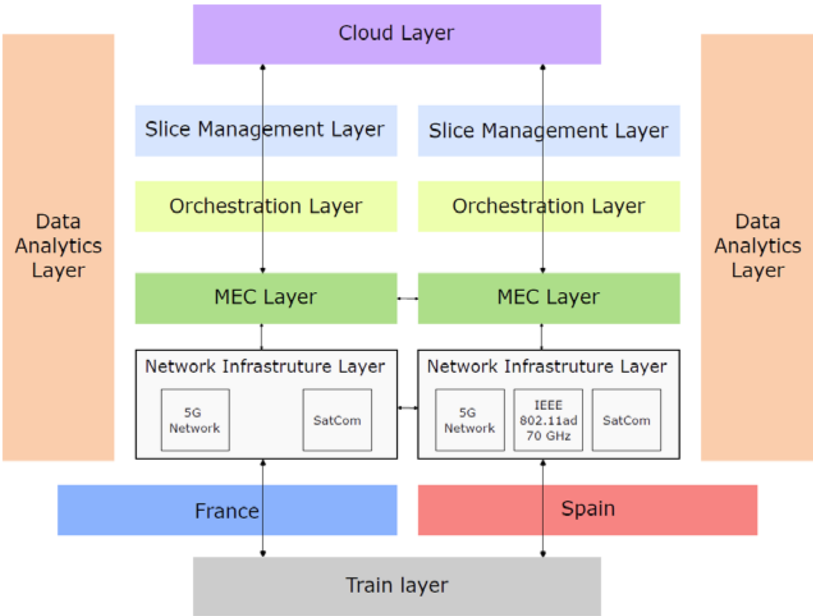

Figure 9.2: 5GMED Architecture [19]

This architecture shows the use, on both sides of a border, of a 5G Stand Alone (SA) network and Satellite connection. Also, when the train is in Spanish land other radio technology can be used: IEEE 802.11ad 70 GHz. In this multi-bearer approach (understand bearer as each radio interface from which the On-Board gateway can communicate the applications), different technologies, arranged by preference for each application, can be used to provide specific services considering the train's location along the rails [20].

9.2.4. X2RAIL-5

X2RAIL-5 was developed inside the scope of Shift2Rail program, which was the first European rail initiative to seek focus on research and innovation [21] being its main goal to overcome the limitations of the existing communication system by adapting radio communication systems that establish the backbone for the next generation of advanced rail automation systems. X2RAIL-5 was completed in October 2023 [22].
It is particularly of interest the research carried out in Work Package 3 where an Adaptable Communication System (ACS) was developed for all railways and the field test of prototypes and different demonstrators (for highspeed/ mainline, urban/suburban, and regional/freight lines). ACS is aligned with FRMCS in several aspects and aims to investigate various business models, considering both dedicated and public networks. In that line, ACS intends to be a bearer agnostic approach capable of performing the decoupling of digital applications from the communication system, to take advantage of different wireless technologies [23].

Figure 3 (which is a reproduction from [23]) describes ACS through its components. It is important to highlight two points: on the one hand, despite not being illustrated in the figure for simplicity, the same functions of the Trackside are present in the On-Board system and on the other hand, the bearers showed are examples and the system is not bound to those or even limited in number.

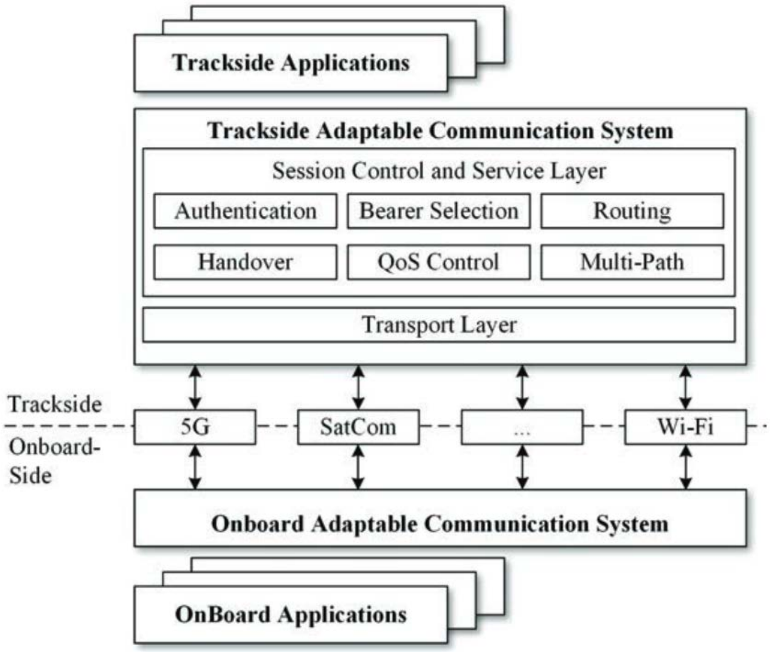

Figure 9.3: Adaptable Communication System Block Diagram [23]

9.2.5. Europe's Rail FP2-R2DATO

The vision of Europe's Rail is to create a high-capacity, flexible, multi-modal, and reliable European railway network through an integrated system approach. This will be achieved by removing interoperability barriers and offering solutions for full integration, benefiting both European citizens and cargo [24]. Europe's Rail counts with a list of flagship projects, among them the R2DATO project with the goal of using the digitalisation and automation of rail operations to develop the next generation of ATC and implement scalable automation in train operations, aiming to achieve GoA4 by 2030 [25]. The activity of this project is expected to last until May 2026 [26].

9.3. CEIT's Multi-connectivity Platform (MP)

Within the scope of Europe's Rail Flagship Project 2, CEIT is participating in the development of a prototype of the ACS/Multi-connectivity Platform for Regional Lines. This includes the architecture design, specification, prototyping, and testing of both, On-Board and Trackside gateways.
CEIT MP, unlike FRMCS, does not use only a dedicated network, instead seeks to use combinations of public and private networks with the applications being agnostic to the bearers employed. Following this multi-bearer approach, it aims to integrate features of FRMCS, such as the interface of the gateways for applications, to have information about the different applications and control their access to the system, and the capacity to serve applications with critical and non-critical uses.
Figure 4 shows a diagram of CEIT MP system concept. It can be highlighted that CEIT's MP consists of the following:

- An On-Board MP with its Trackside MP counterpart. A single Trackside MP can handle more than one On-Board MPs.
- The connection between On-Board MP and Trackside MP shall be performed through five different bearers: IEEE 802.11ad 70 GHz, a private network (having different interfaces for communication at the front and rear of the train, this technology has two bearers), two fifth-generation public networks from different operators, and SATCOM.
- The applications considered are ATO and ETCS on the On-Board and Trackside and, WiFi for passengers On-Board which does not need to connect to the Trackside pair, so the traffic should be redirected to the Internet without needing to be processed in the Trackside gateway.
- An Operation Management and Control Subsystem (OMC) from which an administrator can manage configurations, visualize performance indicators, and track and solve errors.
- The tests are foreseen at different levels from laboratory to on-site. At the first level at CEIT laboratory, tools such as SATCOM emulator are planned to be used. Then the integration with other systems in the locations is also foreseen, where real equipment for ATO and ETCS applications and for the bearers (IEEE 802.11ad 70 GHz, MNO_1 (4G/5G), MNO_2 (4G/5G) and SATCOM) is planned to be used. Finally, field tests are foreseen.

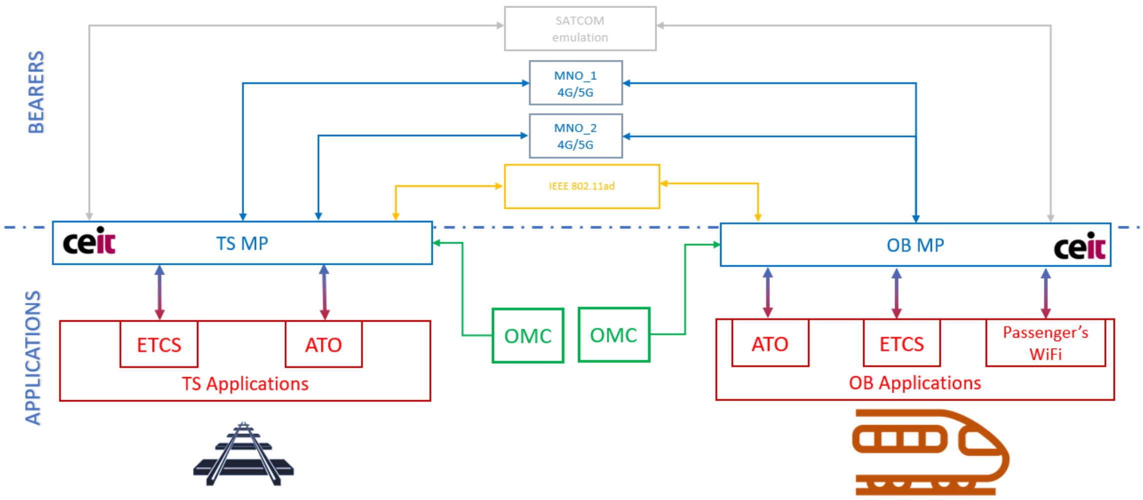

Figure 9.4 CEIT Multi-connectivity platform diagram

The CEIT Multi-connectivity platform has been influenced by previous work. It principally follows the ACS principles regarding the integration of different networks, bearer agnosticism, and transparency in the use of bearers from the point of view of the applications. The influence of the FRMCS application-gateway interface can also be spotted in the development of that interface in the CEIT platform, as well as the utilization of 802.11ad as a radio technology for 5GMED.

9.4. Conclusions and Future Work

In a context where the railway industry is expanding to new applications and requiring greater sensor coverage, which demands greater capacity of data transmission, a traditional communication system like GSM-R is facing the obsolescence. In consequence, research efforts have been put into the development of new systems for train-trackside communications. In particular in the design of a network where non-critical and critical applications can coexist and the development of the gateways needed to the access of the applications to the network services. Different approaches have been taken to address these issues considering, to a certain extent, the FRMCS directives.

The most noticeable difference among the approaches lies in the network models, in terms of ownership of the network. FRMCS and the system implemented in 5GRAIL are in line with using a dedicated private network under Infrastructure Manager control and ownership. This provides greater flexibility, as the design can be adapted to operational requirements. Less flexible but more economical options can be found in 5GMED, where the radio access networks of mobile network operators and SATCOM are used, and in the cases of X2RAIL-5's ACS and CEIT MP, which seek a system that can adapt to and use any type of network.
As part of the FP2-R2DATO Work Package 28, CEIT is developing a pair of On-Board and Trackside gateways. The central idea of the CEIT proposal is aligned with the ACS principles of bearer agnosticism, using a set of radio bearers and a set of applications for which the communication system should be transparent. After the design step, the prototyping of the CEIT MP system and performance test will be carried out.

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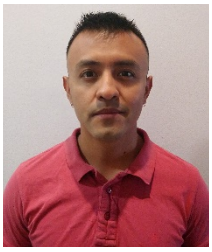

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Funded by the European Union

This project is under the scope of the Europe’s Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102001. The project is supported by the Europe’s Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe’s Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

10. Development of the Preliminary Stages for ATO Lab Prototype in Sight of a Future Inspection Vehicle

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10.1. Introduction

CEIT is actively participating in diverse Work Packages within the R2DATO Project [1] under the European Rail Joint Undertaking (ERJU) [2], a European partnership dedicated to rail research and innovation as part of the Horizon Europe program (2020-2027) and the successor to the Shift2Rail Joint Undertaking (S2RJU) [3]. Notably, CEIT is an active partner in Work Package 10, aiming to develop a lab prototype for an inspection vehicle utilizing an automatic driving system. This system is being designed according to the novel reference architecture from the System Requirement Specification (SRS) of the X2Rail-4 project (baseline 1.0.0) [4] and adheres to relevant standards such as the Technical Specification for Interoperability – Control Command and Signalling (TSI – CCS) [5]. The current SRS with its reference architecture from the X2Rail-4 project have been transmitted to EU-Rail for further evolution of the SRS ATO up to GoA 4 system.

This study provides an overview of the current state of an ATO laboratory prototype designed to adhere to railway industry standards. The preliminary architecture of the lab prototype is based on the novel reference architecture from the X2Rail-4 project, and it is expected to serve a critical role in enhancing railway inspection procedures by facilitating research and trials aimed at improving safety and efficiency on tracks. The remainder of this work is organized as follows: Section II introduces the novel reference architecture. Section III outlines the preliminary architecture of the ATO lab prototype for inspection vehicle, where novel components and relevant standards are introduced. Section IV introduces the future works. Finally, the conclusions are outlined in Section V.

10.2. Novel reference architecture for GoA 3/4 systems

The reference architecture for GoA 3/4 system proposed in the X2Rail-4 project is depicted in Figure 1.1, which includes a diverse range of components for a complete railway system. This reference architecture encompasses both trackside and onboard systems. The upper part of the architecture is focused on the trackside components, which includes the Train Management, Traffic Management, Route Control, Train Control, Incident Solving Manager, Operational Execution (OE), Digital Map (DM), Train Data (TD), and Mission Data (MD). On the other hand, the lower part of the framework is dedicated to the onboard components, which includes the Train Protection, Signal Converter, Signal Detection, Onboard Recording Device, Localization (LOC), and four novel GoA 3/4 components, namely Automatic Driving Module (ADM), Automatic Processing Module (APM), Repository (REP), and Perception (PER). Finally, the railway system actors are representing externally to logical system [6].

The reference architecture guarantees seamless interaction and integration between trackside and onboard components via communication networks and data exchange via relevant standards. Trackside systems supply real-time data and instructions to the onboard systems, while the onboard systems deliver status and operational data back to the trackside components. This reciprocal communication is essential for maintaining synchronized operations, ensuring safety, and maximizing performance [6].

Some components of the ATO lab prototype are being specifically designed to meet the requirements of an inspection vehicle based on the SRS described in the X2Rail-4 Project. To make these components a reality, CEIT has organized several research groups, each dedicated to the development of a specific component highlighting the collaborative effort and expertise that is being applied to the ATO lab prototype.

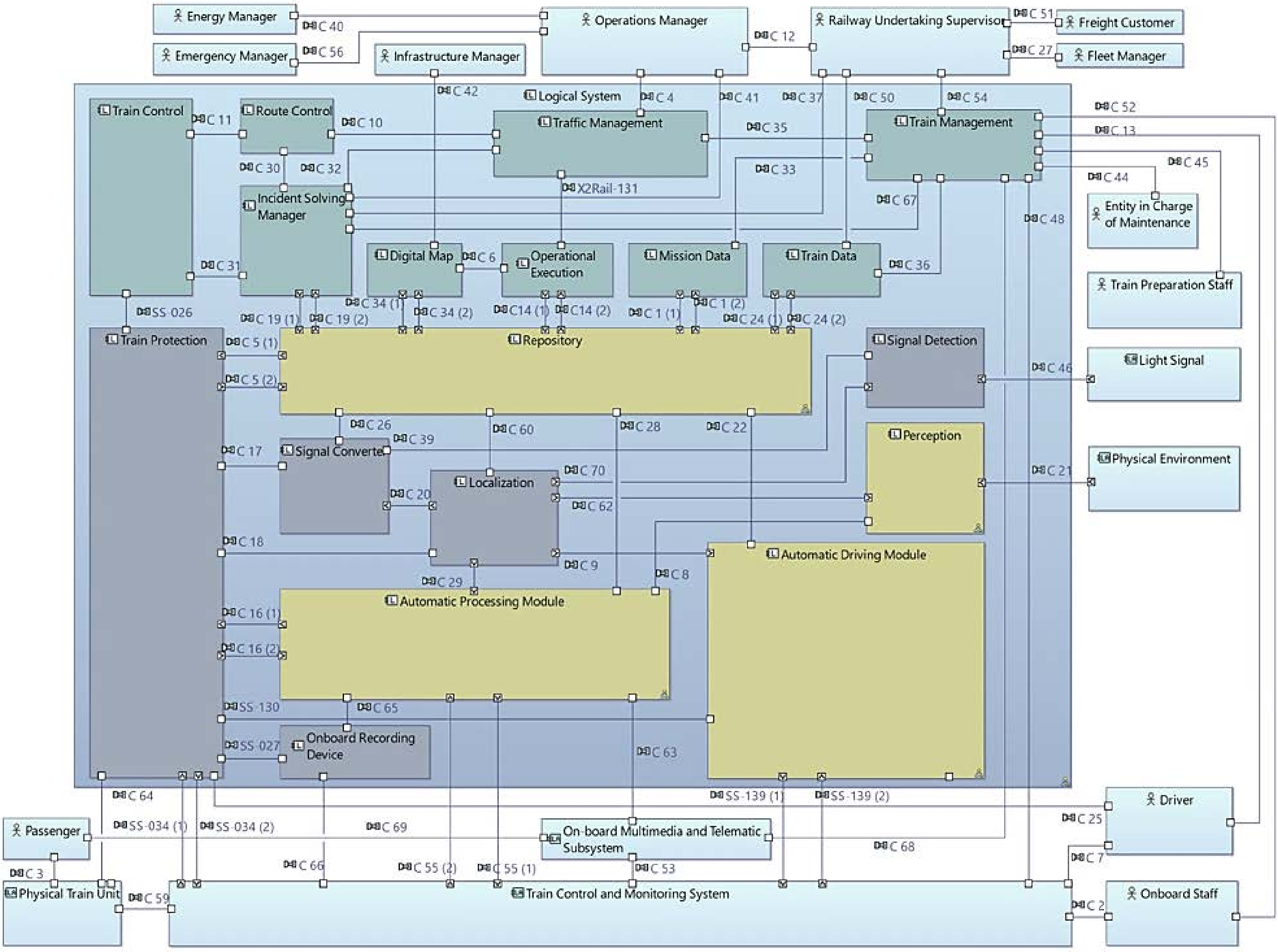

Figure 10.1 ATO up to GoA 4 - Logical reference architecture [6].

On the other hand, Figure 1.2 illustrates the preliminary architecture of the ATO lab prototype. This architecture reveals the components and standard interfaces that are in the process of development and will be integrated in subsequent stages of the project. Among the components to be developed are Localization (LOC), Train Control and Monitoring System (TCMS), Repository (REP), Perception (PER), Automatic Processing Module (APM), and Automatic Driving Module (ADM). It is important to note that the SS-126 [7] and SS-139 [8] interfaces are currently undergoing lab testing, while the remaining standard interfaces are still being defined.

10.3. Test environment

The selection of Open Rails [9] as the test environment for the ATO prototype laboratory was based on its status as a transport simulation platform that operates as an open-source train simulator, compatible with routes, activities, trains, locomotives, and rolling stock designed for Microsoft Train Simulator. To facilitate interaction with Open Rails, adapters (AD) will be developed that will interpret the packages defined in the standard interfaces specified in the SRS of the X2Rail-4 project. This will enable the use of Open Rails as a test environment until the inspection vehicle is available for field testing.

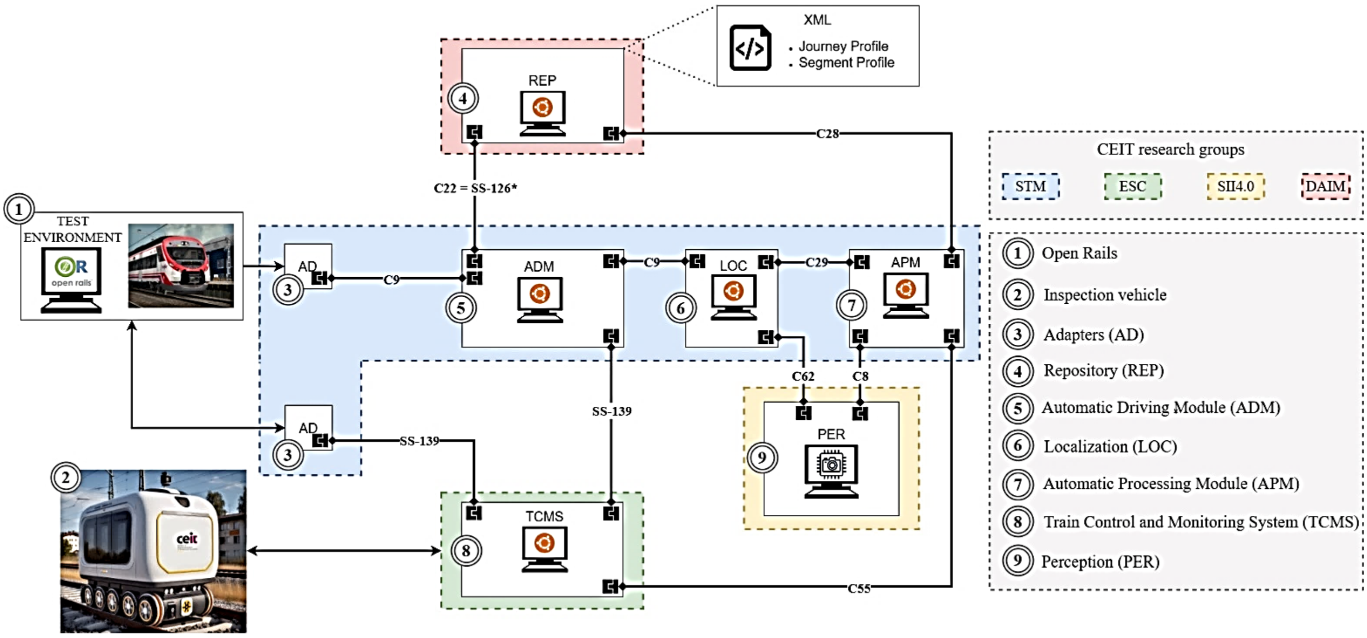

Figure 10.2 Preliminary reference architecture for ATO lab prototype based on X2Rail-4 project.

10.3.1. Components

10.3.1.1 Perception (PER)

The Intelligent Systems for Industry 4.0 (ISI 4.0) research group [11] is currently working in the PER module, which is considered as the “eyes” of the driver in GoA 3/4 systems, comprising a group of onboard sensors with the aim to evaluate the Physical Railway Environment and enhance the perception of the driver, encompassing not only visual sensing but also other factors that contribute to safety and dependability in operations.

10.3.1.2 Train Control and Monitoring System (TCMS)

The Electronic Systems and Communications (ESC) research group [12] is currently working in the TCMS module, which operates similarly to the central nervous system in humans as it oversees and connects all subsystems of rail vehicles and trains. A crucial function of this module is the control of train propulsion and braking, in accordance with the information provided to the ADM module.

10.3.1.3 Repository (REP)

The Data Analysis and Information Management (DAIM) research group [13] is currently developing an onboard module named REP, which is designed to collect, validate, and filter data received from the trackside system in accordance with the requirements of the onboard components. This module will subsequently transmit the data via the relevant interfaces.

The Sustainable Transportation and Mobility (STM) research group [14] is currently developing in the following modules:

10.3.1.4 Localization (LOC)

This onboard module provides tachymetry and location information for all onboard subsystems.

10.3.1.5 Automatic Processing Module (APM)

This module is responsible for emulating the responsibilities of the driver and train attendant in responding to incidents. This onboard module oversees the execution of missions, evaluated reactions related both train and track incidents.

10.3.1.6 Automatic Driving Module (ADM)

This module is a key component that executes the driving functions. As depicted in Figure 1.3, the ADM employs individual functions such as TTSM, SSEM, and ATSM to calculate the optimal speed profile. Furthermore, the optimal speed profile calculated by these three functions is supplied to the ATO Traction/Brake Control function. This function produces output commands (traction/braking commands) that are utilized to drive the train, respecting the optimal speed profile calculated.

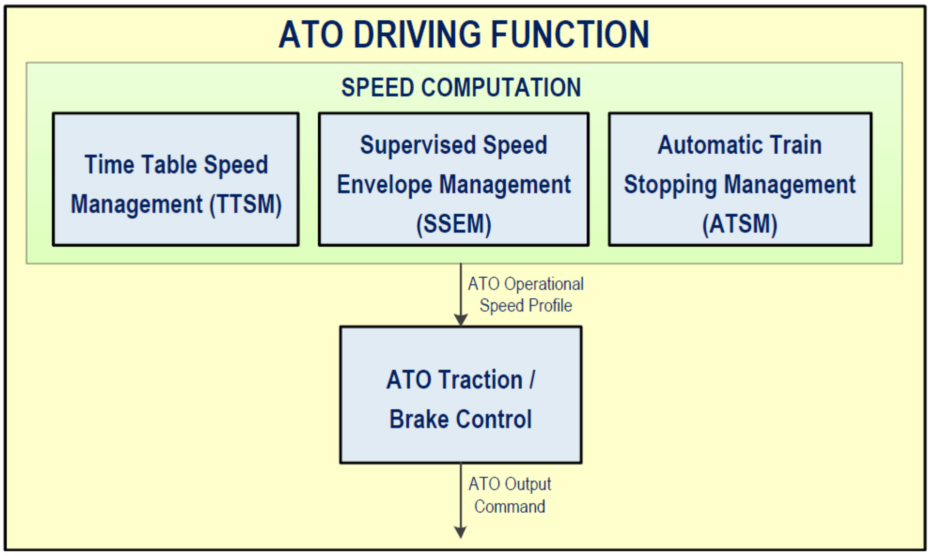

Figure 10.3 Schematic speed calculation process defined in the SUBSET-125 [15].

10.3.2. Relevant Interfaces

The mandatory specifications from TSI – CCS [5], outline a set of relevant interfaces, which are designed to facilitate seamless communication and integration among the various components of the novel reference architecture developed in the X2Rail-4 Project [4]. In addition, the ATO lab prototype is currently focused on developing the SS-126 and SS-139 interfaces. However, the remaining interfaces shown in Figure 1.2 are still pending development, highlighting ongoing work in the project.

10.4. Future works

The subsequent phase of this project entails the development and integration of adapters (AD) into the Open Rails simulator. This integration will facilitate the bidirectional exchange of data between the vehicle within a simulated environment, ensuring seamless communication via standard interfaces to modules such as the ADM, TCMS, and REP. Concurrently, efforts will be dedicated to testing the SS-126 and SS-139 interfaces to achieve comprehensive integration into the Open Rails simulator. This process is essential for accumulating experience in the development of these interfaces, which will be instrumental in defining the remaining interfaces.

Furthermore, each research group involved in this project will persist in enhancing the functionalities of their respective modules. This continuous development will gradually increase the complexity of the system requirements, which are based on the SRS of the X2Rail-4 and R2DATO projects. Through this iterative process, the project aims to elevate the overall performance and functionality of the system, ensuring that the Automated Train Operation (ATO) laboratory prototype meets the stringent standards required for advanced rail automation and inspection.

10.5. Conclusions

CEIT is actively participating in Work Package 10, which aims to develop a laboratory prototype for an automatic driving system that is specifically designed for an inspection vehicle. This system is being designed in accordance with the reference architecture for GoA 3/4 systems that is outlined in the SRS from the X2Rail-4 project, as well as the relevant standards, such as the TSI – CCS.

At present, the lab prototype is in its initial phase, which is focused on the conceptual development of its key components, including the TCMS, LOC, PER, APM, and ADM. Although these modules are still in the development phase, the team is working on defining their architecture and integration strategy. The project plans to use the Open Rails simulator as its test environment, with ongoing efforts geared towards designing adapters and interfaces that will ultimately enable comprehensive testing and validation of the ATO prototype as development progresses.

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List of Abbreviations

AD	Adapters
ADM	Automatic Driving Module
APM	Automatic Processing Module
ATO	Automatic Train Operation
ATSM	Automatic Train Stopping Management
CCS	Control Command and
DAIM	Data Analysis and Information Management
DM	Digital Map
ERJU	European Rail Joint Undertaking
ESC	Electronic Systems and Communications
GoA	Grade of Automation
ISI 4.0	Intelligent Systems for Industry 4.0
LOC	Localization
MD	Mission Data
OE	Operational Execution
PER	Perception
REP	Repository
R2DATO	Rail to Digital automated up to autonomous train operation
SRS	System Requirement Specification
SSEM	Supervised Speed Envelope Management
STM	Sustainable Transportation and Mobility
S2RJU	Shift2Rail Joint Undertaking
TCMS	Train Control and Monitoring System
TD	Train Data
TTSM	Time Table Speed Management
TSI	Technical Specification for Interoperability

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Funded by the European Union

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This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102001. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

Projects

11. Planning Problems in a Combined Yard and Intermodal Rail Freight Terminal

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11.1. Introduction

Many European train terminals are approaching their capacity limits. With national and international ambitions to increase the modal share of rail freight considerably over the next years, this poses a large problem to the infrastructure managers (IM). The physical enlargement of such terminals is often connected to a disproportionate large cost due to space constraints, being embedded in already developed and well-established industrial areas. Even if the decision would be taken to enlarge those terminals, planning and building would not be able to keep pace with the expected traffic increase.

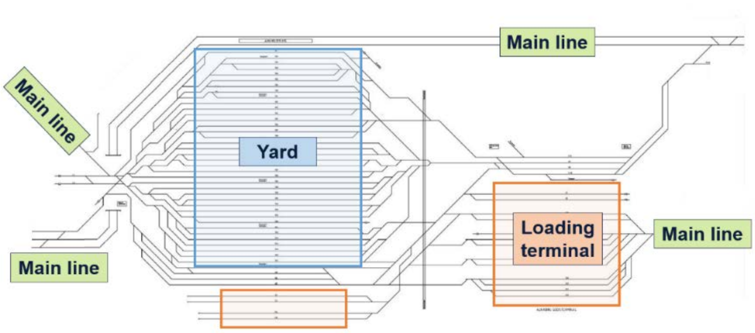

Figure 11.1 The Alnabru terminal has a loading terminal next to the yard (Bane NOR, 2024)

The FP5 TRANS4M-R project within Europe's Rail seeks to address this issue by providing tools that improve processes to better utilize capacity instead of adding more capacity, pursuing to develop rail freight as the backbone for European logistics. This paper reports findings within the work stream of Seamless Rail Freight, and emphasizes some aspects related to planning, and especially coordinated planning, that occurs in a combined terminal yard setup with multiple actors. In such a case, several operational areas are located near each other, like the (marshalling) yard, the loading terminal and the main line. The main actors operating in these areas involve different cargo operators performing shunting or loading/unloading (L/UL) operations, the dispatchers and the IM. Planning may include schedules, sequences or resource allocations deciding when or where operations on trains should be done, or what should be done. Within rail freight we often observe that operations are driven by ad hoc activity and fragmented planning, lacking proper coordination with other operational areas or actors. Locally created plans may appear resource- or time-effective when seen in isolation, but turn out to be hard to realise as surrounding circumstances affect the arrival times, physical states or compositions of the trains. For example, one may have different actors working in the same area. These actors will have to share resources like tracks or equipment. Uncoordinated plans for each actor may lead to conflicting resource utilization, which can cause delays and inefficiency.

Enabling coordinated planning is time-consuming and difficult for several reasons. To investigate the challenges and effects related to coordinated planning, we study the Norwegian rail freight terminal Alnabru in Oslo. This terminal has a high activity of operations on both national and international trains. As shown in Figure 11.1, it consists of different areas. In the loading terminal trains are loaded or unloaded, the cargo is placed in depots, and customers deliver and pick up containers and semi-trailers for further distribution. Located not far from the loading terminal is the yard, where wagons are stored, disassembled and assembled. There are currently three terminal operators who all perform shunting and loading operations within Alnabru. This makes coordinated planning important for enabling seamless, safe and effective operational processing in Alnabru.

11.2. Challenges when planning operations

We now highlight some key issues that may arise in an environment with multiple actors and operational areas, as identified through studies at the Alnabru terminal.

11.2.1. Time horizons

As described in the FP5 deliverable D25.1 (Hildebrandt, 2023), one may separate the time horizon for planning:

- **Long-term** planning involves decisions made sufficiently long before implementation, like weeks or months. Long-term schedules should be consistent and active for a long time period, unaffected by minor surrounding aberrations.
- **Short-term** refers to a period where anticipated or observed changes in the conditions call for updates to the long-term schedule. The horizon starts when the long-term horizon ends and lasts until a few hours before the realization of the plan.
- **Real-time** refers to the phase where the operations are in progress, and deviations or other unforeseen events may cause a need for rescheduling. The horizon spans from hours before the operations start and to the end of the relevant operations.

We often observe that the different train operations are planned independently within different time horizons, even though they are in fact intertwined. Long-term plans may naively assume real-time feasibility, while in real-time the same plans may be regularly overridden by short-sighted practical or even egoistically convenient changes. A combined planning process needs to take potential adjustments in other time horizons into account. Long-term planning should anticipate the standard modifications occurring in short-term and real-time planning and create a robust long-term plan that allows for those modifications without the need of disrupting the whole plan. In short-term and real-time replanning, changes need to be communicated so that the new plan can take the whole environment into consideration.

11.2.2. Competition between actors

When multiple actors share resources during their operations, several identified aspects burden the collaborative planning processes:

- **Unreliable input data:** Actors may provide estimated or unrealistic input data as that data may be unknown at the point of planning, or to encourage a plan that favours this actor's goals.
- **Technical data-sharing:** Although a common desire may be present, there exist technical barriers for sharing plans and updated information in real-time. This limits the possibility for a harmonized and information-filled decision-making processes.
- **Collaborative costs:** Plans that are individually sub-optimal, but globally optimal, may be considered undesirable. The existing ad hoc operations amplify incentives to choose in a way that creates less than optimal outcomes for the individuals. In addition, the benefits of a globally optimal plan seem harder to measure than the costs per actor in a plan that favours that actor.
- **Self-selected KPIs:** What defines a 'good plan' varies between the actors of the same type and between different types of actors, like an operator and IM. Conflicting priorities may cause disagreements and unwillingness to share resources in all time horizons.

11.2.3. A web of related planning problems

Within a loading terminal and a yard there exist plenty of decisions that can be made through planning. Let us give a few examples. One problem concerns how a set of wagons should be disassembled and assembled into new train sets in the yard. Other decisions relate to coordination of different shunting operations happening simultaneously, both inside the yard and between a loading terminal and the yard. And in case of delays or other changes, the sequence of different train operations may need to be adjusted. Classically, many such decision-making problems are studied in isolation. However, when solved in this way, the locally meaningful decisions for one problem yield constraints for other planning problems. While many of these single planning problems are already hard to solve individually, an ideal planning process would be able to take the connection between the different problems into account to provide a good overall solution.

11.3. Case-study: Optimizing loading tracks assignment

One planning problem that stands out in the Alnabru terminal is the challenge of assigning loading tracks and L/UL times to the freight trains that stop at Alnabru. Each year, the IM receives a set of applications from the different terminal operators. For each of those, the IM must decide when and where the applied train should be served. At the time of planning the upcoming train timetable is unknown, but the applied paths are provided as input. Each train has to be served within the provided arrival and departure time, and the IM must balance different challenges and desires when suggesting the assignments:

- Some timeslots are more important than others, like mornings and afternoons.
- The tracks have different properties like length, heating and access to portal cranes.
- For safety reasons each track should ideally be assigned to only one operator.
- The assignment must appear fair, so that the operators are fairly equally pleased.

11.3.1. Planning in isolation

By itself, this long-term loading tracks assignment is a variant of the flexible job shop scheduling problem, which is a computationally hard optimization problem (Dauzère-Pérès et al., 2023). The track assignment is currently solved by hand through manually made suggestions from the IM that are discussed with the operators in an iterative process. When the timetable is settled, the finalized plan is implemented. The track assignments are followed, but as delays or unforeseen events occur it is left to the operators themselves to reschedule on-demand within their assigned tracks. Currently, these rescheduling decisions are mostly made without the help from any decision-support system and not in coordination with the other operators.

11.3.2. Combining with yard planning

In real-time, the L/UL of trains in the loading terminal is highly dependent on what happens in the yard. A train cannot be loaded as planned if the wagons are not shunted from the yard in time, nor may unloaded wagons be shunted out from the loading terminal if the yard is filled. The Alnabru yard has a burst capacity which makes the realisation of the long-term loading track assignment very hard. Ideally, one would assign track-time-slots in the terminal combined with assigning tracks in the yard, and ensure a schedule where the necessary shunting of wagons to/from the yard is feasible. Making plans that coordinate all of these decisions is very hard for a human planner, especially when without any support system.

11.4. Decision Intelligence support

Decision Intelligence (DI) is an application of artificial intelligence which aims to improve decision-making processes by integrating data-driven insights such as efficient evaluation and comparison of decisions (VanderLinden, 2023). With advanced AI techniques like data analytics and machine reasoning, systems with DI may assist human planners in systematizing data and visualizing intelligently computed solutions. Through its capabilities of designing plans that can involve different actors across areas and time horizons, DI will play a pivotal role in shaping the future of rail freight planning.

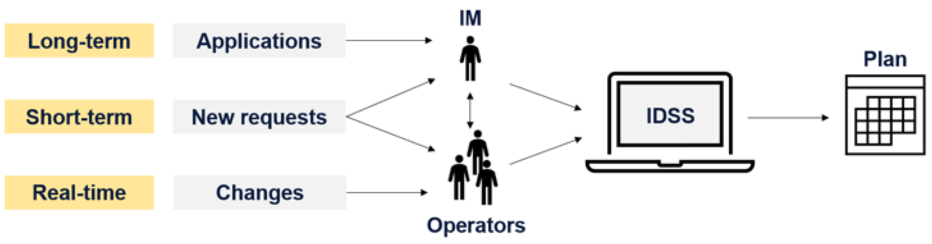

Figure 11.2 Using an Intelligent Decision-Support System (IDSS) for planning

FP5 will develop DI that uses mathematical optimization-based algorithms for suggesting L/UL schedules, demonstrated through the Alnabru case-study. The developed Intelligent Decision-Support System (IDSS) will take as input the abovementioned data provided to the IM, together with knowledge about terminal-specific rules and preferences, and use this to compute L/UL assignments that are optimal with respect to a specified objective. The aim with this is not to replace the human planner, but rather to empower him by suggesting plans. These can be easily altered in isolation or together with the operators through features like drag and drop and information display. Further on, through the possibilities of receiving new requests and real-time changes to the train timetable, the system can automatically suggest optimal alterations to the plan. For example, when a train is delayed, an IDSS can compute when and where to serve the train in order to minimize deviations from the existing plan.

Although DI systems can initiate smarter and more coordinated planning processes, there are unavoidable challenges related to the implementation and use of such systems. Gaining trust and competence in using a digital system, as opposed to having no intelligent support, may be time-consuming. For the system to work, correct data about the relevant areas (e.g. track lengths) must be provided. The challenges related to competition between actors may lead to hesitation towards a centralized support system. In addition, there are difficulties related to the intelligence itself. Ensuring a proper representation of the planning problem, constraints and parameters requires domain expertise, and research must be done on how the solutions may be calculated and proposed efficiently.

For the loading track assignment in Alnabru, this problem will first be solved in isolation to inspect how an IDSS can assist in long-term planning. Discussions with the IM and operators have been held to understand the constraints that apply and how a fair objective looks. For Alnabru, an optimal plan respects the applications, balances a large operator's wishes with the requests from a small operator, and avoids shared tracks. For other terminals this will likely be different. One of DI's strengths is the support of, but not requirement of, user-specific preferences when proposing solutions. In the future of Europe's Rail, we hope to extend the IDSS to also take yard decisions into account, as an important step towards enabling coordinated planning in a combined yard and intermodal rail freight terminal.

11.5. Conclusions

A freight train's path includes stops at several operational areas. Among these are yards, where vehicles and wagons are sorted and assembled, and intermodal terminals, where the cargo is unloaded and further distributed by other modes of transport. Challenges related to the planning of operations arise in environments where a yard is located physically near a terminal. Within rail freight, planning is too often performed in isolation with respect to areas, actors or time horizons. Moving forward, more coordinated planning is seen necessary for realising effective plans that can reduce delays and operational dwell time. We highlight Decision Intelligence as one key enabler that may assist human planners in performing more coordinated planning. As exemplified through the loading tracks assignment at the Norwegian Alnabru terminal, optimization-based AI models may be implemented into a system that can suggest high-quality plans to the user. Although there are barriers related to the implementation and use of digital decision-support systems, they stand out as valuable and future-oriented technical enablers for coordinated planning across different areas of the rail freight service.

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List of Abbreviations

DI	Decision Intelligence
FP5	Flagship Project 5
IDSS	Intelligent Decision-Support System
IM	Infrastructure Manager
L/UL	Loading/Unloading

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102009. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

12. Digital Twin Development for Test Site: Foundation for Innovative Cost-Effective Train Positioning Alignment

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12.1. Introduction

Across Europe, many regional and capillary rail lines face the threat of closure due to low traffic volumes, despite ongoing efforts to boost rail transport across the continent. Revitalizing these lines to ensure their economic sustainability has become an urgent priority. In response, the EU launched the "FutuRe" project, which focuses on innovative services such as digital solutions, automation, and advanced maintenance strategies to breathe new life into these critical rail networks.

One of the main challenges facing regional rail lines is their remote locations, which make maintenance difficult. This issue is compounded by inaccuracies in train positioning systems. In many countries, specialized measurement vehicles are deployed to monitor track health, but these systems often suffer from positional inaccuracies. This can lead to discrepancies between the recorded data and the actual track location, forcing maintenance crews to conduct additional manual inspections to accurately identify problem areas. This not only increases the complexity of maintenance but also escalates costs—an especially unfavorable situation for the already strained regional rail lines.

Currently, train positioning relies on a combination of differential GNSS, satellite-based augmentation systems, and inertial navigation. While these technologies are essential for the safe and efficient operation of railway networks, they each have significant drawbacks. Differential GNSS, although highly precise, requires expensive infrastructure. Satellite-based systems can be unreliable in challenging environments like tunnels and valleys, and inertial navigation systems are prone to accumulating errors over time, leading to positional drift. These limitations often result in substantial discrepancies between reported and actual train positions, complicating monitoring and maintenance tasks.

Digital twin technology has recently gained significant attention for its wide-ranging applications, from basic visualization to advanced health monitoring of various structures. It has been extensively used in structural health monitoring across diverse fields, including bridges, standard constructions, and aerospace components (Li, Mahadevan et al. 2017, Ye, Butler et al. 2019, Liu, Liu et al. 2020, Zhu, Wagg et al. 2020). A recent study by Doubell et al.(Doubell, Kruger et al. 2022) underscores the significant potential of digital twin technology in railway infrastructure management. The study suggests that by integrating historical and real-time data, more efficient maintenance routines could be developed.

Building on this potential, research efforts have explored innovative solutions that utilize digital twin technology to address train positioning challenges. This work aims to integrate a geo-referenced 3D digital twin with real-time sensors such as onboard GNSS, inertial navigation systems, and satellite-based augmentation systems along with additional technologies like cameras to enhance train positioning accuracy. This approach is particularly beneficial in challenging environments like valleys and tunnels, where traditional signals are often unreliable or unavailable. By leveraging cameras and fragments of position data, the train's location can be triangulated with greater precision, ensuring more reliable positioning even in difficult conditions. This not only addresses the critical issue of positional accuracy but also supports the broader goal of revitalizing regional rail lines by enabling more efficient and cost-effective maintenance practices.

12.2. Method

The proposed method consists of two phases: an offline phase, which involves generating a digital twin of the railway track environment using a model-driven approach with Terrestrial Laser Scanning (TLS), and an online phase, where data captured from onboard sensors—such as GNSS sensors, an IMU, and cameras—will be combined and matched with the offline digital twin model to obtain the train's real-time, highly accurate locations. See Figure 12.1 for a schematic of the proposed method.

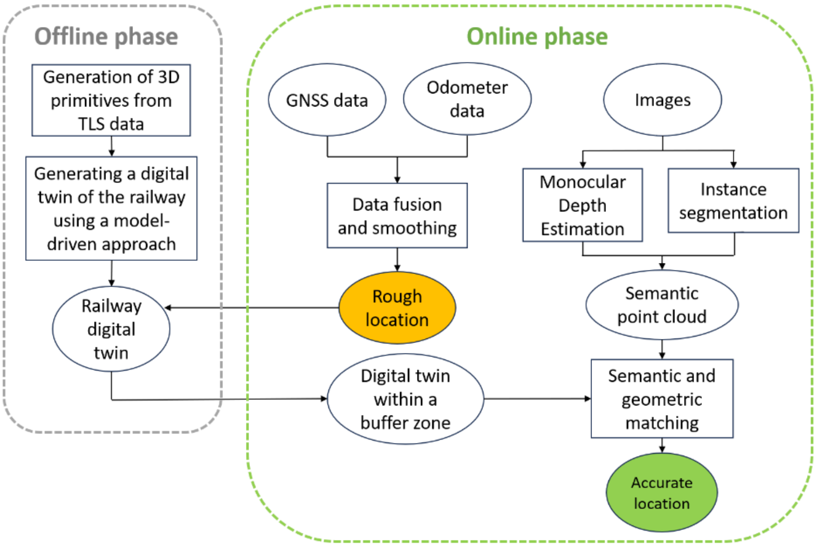

Figure 12.1 Proposed method

This work focuses on the Digital Twin Development for the Test Site, which belongs to the offline phase and serves as the core foundation of this innovative method. The test site will be located at the Norwegian University of Science and Technology, and Figure 12.2 shows its appearance. This location is chosen for its ability to simulate different scenarios, such as buildings in close proximity to simulate valleys, building underpasses to represent tunnels, and open spaces to represent general track conditions.

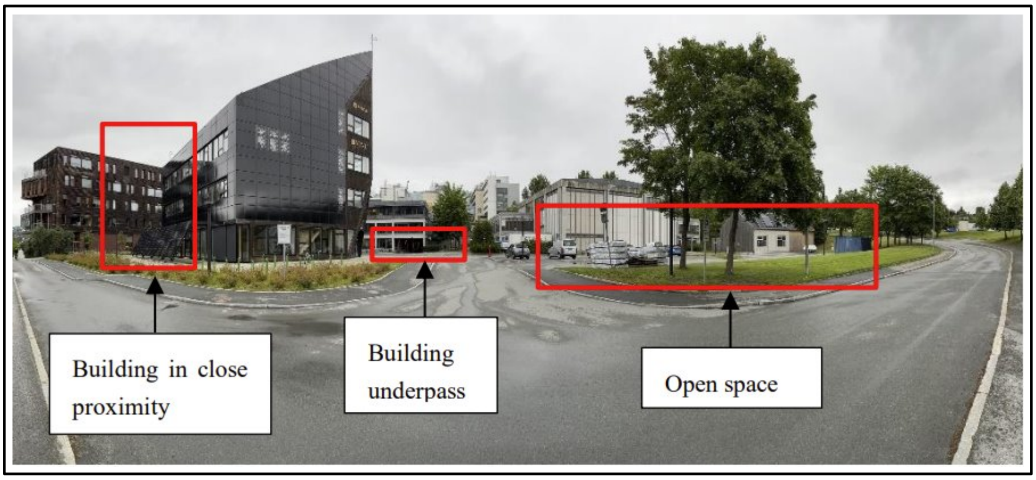

Figure 12.2 Test site

To achieve this, dense point clouds will be collected using terrestrial laser scanners and processed to create a geo-referenced 3D geometric model of the site. Semantic labeling will be added to identify different objects like buildings, trees, and poles, thereby enhancing positioning accuracy. The site will include various scenarios such as open spaces to represent open tracks, building underpasses to simulate tunnels, and closely situated buildings to simulate valleys. The digital twin will be converted into CityGML (City Geography Markup Language), an open standard data model and XML-based format for representing 3D city models, linking semantic information with the geometric model.

To test the method, an unmanned ground vehicle (UGV), as shown in Figure 12.3, will be used. The UGV is equipped with GNSS sensors and an IMU, similar to those used on regular trains. Additionally, it is equipped with several cameras. It is anticipated that the data from these sensors can be integrated into CityGML to align and refine the vehicle's position.

Figure 12.3 Unmanned ground vehicle

12.3. Results

This section presents the digital twin developed for the test site. Figure 12.4 illustrates the 3D geometric model of the digital twin, visualized in true colour to provide an overview of the site’s structure. Figure 12.5 shows its semantic labels, where different colours are used to categorize and identify different types of objects within the model. Figure 12.6, Figure 12.7, Figure 12.8 offer close-up views of specific areas of the digital twin, which have been specifically chosen to simulate railway features such as tunnel, valley, and open space. The test site replicates a typical railway track environment, incorporating various elements such as trees, poles, traffic signs, and diverse building styles.

Figure 12.4 Geometric model of the test site digital twin

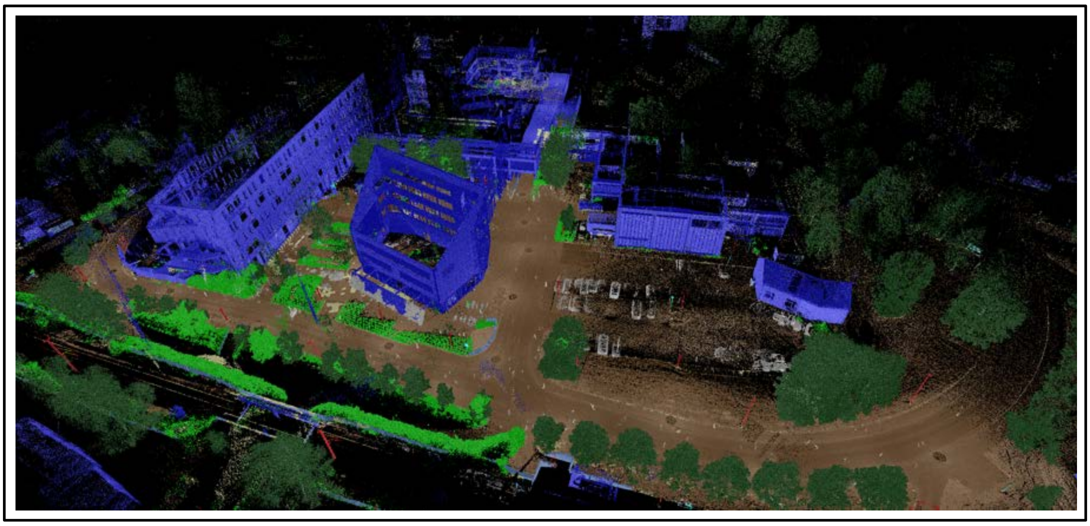

Figure 12.5 Semantic labels

Figure 12.6 Simulated tunnel

Figure 12.7 Simulated valley

Figure 12.8 Simulated open space

12.4. Future work and expected outcomes

The next step is to integrate the UGV into the digital twin to develop algorithms that can improve the accuracy of positioning using onboard sensors. The sensors are kept similar to those on regular trains to ensure that these technologies can be easily transferred to standard trains. The goal throughout this methodology is to achieve train positioning precision within ±25 cm, which marks a significant improvement over the current Norwegian maintenance vehicles, which have positioning accuracies exceeding ±15 m. Achieving such accuracy is expected to reduce costs for regional lines by minimizing the need for balises. Additionally, maintenance will become more effective, as identifying faulty locations will be easier, thus reducing costs. The digital twin solution is also expected to enable continuous train positioning, even in challenging environments like tunnels and valleys, by improving georeferencing through the digital twin.

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101101962.The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

This research project is funded by Norwegian Railway Directorate (NRD) and Europe's Rail Joint Undertaking (grant number 101101962-FP6-FutuRe-HORIZON-ER-JU-2022-01).

13. EURAIL – FA6 FutuRe Project: Innovative solutions for G2 regional lines

Fabrizio Burro - Wabtec Corporation, Libor Lochman - Wabtec Corporation, Alessandro Mascis - Wabtec Corporation

13.1. Abstract

European regional lines are an essential part of the multimodal mobility scheme. Despite their relevance, they are gradually being abandoned due to the increasing total cost of ownership (TCO). FutuRe FP6 project aims at the development of the traffic management/control/command and signalling system for low density lines that are not functionally/operationally fully connect-ed with the mainline network (ER JU Multi Annual Work Program – [1]) – so called Group 2 Lines (G2), that are operated by passenger and/or freight services that do not usually enter mainline infrastructure. Following the analysis of the current regional railways key cost drivers, we will demonstrate less expensive and more advanced solutions for COTS (Commercial Off The Shelf equipment) based
Group 2 lines, having as funding pillars public radio communication & satellites in support to fail-safe highly accurate positioning, intelligent systems on-board, cloud-based control centre for vital fail-safe Interlocking and RBC (Radio Block Centre) related functionalities.
Today's available technologies are suitably mature for creating new solutions for low density railway; use of COTS products dramatically reduces the CAPEX and OPEX costs paving the way for long-term viability of these lines.

Keywords: regional; low density, CAPEX; OPEX.

13.2. Introduction

Within the [1] Multi Annual Work Plan (MAWP) of the ERJU, G2 lines have been identified as the ones at major and immediate risk of decommissioning. This is true both for passenger regional and freight services. The pressure of competition (trucks, buses, cars) on the railway operators is intense and growing, requiring more efficiency in terms of performance and energy saving. For those lines very low-cost solutions, without compromising the need for standardization and safety.
The signalling/train control world is heading in a clear direction towards minimisation of wayside equipment, wireless communication, integrated intelligence on-board and large national traffic management centres

13.2.1. Key cost drivers affecting regional low-density lines competitiveness

To reduce the cost of G2 regional low-density lines it is required to consider what is in Figure 13.1:

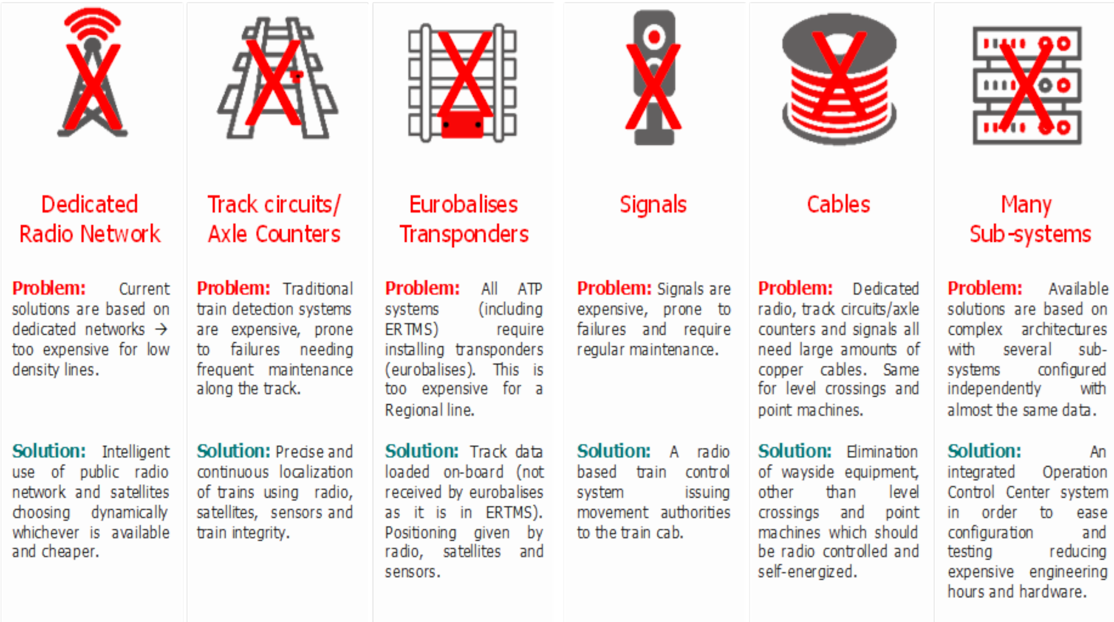

Figure 13.1 Key cost drivers currently characterising regional lines

There is a clear need to define a modern signalling/train control system based on the below described pillars:

- Significant limitation of wayside installations deploying more onboard centric solutions by monitoring the train integrity and determining location through communication systems/sensors (Satellite, Radio).
- Usage of geographical data in Onboard Track databases, similar as to CBTCs, in support to train positioning and detection.
- Moving wholly to Moving block techniques allowing the removal of lineside signals.
- Moving away from expensive, soon obsolete dedicated radio network solutions in favour of public networks.
- Rationalisation of the Traffic Management & Control Centre.

There are, worldwide, no Railway lines equipped with such a minimalist solution while introducing low cost high performing technologies.

13.3. G2 Lines Architecture

A high-level description of main building blocks, internal and external interfaces of the G2 Lines system architecture is provided, in adherence to the [1] and [2] statements to propose innovative solutions for regional lines having “no or limited connection to mainline traffic” ([1] sect. 7.6.2.3).

13.3.1. Rationale

Due to the nature of the traffic targets characterising the G2 Lines, reduced, or not required, interoperability is the reference operative scenario. Similarly, while guaranteeing high-level of the system safety, safety requirements for the G2 Lines subsystems shall result from the review of European and national regulations and proposed amendments to them when need be. The above implies a new concept of traffic management system (TMS) and associated services delivery, supporting “*long term viability of regional railways by decreasing the total cost of* *ownership (TCO), in other words, cost per kilometer both in terms of OPEX and CAPEX, while offering a high quality of service and operational safety*" (ref. [1] sect. 7.6.1.1). The implementation of the G2 Lines requirements should bring to (ref. to [1] 7.6.2.1) *a low-cost technical and operational framework for low density lines to reduce the cost per kilometer both in terms of CAPEX and OPEX as a well as an increase in customer satisfaction, which should be applied as a European solution.*

13.3.2. Standardisation and Interoperability

G2 Lines are expected to (ref. to [1] 7.6.2.3) ensure standard interfaces and standard data protocols (preferably supporting the use of COTS). Intentionally we avoid defining the architecture of each key component: our approach is to define the minimal data to be exchanged among the components and leave to the industry the freedom to develop innovative solutions without being constrained by pre-defined architectures. For example, we do not care about the architecture of the train on-board systems, we care that the train is able to receive and send the data needed to ensure a safe and performant travel. In other words, in our approach trains equipped with different ATP systems can run in the same line until they are able to communicate with the standard protocols and until they are able to safely respect the movement authorities received by the control room. This interoperability among different equipped trains and different control rooms will bring competition and innovation. We do think that in the past the railway market had the tendency to over specify and constrain the architecture of systems with the unexpected result of delaying innovation, increasing costs and facing obsolescence

13.3.3. Building blocks

Following the key drivers, the proposed solution is depicted in Figure 13.2 below. The G2 Lines architecture is based on four main segments, substantially the inter-related building blocks on which it can be decomposed from an Operational, Functional and System point of view such as: Communication data network, Train On-board, Wayside, Traffic Management and Control Centre (CCS, including signalling).

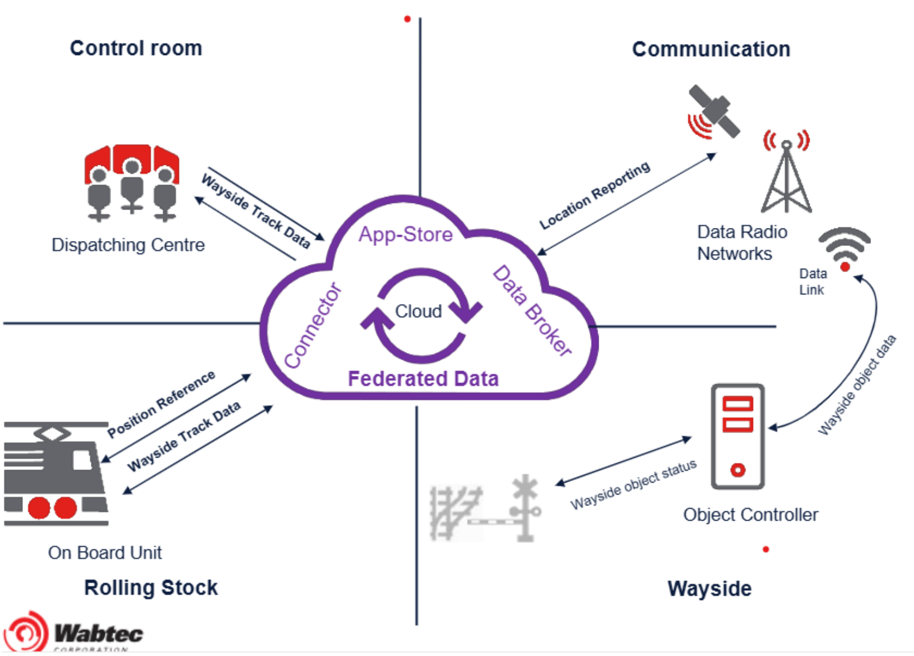

Figure 13.2 G2 regional lines high level architecture

<u>Communication Data Network</u>.
A dedicated radio network typically represents around 20% to 30% of the overall CAPEX cost of new signalling systems, not to mention the OPEX costs for its maintenance. Telecommunication technology evolves faster than

railway technology: therefore, it is critical to keep the train radio communication module separated from the Railway applications (i.e., the ATP and ATO). Therefore, it is strategic to use Internet Protocol standards-based messaging, public networks and routing COTS solutions allowing:

- Transparent access to cellular, wi-fi and satellite communication (and future technologies) with an automatic selection of the available and cheapest one for maximum availability and minimised costs. Data communication, for exchange of train position reference, location reporting, data link with controlling equipment is extensively based on standard Internet Protocol messaging/routing.
- Cloud and Web based application, either through public services with certified proper level of security or implementing “Cloud-like” concept in legacy/proprietary communication system of infrastructure manager, accessing to most advanced encryption and authentication algorithms.

When developing the above concept, reference will be made to Shift2Rail X2Rail-5 WP3 and WP12 outcomes.

Based on the above, the G2 Lines communication data network should result in a “telecom technology agnostic” architecture. As per [1] 7.6.2.2, the proposed G2 Lines approach embraces a cost-effective use of dedicated railway mobile networks or communication infrastructures owned by a third party (e.g., LTE, 4G, 5G, satellite comms and IoT communications) for the innovative ways to exchange of the information between the regional railway subsystems (e.g., Train to Train, Train to Trackside – wayside assets, Trackside to Trackside).

Train onboard assembly.
Train Detection. On-board segment of the G2 Lines architecture recalls the well-known concept of Communication Based Train Control (CBTC) to which positioning based on radio communication technologies can be now integrated. Modern train control solutions are radio based (various CBTC systems for automatic metros, Railways by ERTMS L2/L3 and Positive Train Control): information among traffic control rooms, trains and wayside elements is exchanged wirelessly. In G2 Lines proposed concept radio and satellites provide (augmented high precision, where required) train positioning to the on-board unit, which can use this to index an onboard track digital map (resulting from a standardised validation process) thus removing the need for wayside balises/transponders along the track. For safety considerations, to remove high-cost track circuits and axle counters the system requires the on-board unit to determine train length and train integrity

Train Positioning. Positioning technology performance is mature, currently till precision of few centimetres using satellites plus publicly available correction services. Soon, 6G & 7G will make localization cheaper and easier to implement (integrating cellular with satellites technology). Such technologies will evolve quicker than railway technology, therefore that scope must be separated from the railway applications (i.e. the ATP, ATO, train control). With such an approach the proposed solution implements the positioning exploiting COTS hardware & software, without changing the railway on-board applications. It is possible to achieve a SIL4 (Safety Integrity Level 4) positioning using alternative non SIL certified components without the need of a wayside transponder. The G2 Lines approach will meet the implementation of a cost-effective, interoperable, fail-safe, highly accurate train positioning (including dead reckoning where required) based on data fusion of information from hybrid, multi sensor technologies, digital maps, onboard database, as a mean to reduce balises installations, increase operational efficiency and decrease TCO in the context of regional lines

Wayside.
Minimisation of the wayside equipment deployment is a target for the G2 Lines concept that does not include the integration and exploitation of any wayside based train detection and train positioning technologies, as well as lineside visual signaling equipment and cables. The proposed System Architecture, at wayside level, encompasses the level crossings (wirelessly controlled or autonomous) and point machines (including also self-returning type). Such equipment is essential for safe operation of the infrastructure, then it cannot be removed either for cost reasons or to manage capacity. G2 Lines architecture addresses an upgrade of these elements to make them renewable energy operated (bringing a minimised impact on environment) and radio controlled (not requiring any expensive signaling and power cables). The combination of batteries, solar panels and radio communication allow

to align these structural elements to the modern solution proposed becoming an integral part of the overall solution.
Summarising, the proposed G2 Lines approach will meet the need of *infrastructure components and wayside elements for regional railways including signalling, level crossings, switches and track vacancy detection which are energy self-sufficient and/or wireless enabled to reduce costs, cable and power supply and enable remote control or full or partial automation and/or autonomous operation. ([1] 7.6.2.2).*

Integrated Control Room / Centralised Traffic Control & Traffic Management System.
Existing system architectures are based on several layers to efficiently manage railway traffic, but that results in being too expensive for much simpler low-density lines. Therefore, low density lines need a fast and easy configurable low-cost Integrated Control Room: one HW unit can manage all functions needed: Traffic Management System (TMS) / Centralised traffic Control (CTC); Interlocking; Radio Block Centre (RBC). A single database will ease the configuration and testing, reduce expensive engineering hours and software maintenance. Such Integrated Control Room can control trains optimizing their journey to increase punctuality, reduce travel time and allow on-demand passenger services encompassing, but not limiting to, maximum safety (SIL4) and non-safety related functions via radio such as the management of interlocking functions, the commanding and control of point machines and level crossing, the optimisation of real-time routing and scheduling of train operations, the remote control of trains and the interface to intermodal traffic management. Finally, cloud-based services provided by third parties can reduce the cost of managing and maintaining servers, applications and database allowing web-based access for remote operators (e.g., maintenance staff on the track side)

13.4. Conclusions

The proposed innovative approach is a game changer for the railway system. Today's available technologies are suitably mature for creating new solutions for low density railway lines based on radio public networks, cloud computing, satellite and COTS products, to reduce at least 30% on CAPEX and 40% on OPEX preserving them from the risk of closure. The key beneficiaries are the public transport authorities in charge of regional mobility, operating passenger low density (G2) lines and freight delivering cargo in remote areas. The presented concept paves the way to the introduction of several advanced services for both passengers and freight lines such as precise forecasting, flexible/on demand service and intermodality. By its nature, the proposed approach brings huge benefits by a smooth transition from pre-existing/old signaling system, to the new CCS technology. That includes the possibility to act as an overlay ATP during the time required for a complete migration to fully digitalised system

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[1] Europe's Rail Joint Undertaking Multi-Annual Work Programme – 2.0 March 2022
[2] Project 101101962 - FutuRe FP6 Grant Agreement.

List of Abbreviations

ATO – Automatic Train Operations
ATP – Automatic Train Protection
CAPEX – Capital Expenditures
CBTC – Communication Based Train Control
COTS – Commercial Off The Shelf
ERJU – Europe Rail Joint Undertaking
ERTMS - European Railway Traffic Management System
OPEX – Operational Expenditures
WP – Work Package

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Funded by the European Union

Europe's Rail

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101101962. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

The work presented in this paper has received funding from the Europe's Rail Joint Undertaking, Grant Agreement no. 101101962. The contents of this publication only reflect the authors' views; the Joint Undertaking is not responsible for any use that may be made of the information contained in the paper.

14. Demand-driven Optimization of Public Transit

Christian Schwingenschlögl, Siemens, Rolf Gooßmann, Hacon, Ira Kataria, Hacon

14.1. Introduction

Focusing on the main objectives of ERJU Flagship Project 6-FutuRe, we describe our work based on data from MaaS platforms to analyse and predict demand and thus to better understand when and how public transit systems are used by its customers. After describing some technical background of the analysis, we present several applications which are possible based on this data and the outcomes of its analysis. This highlights many opportunities regarding how to lower CAPEX and OPEX while, at the same time, improving customer satisfaction. While this might sound contradictory, we are convinced that this can be achieved by understanding travel demand and tailoring public transit offerings to the real needs of the customers.

14.2. Technical Background

14.2.1. Data Analysis for Occupancy Estimation

In a MaaS platform, many requests from travellers are getting processed (Figure 14.1). This includes the route requests as well as the route recommendations which are sent back to the travellers. Using this data, it is possible to learn about frequently requested origin/destination relations. In addition, much more contextual information can be derived from this data, including footpaths to the first public transit station, recommended lines, and even interconnections and delays. If samples are available from other data sources, e.g., automated passenger counting systems, we like to use those to calibrate and validate any calculations. It is not required to have all vehicles equipped with passenger counting systems; calibration already benefits if data is only available from any given subset of vehicles. Figure 14.2 depicts the main features of the two datasets. Route request data is available for the entire network, has information about the entire trips including door-to-door information, and is even predictive. This means that requests are often made for trips which are planned for the next days, especially in case of any event like e.g., a soccer game. The passenger counting data does not include this contextual information. Depending on the fleet at hand, it might not cover the entire network and is often available with a significant delay only (in case of off-line counting systems). Nevertheless, its relatively exact counts help to improve the accuracy using calibration and allows to validate the results of our calculations. Figure 14.3 shows results which have been achieved in a large-scale validation in a live customer system, running several months. The values shown in this figure are very well comparable to results we see in other transit networks. Request data from HAFAS is considered and partial passenger counting data is considered during the training period. During operations, the training data is used along with the request data to make the predictions. The predicted values are then again compared with the partial counting data to arrive at the error percentage.

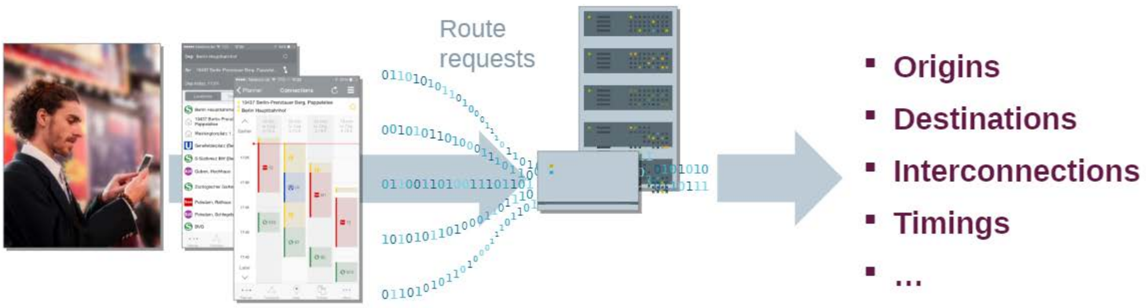


Figure 14.1 **Route Requests**

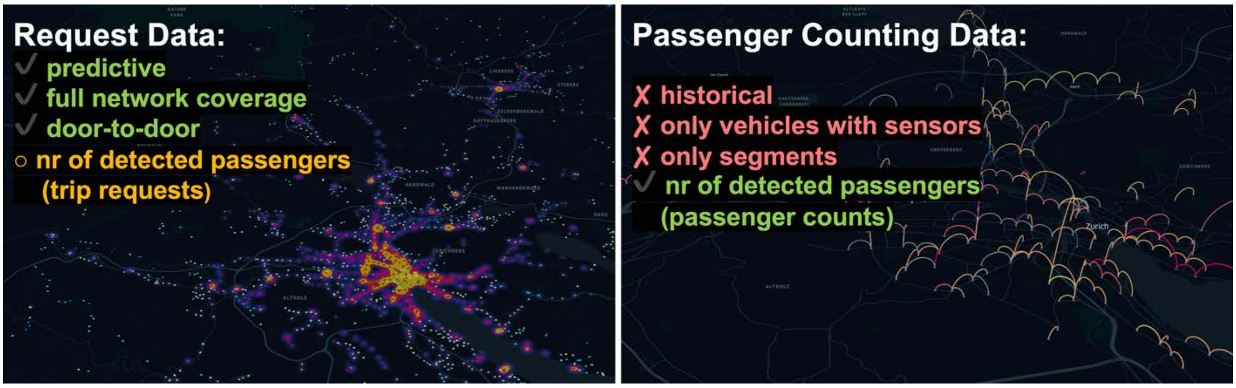


Figure 14.2 Features of Request- and Passenger Counting Data

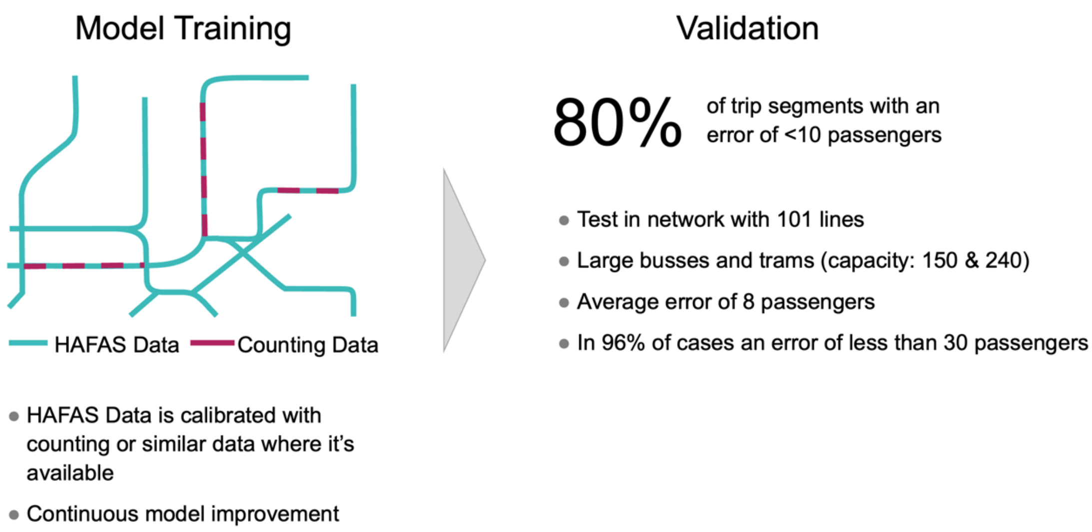


Figure 14.3 Exemplary result from a validation running several months

14.2.2. Addressing Data Imbalance in Occupancy Prognosis with SMOTE

In the present use case, the dataset is anticipated to exhibit significant class imbalance, characterized by numerous segments with low occupancy. This imbalance arises due to coverage of remote regions and off-peak or nighttime services, presenting additional challenges for machine learning models. To mitigate these challenges, we employed the Synthetic Minority Oversampling Technique (SMOTE) [3] on the training dataset. SMOTE [3] effectively generates synthetic samples of the minority class, thereby balancing the class distribution and enhancing model performance.

14.2.3. Modelling Approach

We continuously evaluate the performance of various machine learning models and adapt our algorithms based on their outcomes. Notably, we have achieved robust results using Supervised Machine Learning, particularly with Gradient Boosted Trees [5] implemented via the XGBoost framework [4], for medium- to long-term forecasts, typically considering a time window of 10 to 14 days. A primary limitation of simple decision trees is their lack of predictive power, despite their simplicity. To address this, ensemble models enhance a base learner (a shallow decision tree) by iteratively combining multiple base learners (weak learners) into a strong learner. This combination is achieved by generating different base learners for subsets of the dataset either in parallel or sequentially. When performed sequentially, this process is known as boosting, where individual tree functions are greedily added to a loss function l to minimize the regularization objective L. In gradient-boosted trees, the steepest descent direction for minimization is estimated using a gradient descent function. This function aims to predict the optimal gradient for the additive model to achieve a local minimum of the loss function. The model is initially constructed with a set of weights, and the loss function is minimized by iteratively updating these weights. Specifically, XGBoost [4] employs K additive functions to predict the target variable. Given the imbalanced nature of the dataset, the results are heavily biased towards the low occupancy class, as most samples belong to this class. Consequently, the model's objective to minimize overall error is best achieved without distinguishing between the three classes. However, through hyperparameter tuning, we increased the model's complexity, risking overfitting but enabling the model to detect more intricate relationships. Additionally, we fine-tuned the parameters to improve classification performance for the high occupancy class, compelling the model to allocate more effort towards distinguishing this class.

14.2.4. Short-Term Forecasts

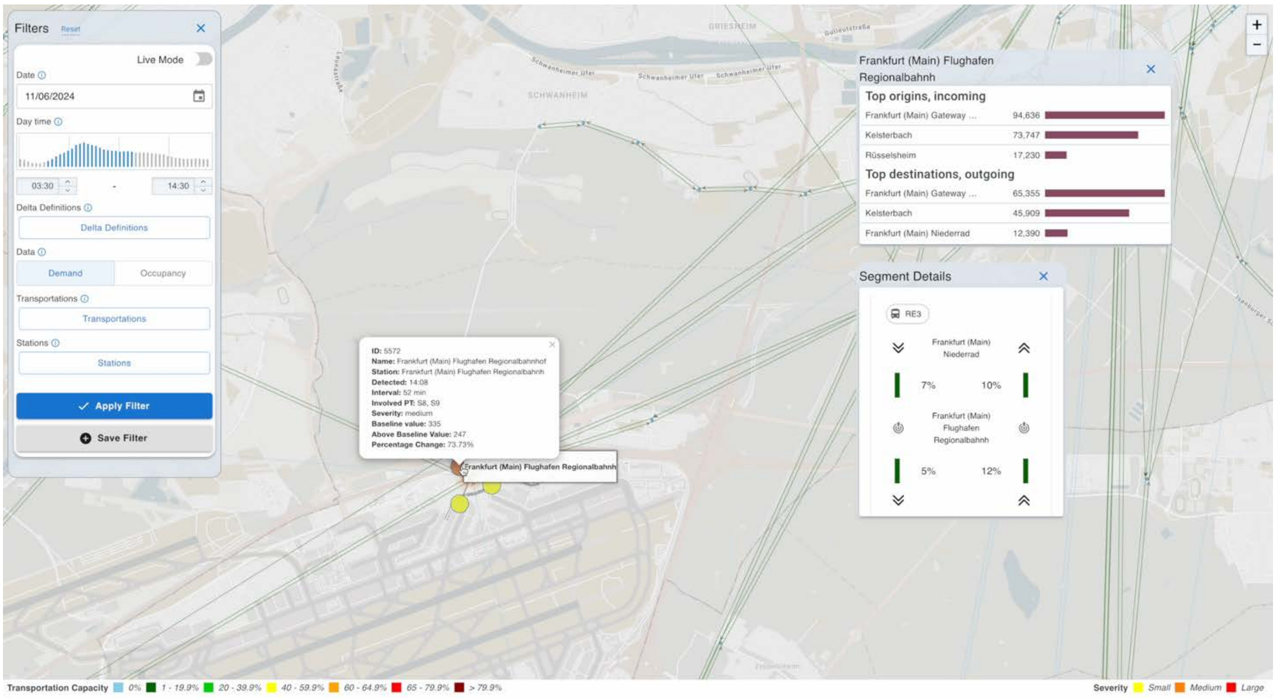
In case real-time passenger counting systems are deployed in any of the vehicles covered by our prognosis, we can use this real-time information to provide short-term forecast updates. Due to the usually very high number of segments which are supplied with a prognosis, the short-term forecasts are done very selectively as follows: If, after vehicle departure, a significant mismatch is detected between predicted and counted occupancy, an updated prognosis is sent to the HAFAS server for the remaining vehicle run. Other types of short-term forecast updates consider real-time delay information (if available). We are currently working on an approach using Graph Neural Networks to respect the effect of delays on occupancy and update the prognoses accordingly if such delays are detected.

14.3. Applications

14.3.1. Occupancy Prognosis

One application which has its value but is also used as foundation for many other applications presented here, is occupancy prognosis. With the data at hand, it is possible to calculate good estimates of the occupancy of every single vehicle. Occupancy prognoses are provided for each vehicle run and each segment individually. The occupancy prognosis can be directly used by the routing algorithm in HAFAS, so it is possible to use this information to guide customers to trip alternatives with lower occupancy. This is done in a way that the customer always receives one additional trip proposal, which might arrive a bit later or has longer trip duration but avoids crowded vehicles.

14.3.2. Incident and Event Detection



igure 14.4 Incident Detection

Knowing patterns does help to estimate demand in public transit, but relying on this as the only thing can lead to very wrong assumptions when it matters most: crowding situations in incident- and event situations. In such situations, demand is significantly different from the usual patterns. Using request data, we can identify incidents via a sudden, unexpected rise in the number of trip requests departing from a certain place. With a real-time data processing backend in place, we can do this in real time, right when it happens. While it is not possible to know the exact reason for the incident with this system, it tells us how many travellers are affected by the incident, i.e., if the transit authority must deal with an incident involving just a few travellers or with several hundred or more. As seen in igure 14.4, the system also provides information about the utilization of lines and vehicles in the area which are still operational, as well as the most important destinations of the affected travellers. This information is available in a dedicated HAFAS.analytics application but can also be shared via open APIs.

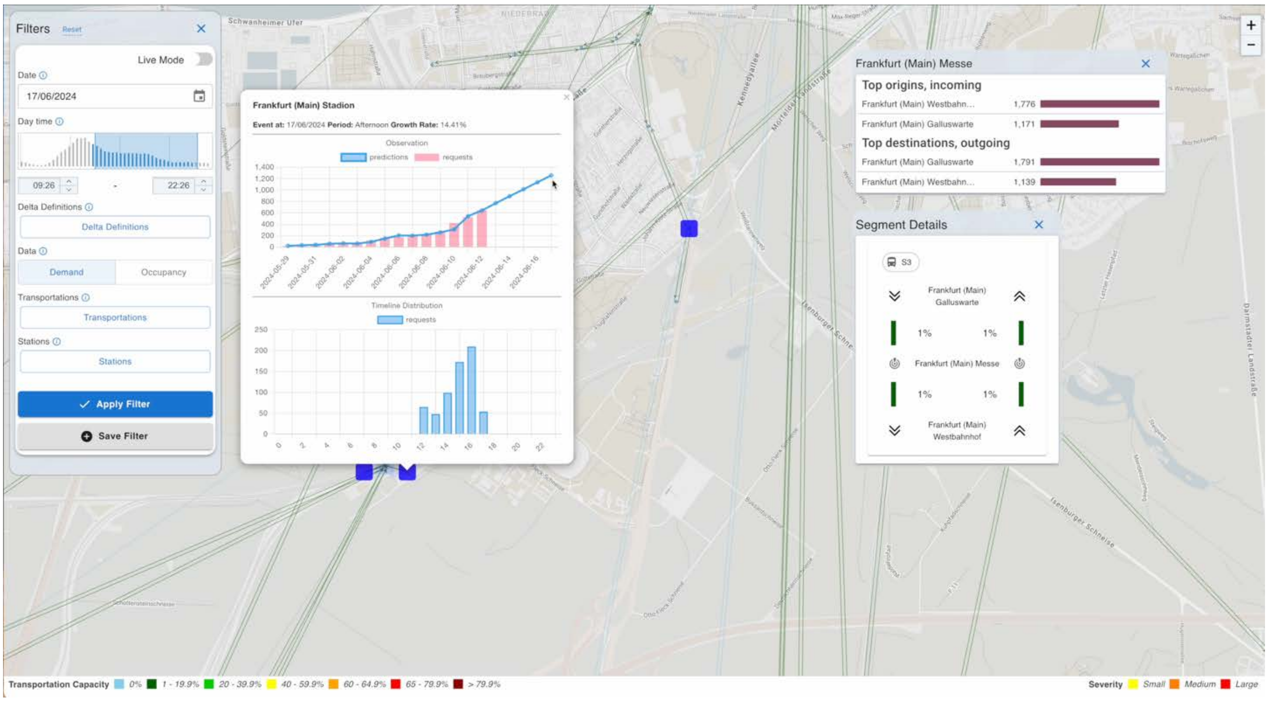


Figure 14.5 Event Detection

Currently, we are working to integrate this information in our TPS portfolio to support re-planning in case of incidents and delays. By knowing the entire trips of the travellers, this re-planning can be very elaborate. For example, we can estimate the number of travellers who are planning to transit at any given station. In case of delay situations, it is possible to delay any outgoing train in a way that as many travellers as possible can still make their transit successfully. As shown in Figure 14.5, events can also be predicted many days in advance due to many travellers planning their trips early. This information can be used to accurately estimate unique demand patterns for that day and plan accordingly. Additionally, data exchange via open APIs is possible, and we are planning to make this information available for demand-based capacity planning for our TPS portfolio [2].

14.3.3. Planning and Operation of Demand-Responsive Transport (DRT)

Using the analyses described above, it is also possible to identify lines and segments that experience very low utilization most of the time. Such services are usually very expensive and even worse, don't provide good service as they tend to operate infrequently. In such situations, HAFAS.analytics and TPS can be used to improve capacity planning to utilize available vehicles in the best possible way. Another option is to use the demand estimates to plan and operate demand-responsive transport offerings instead of fixed lines. Here too, the request data proves an invaluable resource to plan and operate such services in the most efficient way. Using the First- and Last-Mile Analysis (Figure 14.6) which is also part of the HAFAS.analytics portfolio, it is possible to match the transport services even more closely to the existing demand. This application shows where and when many travellers must walk long distances to reach the first public transit station or their final destination. Also, the waiting times can be analysed to understand if the right connections are available when they are required most. In addition, it is possible to tap into the HAFAS.analytics Trip Time Analysis module which allows for comparing the trip times between public transit and individual transport for selected origin/destination relations. Using this information, e.g., DRT can be strategically deployed to offer public transit options with reasonable trip times between places which are not yet well-served by the existing network.

Figure 14.6 First- and Last-Mile Analysis

14.3.4. Building Timetables Based on Real Demand

The design of timetables for large public transport networks is a complex task which is done using specialized software like TPS.plan. The additional consideration of demand- and travel patterns from HAFAS.analytics, can help to plan the schedules in a way to match with the demand of travellers in the best possible way. Using KPI Monitoring (Figure 14.7), it can immediately be seen where and when the highest demand is to be expected. Using this tool, it is possible to analyze KPIs like travel time, waiting time and number of interconnections between any regions. When a new timetable is being planned, it can be directly compared with the existing one to see if and how the service offering has improved for the most important origin/destination relations. As, especially in regional traffic, it is often important to also focus on areas with less demand, KPI Monitoring makes the entire dataset available and allows to zoom into any areas and origin/destination relations independent from the number of expected travellers.

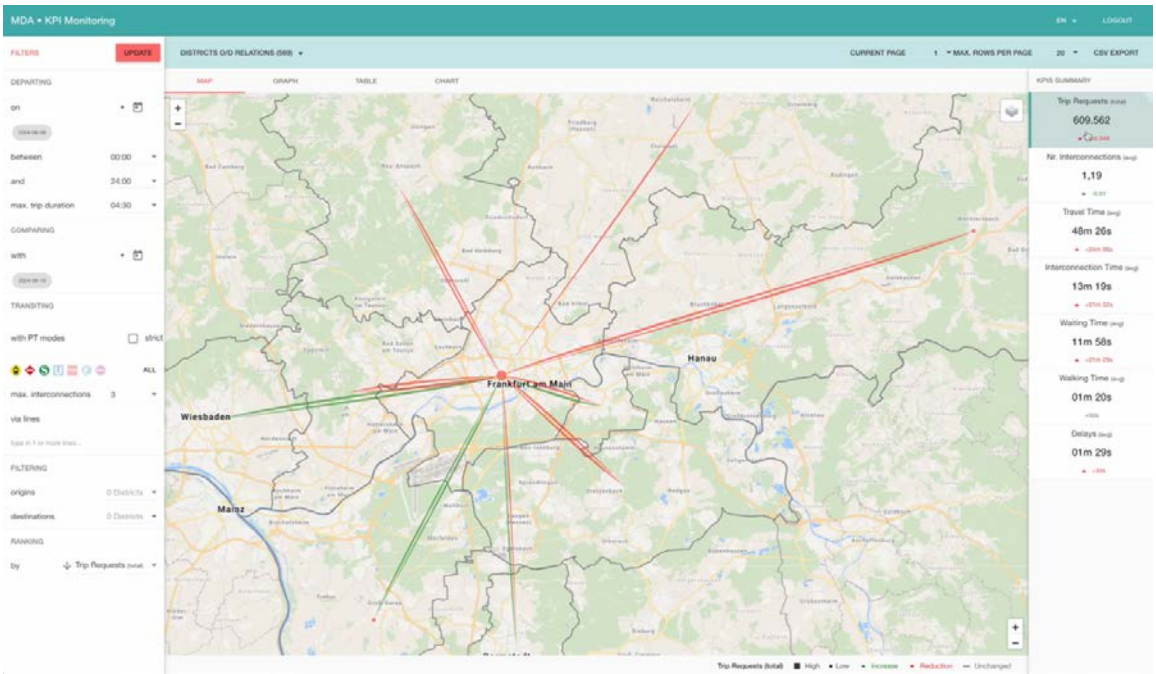


Figure 14.7 Transportation Demand between different regions shown in HAFAS.analytics KPI Monitoring

14.4. Conclusion

In conclusion, the integration of data from MaaS platforms and other sources provides a comprehensive understanding of public transit demand. By leveraging advanced machine learning techniques such as SMOTE and Gradient Boosting, we can generate accurate occupancy prognoses and optimize transit operations. This not only enhances customer satisfaction by reducing overcrowding but also lowers operational expenses (OPEX) by aligning capacity with actual demand. The ability to predict and respond to incidents in real-time further underscores the potential of data-driven approaches in public transit planning. Future work will focus on refining these models and expanding their application to other aspects of transit operations, ensuring a more efficient and responsive public transportation system.

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List of abbreviations

HAFAS (HaCon Fahrplan-Auskunfts-System): A comprehensive software suite for public transportation planning and passenger information, developed by HaCon.
MaaS (Mobility as a Service): A digital platform that integrates various forms of transport services into a single accessible on-demand service.
SMOTE (Synthetic Minority Over-sampling Technique): A method used to address class imbalance in datasets by generating synthetic samples of the minority class.
Gradient Boosting: A machine learning technique for regression and classification problems, which builds a model in a stage-wise fashion from weak learners.
XGBoost (Extreme Gradient Boosting): An optimized distributed gradient boosting library designed to be highly efficient, flexible, and portable.

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Funded by the European Union

Europe`s Rail

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101101962. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

15. Use cases and conceptual system specification for Self-Propelled Wagon

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15.1. Introduction and aim

The objective of this contribution is to present the analysis of the technical enabler “Self-Propelled Wagon” within the modern trends of the freight train digitalization. This document starts with an analysis of the state of the art and after the stakeholder needs analysis, it introduces the most significant use cases. As a result of the preliminary calculations, a conceptual system specification for Self-Propelled Freight Wagon (SPFW) is disclosed.
A state of the art review for the SPFW concept has been carried out as well as identifying and analysing essential use cases; Private yard load automation, Challenging Tractive Power and Braking Scenarios, Coordinating groups of self-propelled wagons and Autonomous loading/unloading. In order to understand the needs of operators, infrastructure managers, suppliers, and research centres, stakeholder needs analysis was carried out through conducting a physical workshop for Nordic railway stakeholders and an online survey at a European level. Moreover, this study presents, as a result of the state-of-art analysis, the needs analysis and identified use cases, a conceptual analysis on the impact of self-propelled objective on the digitalization of the freight trains, introduces a high level system architecture as well as a preliminary test.

15.2. State of the art

The state of the art with respect to self-propelled freight wagons (SPFW) shows sporadic developments over the past decades. Simple self-propelled wagons have existed for around 100 years, but recent technological advances with respect to remote control and sensing, artificial intelligence and energy storage have led to a surge of developments in recent years. In general, the incorporation of some sort of propulsion into a wagon is done in order to reduce the number of locomotives at various stages of a wagon’s travel and operation, thus reducing capital and personnel expenses as well as increasing flexibility in the movements of the wagons.
In Figure 15.1, below, three commercial references are presented and recognized for the development self-propelled wagon or similar projects.

Figure 15.1 From left to right: IntraMotev “ReVolt”, RZV Čakovec “Self-Prop Rail”, Parallel Systems transport unit prototypes [1],[2],[3]

First of all, Intramotev, an American company is developing self-propelled battery-electric freight cars as “ReVolt” shown in Figure 1 above. The main goal of Intramotev is to distinguish itself by its focus on integrating “cutting-edge" battery technology, autonomous driving algorithms and regenerative braking to revolutionize rail transport. This aims also to reduce diesel consumption from locomotives in the course of mainline operations. The current state of development at Intramotev is unclear in Europe, but a reference has been deployed on Iron Senergy’s Cumberland mine in Pennsylvania. Few details about the actual design or capabilities have been published. [4]

On the other hand, RZV Čakovec and collaborators devised a self-propelled wagon equipped with a 55 kW diesel generator and hydraulic transmission, enabling it to go up to 100 km/h under remote control around work sites. The drive works via friction wheel applied directly to the rail, thus obviating any need for modifications to the bogies themselves. A prototype was displayed at the InnoTrans in 2014 but any further developments or use of this prototype are known after the conclusion of the project [2] [5].
Parallel Systems, a California-based start-up founded by former SpaceX employees, is developing an ambitious self-propelled freight wagon concept. This concept actually forgoes the traditional freight wagon altogether and consists of pairs of independently mobile drive units or carriers, each roughly in the format of a traditional bogie and joined together by a subframe/carrier, upon which normal intermodal containers can be placed directly. These electric rail carriers are autonomous and self-sufficient in terms of energy supply, traction and braking, are claimed to have a range of approximately 800 km between charges and are intended to supplant conventional rail and road freight over distances of up to 1600 km. The units are not intended to be mechanically coupled, but would, as the company has demonstrated with their existing prototypes, drive together in physical contact through their centre buffers, thus minimizing aerodynamic drag and occupied track length [3].
All these entities are linked to self-propelled wagon initiatives through their respective focuses on different aspects of the technology and infrastructure required to make autonomous rail freight a reality.
While the above references stem from commercial entities, an example of research project into SPFW comes from the RWTH Aachen. A classical approach to achieving many of the benefits of self-propelled freight wagons is simply equipping an existing freight wagon with the equipment necessary to propel itself, as represented by the FlexCargoRail concept in Figure 15.2.

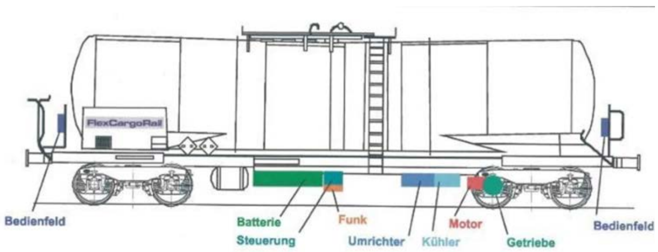

Figure 15.2 Representation of the components under the wagon body [6]

The objective of this project was to link one wheelset of that wagon with a fully decouplable electromechanical drive system, which can also haul another wagon together [7]. The FlexCargoRail concept fulfils many of the requirements for basic shunting and last-mile-operations, however it requires significant modifications to the wagon and at least one bogie and may thus not be suitable for some common types of wagons. Aspects of the development of this concept have been carried forward in the Wagon4.0 project, which additionally focuses on the technologies needed for automated and autonomous operations.

15.3. Use case definition

Four essential use cases for self-propelled wagons in freight operations have been identified and analyzed for this report. All of them have been analyzed, detailed theoretically and simulations and preliminary work has been started by the partners involved in them. Further work and results, for the one selected for the implementation, will be disclosed at the end of the project funding this research.
The **first use case** focuses on private yard load automation, where traction motors, converters, and batteries could be integrated into existing freight wagons to automate yard operations. The main interest of the partners involved in this use case is the definition and design of a proper motor that cope with the requirements of the use case and fit into the characteristics of the axle/bogie proposed. As we are seeking to retrofit an existing axle/bogie, the aim is to be as non-invasive as possible, so a direct-drive motor solution that can be directly coupled into the existing axle is being designed. The fact that it is a direct-drive system allows to avoid additional mechanical components, reducing the complexity and cost of the new drivetrain. The definition of the braking system is modified to work with decoupled wagons and, as a complement for both subsystems, communication elements need to be integrated

for speed control, braking and the link with the management of this yard. As a result, this process eliminates the need for shunting locomotives, reducing operational time and labor costs. Preliminary tests of some of these functions are planned in a private yard in Asturias, Spain, with an alternative site in Gijón.
The **second use case** addresses challenging tractive power and braking scenarios, exploring two scenarios: "Power Booster" and "Power Peak Shaving." This is the only one that is foreseen on main lines, as the others are meant for yard operation.
The "Power Booster" scenario aims to enhance traction capabilities on uphill gradients by using self-propelled wagons to supplement locomotive power. This allows the train to maintain a constant speed and maximize line capacity, even on steep inclines. By distributing the traction force across multiple wagons, the overall strain on the locomotive is reduced, which can prevent slowdowns and improve the efficiency of freight transport on hilly terrains. Additionally, this distributed power approach can enable longer or heavier trains to operate without the need for additional locomotives.
The "Power Peak Shaving" scenario focuses on reducing power demands from locomotives during peak loads on the electrical grid. In this scenario, battery-powered bogies are used to provide supplementary power when the electrical substations are overloaded. By communicating with the electrical grid, the system can detect power peaks and adjust the power output of the locomotive and the self-propelled wagons accordingly. The locomotive reduces its traction output while the battery-powered bogies increase their traction output, ensuring that the train's overall power needs are met without overloading the grid. This approach not only alleviates power peaks but also enhances the stability and efficiency of the electrical network.
The **third use case** involves coordinating groups of self-propelled wagons to demonstrate automated shunting operations. The method optimizes the coordinated motion of wagons to maximize efficiency and minimize shunting duration. Traditional shunting operations involve moving one wagon at a time, which is time-consuming and labor-intensive. In contrast, the envisioned process involves concurrent shunting, where multiple wagons move simultaneously. This approach significantly reduces the total shunting time by 40-60% compared to traditional sequential shunting. The optimization algorithm ensures that the wagons move in a coordinated manner, avoiding collisions and near-collisions. By allowing several wagons to move at the same time, the overall efficiency of yard operations is greatly improved, leading to faster train assembly and reduced operational costs.
The **fourth use case** investigates autonomous loading and unloading of freight wagons. It includes autonomous entry and exit from yards and terminals, and the use of specific technologies found in the state of the art, like AutomaticCarConTrain (AMCCT) and Innofreight's SUM for transshipment. The focus is on intermodal wagons, enabling autonomous transshipment of intermodal loading units and reducing the need for manual intervention. The envisioned process aims to streamline operations, reduce costs and enhance efficiency in freight handling. For intermodal terminals, the self-propelled wagons could autonomously disconnect from the train at a siding and enter the terminal. The intermodal loading units are then autonomously transshipped using enabling technologies such as the mentioned AMCCT or SUM. For yards, similarly to what it is proposed for the first use case, the wagons autonomously unload and load on-site or at the final destination. After loading or unloading, the self-propelled wagons autonomously reconnect to the outgoing train at a siding. This process, here again, reduces the need for manual labor and increases the efficiency of freight operations by allowing for continuous and automated handling of goods. The use of autonomous technologies in loading and unloading also minimizes the risk of human error and enhances the safety of freight operations.

15.4. Needs analysis

To understand the needs of operators, infrastructure managers, suppliers, and research centres, both a physical workshop and an online survey was conducted. The aim was to gather comprehensive insights from stakeholders in the rail freight industry.

15.4.1. Workshop

The ¨Nordic Perspective for Future Rail Freight¨ workshop, organised by Lindholmen Science Park in Gothenburg, was held on 2023-03-22. This event sparked extensive discussions and provided valuable insights across a wide

range of stakeholders. The stakeholders were grouped into four teams. Four questions were asked to each team coming from a variety of sectors in rail freight industry.
The questions were broadly framed to assess the interest and curiosity of rail freight industry partners regarding the topic of self-propelled wagons. As a result, the use cases have been prioritized by the participant, resulting in the ones that have already been presented in the previous section of this document.
Another question was related to expectations from SPFW as a potential user. Below are the listed answers:

- Last mile service from the mainline to the industrial area
- Self-loading and unloading
- Reduce the train time and the need of feeder and shunting locomotives
- Infrastructure way of thinking: Trains occupy tracks and they should move as much as possible
- Needs to be safe and reliable
- Knowledge of the tracks (lack of energy), speed that you have to have going up a hill with a certain load
- Cheap
- Battery for the part of the track that don't have electricity

With regard to SPFW, general takeaways from the workshop were that there is broad interest in SPFW, especially in the context of other developments such as the impending implementation of the Digital Automatic Coupler (DAC), and that there are many use-cases in which various stakeholders could benefit greatly from an independent electric drive system in freight wagons. However, it was also put forward that legislative work may be needed in order to support this initiative, as capital costs will be an issue for operators wishing to implement this technology.

15.4.2. Survey

The survey was conducted among stakeholders from the freight transport industry, with a special focus on the requirements and processes in shunting and last-mile operations. The survey consisted of 16 questions on the topics of infrastructure and operations. The survey aimed to collect important parameters for the use case, such as distances, gradients and operating times.
An overview of answers concerning time and distance are shown in the Table 15.1 below. Unfortunately, only a limited number of usable responses were received to this survey, but these were very helpful in determining the performance data and requirements in the specifications.

Question	Minimum	Maximum	$n_{Answers}$
Maximum speed	15 km/h	40 km/h	4
Maximum gradient	4 ‰	9 ‰	2
Maximum distance with own drive	1 km	10 km	6
Track in the train formation between shunting operations	50 km	400 km	7
Time in which the wagons are uncoupled from the train set	24 h	168 h	5
Time of the car at the destination	6 h	168 h	6
Number of start-ups	3	12	5
Smallest radius	90 m		1
Permanently coupled wagon units	1	4	6

Table 15.1 Summary of survey responses

These answers are also very useful in order to adapt the design of components such as batteries and motors, since some of the main input parameters to define the requirements for these components are the needed operation time and distance. The required power/torque for the motor, and thus for the battery, can be calculated from the desired speed profile of the wagon, so optimizing this target speed profile could result in significant weight and cost savings. Adjusting the vehicle’s maximum acceleration would reduce the previously mentioned power requirements, thereby requiring a smaller and therefore cheaper battery and motor.
At the end of the survey, open questions were proposed to give the opportunity to the answerer to tell their wishes and expectations for the future developments in rail freight transport. They would like more hump yards. They expect an energy source on the freight wagon, a possibility of automation and an increased flexibility. Moreover, a

cost reduction will be appreciated. Finally, there were wishes related to the DAC5 and all related "train functions", such as parking brake, wagon mobilisation instead of bleeding, automated brake test, train integrity, etc.
The purpose of the stakeholder workshop and survey was to determine needs from operators, infrastructure managers, suppliers and research centres and to get an overview of the last-mile operations of a wagon. The stakeholder workshop successfully identified critical insights into the potential and needs for self-propelled wagon in the rail freight sector. The outcomes highlight the potential for self-propelled wagon to revolutionize freight operations through increased efficiency, flexibility and sustainability, provided that administrative and resource challenges are addressed correctly. The online survey help understanding the real conditions and the yards and thus optimize the requirements for the SPFW. The values given by the survey's answers allow us to get the range values in term of time and distances travelled by a wagon.

15.5. Conceptual analysis of the impact of the self-propelled wagon on digitalization of freight operation

Self-propelled freight wagons are seen as one of the most promising ways to revolutionise freight transport and improve the efficiency and safety of the transport system in the long term. They stand to contribute to the digitalisation of freight transport by automating and optimising processes.

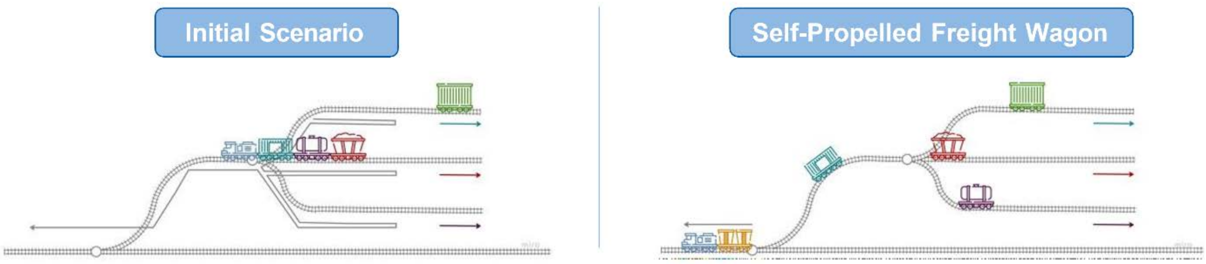

Figure 15.3 Logistical simplification through self-propelled freight wagons [8]

Thanks to the integration of IoT technologies and sensors, self-propelled freight wagons enable a range of improvements in the logistics industry. They can track the transport and supply chain, improve the efficiency of freight movements and increase safety. The control of freight wagons by automated systems enables the avoidance of human error and can improve the punctual and efficient delivery of goods. This technology could also compensate for the shortage of lorry drivers and marshalling-yard workers, and the declining attractiveness of the driving profession, thereby increasing the availability of transport. Figure 15.3 shows the logistical efficiency of self-propelled freight wagon compared to a classic locomotive.

However, the introduction of self-propelled freight wagons also requires a corresponding infrastructure to enable the networking and data transmission of the vehicles. In addition, further tests and developments are required to improve IoT and automation technology in order to ensure reliable operation and safety.
Moreover, the digitalization of freight trains will lead to special requirements for usual freight wagons components. Indeed, an on-board energy storage system is needed in order to feed all the subsystems and increase the efficiency of freight wagons. The presence of this kind of system can also enable the use of energy recovery systems such as braking energy recovery for instance. Through this system, the productivity can be improved and the operating costs reduced. Regarding coupling systems, the DAC offers significant advantages for the entire logistics process for freight wagons by improving effectiveness, flexibility, monitoring, safety and automation, and is a perfect complement to a self-driving ability, as the combination would allow complete shunting movements to take place without any personal human interaction with train hardware.
An autonomous freight car requires a vehicle control unit (VCU), which operates in a similar way to a normal train. The VCU is responsible for monitoring and controlling the various electronic systems of a vehicle, playing an important role in ensuring safe and efficient operation of the vehicle, but also helping with maintenance. One of the main tasks of the VCU in the context of a SPFW is to monitor and regulate speed and braking power. The VCU can also contain additional sensors and monitoring systems that are necessary to control and regulate the operation

of an autonomous freight train such as the communication modules. This means the VCU is the main gateway for every communication between the wagon, the wayside systems and the user. Furthermore, a VCU also enables the storage of maintenance data on the network, which can help to optimize maintenance activities and prolong the lifespan of the train.
Last but not least, communication systems are also affected by the digitalization of freight trains. However, it is important to differentiate two types of communication systems for self-propelled freight wagons:

- The onboard communication system Freight Ethernet Train Backbone (F-ETB), which controls the communication between the wagons inside one trainset
- The FDFT-Link that connects the single wagons to the to the wayside

The communication network between SPFW offers several advantages, including greater insights and the ability to quickly retrieve data in the event of an accident or emergency. The stored data can include information such as the location of the cargo, its weight and dimensions, and other relevant details. In the event of an accident, this data can be retrieved quickly and used to assist emergency responders such as firefighters in understanding the nature of the cargo involved and taking appropriate safety precautions.
Communication with trackside systems enables the position of autonomous trains to be accurately determined in real time, which can help reduce the distances between them. By decreasing the spacing between trains, rail operators can increase the capacity and efficiency of their networks, allowing for more trains to run at a higher frequency.

15.6. Conceptual system architecture

As a result of the analysis shown in this paper, up to now, and considering the freight system architecture agreed within the FP5 TRANS4M-R project (Deliverable D2.3 [8]) and the relations due for the self-propelled wagon concept, the next figure (Figure 15.4) presents the interfaces that are defined for this element.

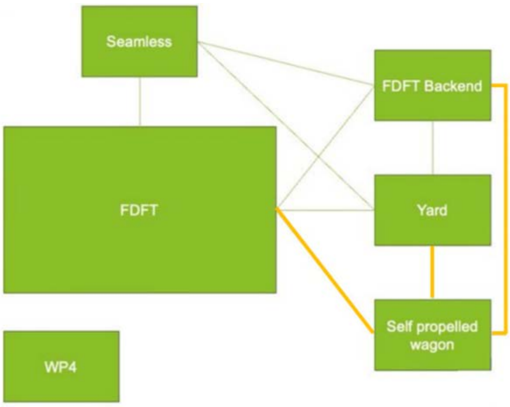

Figure 15.4 Interfaces of the SPFW to the other subsystem of the freight system architecture

Emphasizing the use cases where the SPFW operates in yards and terminals, the links in bold represent the relationships with the FDFT function on-board and with the Yard automation management system. These links are performed by means of the communication system that the SPFW need to be equipped with. There are two ways from the Yard Automation Management System (YMS) down to the operation on its control. The first and priority is by the on-board Automatic Shunting Operation element, which will be the link with any GoA level yards where the wagon would be operated from the YMS. As a secondary option, in a non-operative yard automated area or for validation or test purposes, the control could be taken remotely by an operator. This is why a remote controller element is proposed to be added, at this stage, prior to the confirmation of these technologies by the operators and infrastructure managers.

The next figure depicts which elements are on-board the wagon, with the blue blocks representing the additions provoked by the self-propelled wagon concept.

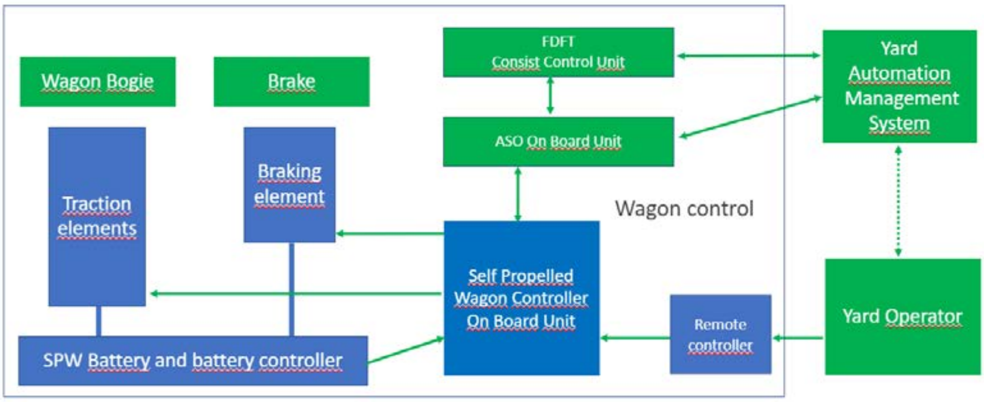

Figure 15.5 Internal subsystems and Interfaces of the self-propelled wagon to Yard

This Figure 15.5 highlights the critical components and their interactions within the self-propelled wagon system. The on-board elements will need to include the propulsion system, braking system and communication modules, which are essential for the autonomous operation of the wagon. There are new components introduced by this concept, such as advanced sensors, control units and energy management systems. These additions are crucial for enabling the autonomous functionalities and ensuring seamless integration with the existing yard and train management systems.
The proposed data, functions and orders shared between the self-propelled wagon controller and other systems include destination and route information, predicted energy requirements for shunting and last-mile operations, train composition and weight estimates, mode of operation and assisted power demand for demanding traction scenarios.
The Yard Automation Management System can control the mode of operation and remotely manage the wagon's acceleration and braking. The SPFW controller provides battery and energy status updates to the ASO and shares its position and perception data during remote control mode with the yard system. Some of these data and functions are not currently implemented but are anticipated as part of future developments. For instance, predicting energy requirements for shunting and last-mile operations is a proposed function that does not yet exist. The task where this paper has obtained the input is still working on the next phases and aims to gather data to develop algorithms for this purpose in future calls, potentially within the FDFT Backend.

15.7. Conclusions

As a conclusion for this document, the state-of-the-art review identified several commercial and research initiatives focused on new wagons or autonomous bogies, which require significant investment. Practical proposals for integrating these technologies into the current freight system architecture were prioritized, providing valuable insights for the proposed high-level system architecture.
Stakeholder needs were analyzed through a workshop and an online survey, revealing critical insights into the potential and needs for self-propelled wagons. These insights highlighted the potential for increased efficiency, flexibility, and sustainability in freight operations, provided administrative and resource challenges are addressed.
The use cases concluded that self-propelled wagons can streamline operations by eliminating shunting locomotives and reducing manual labor, resulting in faster and less costly processes. They highlighted a conflict between powertrain requirements for last-mile delivery and traction support, which could be mitigated by an integrated traction system in selected bogies. Significant efficiency gains were demonstrated with concurrent shunting, achieving substantial time savings compared to sequential shunting. The need for self-propelled wagons, autonomous coupling/decoupling, and transshipment technologies was identified, with only a few technologies meeting the requirements.

Overall, the study provided a conceptual analysis of the impact of self-propelled wagons on the digitalization of freight trains, introduced a high-level system architecture, and outlined a preliminary test and validation plan. Future work will focus on developing deployable, cost-efficient solutions, implementing and pre-testing concepts, and demonstrating the functionality of a preliminary traction system design for self-propelled wagons. This preparatory work will serve as the basis for future demonstrators in upcoming calls after 2025.

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Funded by the European Union

Europe`s Rail

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102009. The project is supported by the Europe's Rail Joint Undertaking and its members.
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

16. Cybersecurity Risk Assessment of Virtually Coupled Train Sets

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16.1. Introduction

In recent years, the increasing digitalisation and interconnectedness of railway systems have underscored the critical importance of robust cybersecurity measures. Notable cybersecurity incidents, such as the sabotage of more than 20 trains in Poland via simple "radio-stop" commands using low-cost equipment[1], highlight the vulnerability of these complex systems to disruptions that can have far-reaching consequences. Moreover, the evolving threat landscape, characterised by increasingly sophisticated ransomware and distributed denial-of-service (DDoS) attacks, poses ongoing challenges that demand continuous vigilance and adaptation (European Union Agency for Cybersecurity (ENISA), 2023). The regulatory response, including stringent EU directives such as the Cybersecurity Act (The EU Cybersecurity Act, n.d.) and the NIS2 Directive (NIS2 Directive, u.d.), reflects a concerted effort to elevate the cybersecurity standards that impact the transportation sector.

The objective of this work is to provide a cybersecurity risk assessment of the Virtually Coupled Train Set (VCTS) design that is developed within the R2DATO Europe's Rail project[2]. This work leverages the methodologies developed under the Shift2Rail (S2R) initiative, particularly the X2RAIL-5 project[3]. The assessment aims to identify potential vulnerabilities and assess the impact of potential threats. Risk and target security level evaluations for VCTS are presented for identifying applicable security requirements from IEC 62443 (ISA/IEC 62443 Series of Standards, u.d.). By applying a risk assessment tool based on IEC 62443-3-2 and CLC/TS 50701 (X2RAIL-5, 2023) (X2Rail-5, 2024) towards regulatory compliance measures, this work seeks to fortify the cybersecurity of railway systems, ensuring safer and more reliable operations in an increasingly digital landscape.

16.2. Background

The following sections provide a brief description on Virtually Coupled Train Sets (VCTS) as well as the method for conducting risk assessment developed during X2RAIL-5.

16.2.1. Virtually Coupled Train Sets

VCTS represents an innovative advancement in rail transportation that enables multiple train consists to operate closely together in a coordinated manner without the need for physical coupling. This system promises significant improvements in railway capacity, energy efficiency, and operational flexibility. The virtual coupling concept has been developed within the X2RAIL-3 project (X2Rail-3, 2020), which produced detailed operational and functional architectures of the VCTS. Further development is currently underway in the R2DATO project, which aims to advance the VCTS architecture with detailed design of internal and external interfaces with other subsystems.

16.2.2. Cybersecurity Risk Assessment

The X2RAIL-5 method employs the Microsoft STRIDE threat model (The STRIDE Threat Model, n.d.), which categorises threats into six types: Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, and

[1] https://www.wired.com/story/poland-train-radio-stop-attack/
[2] https://cordis.europa.eu/project/id/101102001
[3] https://cordis.europa.eu/project/id/101014520

Elevation of Privilege. The method estimates the likelihood of these threats materialising by evaluating several factors: threat type, attacker capability, intent, and targeting. The Common Vulnerability Scoring System (CVSS) exploitability metrics further refine this likelihood assessment.

Compared to other methodologies, e.g., developed by EULYNX RCA OCORA (EULYNX/RCA and OCORA, 2022), the X2RAIL-5 methods specifically targets compliance with IEC 62443-3-2, which addresses security risk assessment for system design (X2Rail-5, 2024). Further, the method is supported by a publicly available Excel-based risk assessment tool that guides implementing cybersecurity measures in accordance with IEC 62443 [7] (part 62443-3-2 in particular), covering both IEC 62443-3-3 and IEC 62443-4-2 requirements.

16.3. System Description

Today's railway architecture is the result of many decades of incremental, component-wise transformations, making it inflexible, challenging to integrate, and costly to upgrade or replace. Additionally, there is no unified EU perspective on a common future railway system architecture, as individual railway systems maintain distinct national or regional technical approaches. This makes it challenging to design, analyse, and integrate innovative solutions like VCTS, which have interfaces with other subsystems. To address this challenge, Europe's Rail Joint Undertaking established a System Pillar (SP) consortium. This consortium aims to ensure that the evolution of the rail system is based on common operational visions and a layered functional architecture. At the time of writing, there are no architectural outputs from the SP. However, expert discussions indicate that the SP architecture of the onboard Control Command and Signalling (CCS) subsystem is expected to align with the Open CCS On-board Reference Architecture (OCORA) (OCORA, 2023). Consequently, in this work, OCORA is considered as a technological baseline for the signalling system architecture.

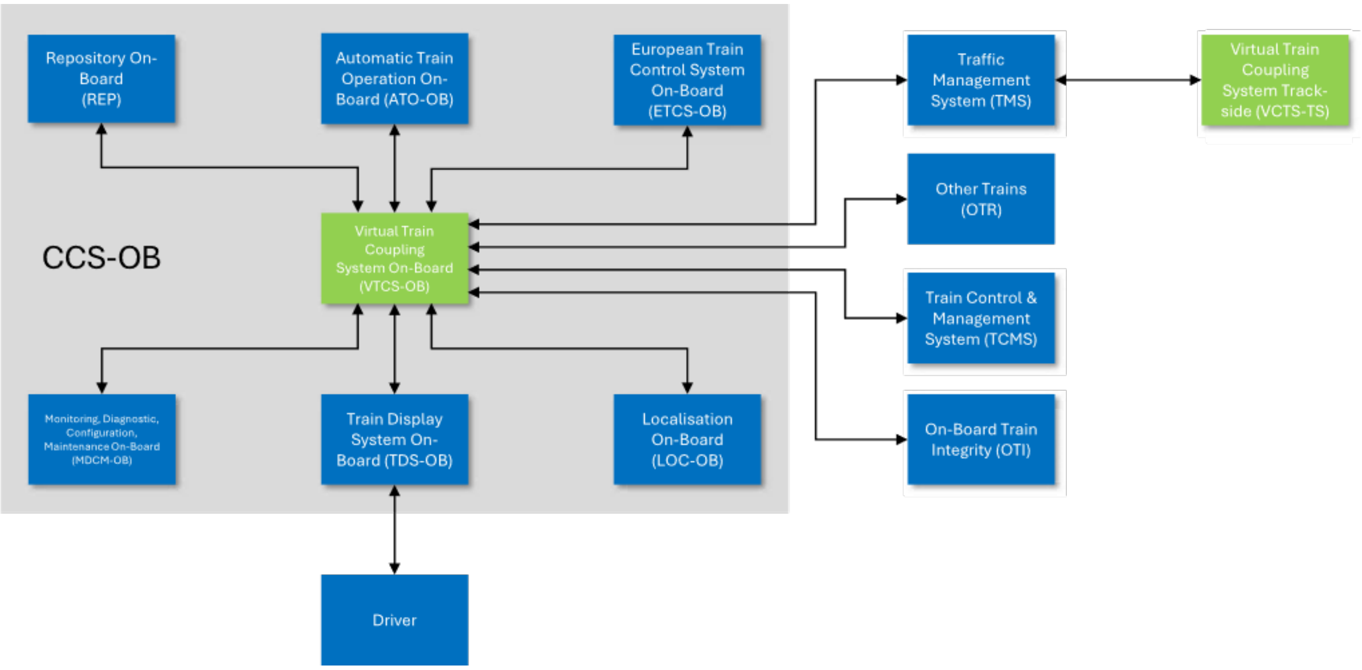

Figure 16.1 Simplified block diagram of the system under consideration showing its interfaces with other subsystems.

By integrating the VCTS architecture developed in X2RAIL-3 with OCORA (OCORA, 2023), we present a simplified block diagram of the system under consideration (SuC) showing its interfaces with other subsystems in Figure 16.1. According to this, we divide the SuC into two security zones (SZ) as shown in Table 20.1 As this work is based on a system architecture which is subject to change, and since the communication channels for VCTS are expected to be provided by the existing train network and other ETCS components such as Euroradio, risk assessment of the conduits is omitted. The cybersecurity risk analysis in this work specifically focuses on VCTS system and its components.

Table 20.1 Security Zone classification of the SuC

SZ Name	SZ-ID
VCTS Onboard	OB-Z
VCTS Trackside	TS-Z

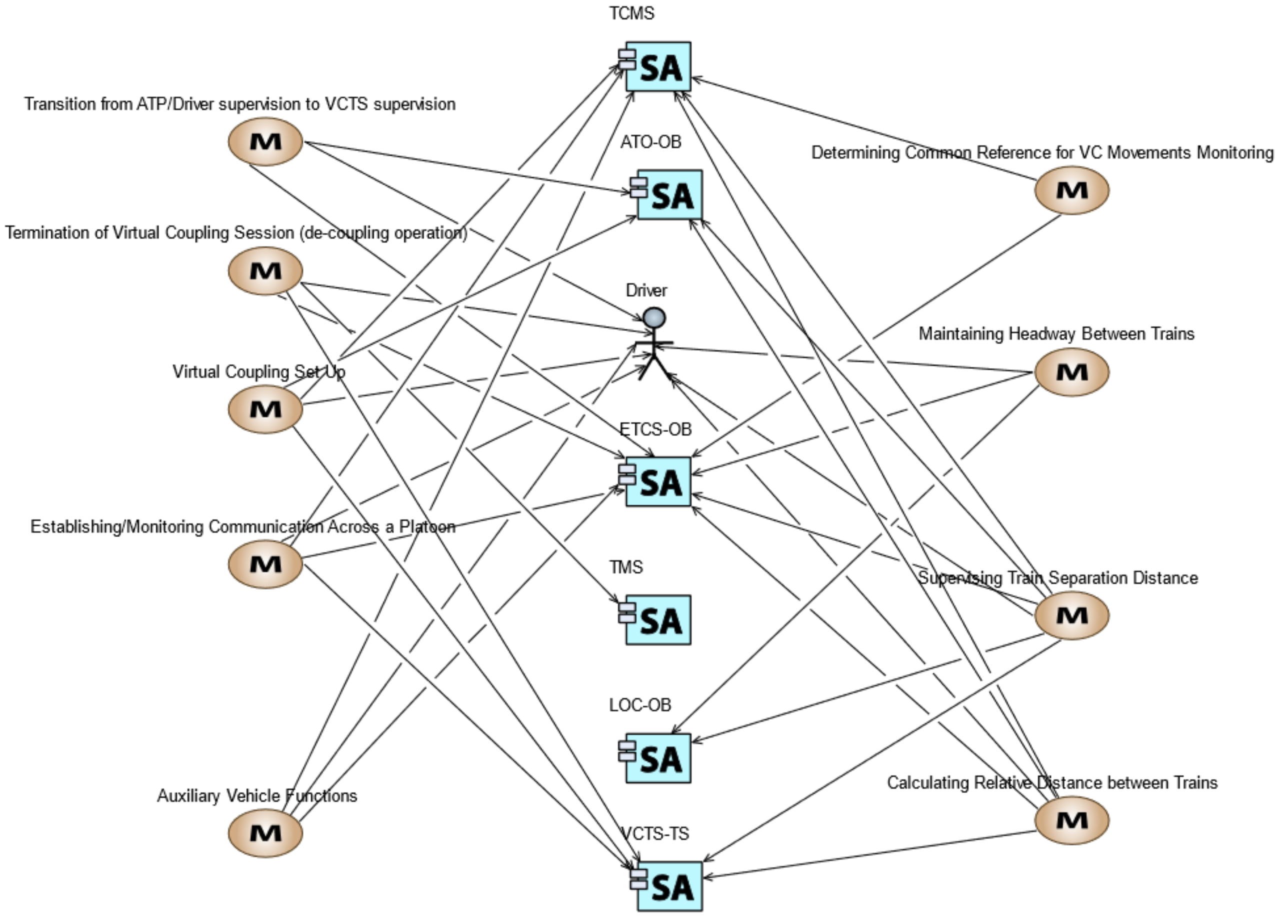

Figure 16.2 VCTS mission diagram (X2Rail-3, 2020)

The VCTS system missions from (X2Rail-3, 2020), as shown in Figure 16.2, are considered as the primary assets (PAs), which are the essential functions of the SuC. At the level of detail of subsystems from Figure 16.1, the identified list of supporting assets (SAs) that the primary assets depend on are listed in Table 16.5. VCTS-OB is a required SA for all the analysed PAs, while VCTS-TS is only required for a few. After assessing risk levels using these primary and supporting assets, cybersecurity requirements from IEC 62443-3-3 (ISA/IEC 62443 Series of Standards, u.d.) and IEC 62443-4-2 should be allocated to the security zones (and conduits) of the SuC.

Table 16.2 VCTS supporting assets, defined as software applications in accordance with (X2Rail-3, 2021)

SA-Title	SA-ID	SA Type	Security Zone
VCTS-Onboard	VCTS-OB	Software Applications	OB-Z
VCTS-Trackside	VCTS-TS	Software Applications	TS-Z

16.4. Cybersecurity Risk Analysis

As the first step, the “Initial Risk Assessment” is performed for each primary asset. This entails evaluation of the impact of each feared event on four different business stakes: “Safety”, “Performance”, “Reputation” and “Compliance”. The level of impact can range from 1 to 4, signifying “Minor”, “Moderate”, “Major” and “Critical”. For a full list of level rationales, as well as details on how “Total Damage Potential” and “Overall Impact” is subsequently calculated, we refer to X2RAIL-5 D11.1 (X2RAIL-5, 2023). An excerpt of our results for the primary asset “Virtual Coupling Set Up” is provided in Table 16.3. The evaluation for each primary asset was performed twice by independent pairs, consisting of experts from RISE, DLR, Renfe, Indra and CEIT. To consolidate the results, the worst-case evaluation of each business stake (Safety, Performance, Reputation, Compliance) was chosen.

Table 16.3 VCTS Initial Risk Assessment (excerpt)

Feared Event	Primary Asset	Safety	Performance	Reputation	Compliance	Total Damage Potential	Overall Impact	Rationale
Loss of Confidentiality	Virtual Coupling Set Up	1	1	2	3	112	2	- Safety: No loss of life, no injuries. - Performance: Train might need to be replaced after the trip. - Reputation: Adverse local/regional media reports. - Compliance: Major non-compliance with contract and regulation.
Loss of Integrity	Virtual Coupling Set Up	3	4	3	3	1300	4	- Safety: Major loss of life. - Performance: Major area blocked, or main infrastructure blocked during >1 week. - Reputation: Extensive national media reports. - Compliance: Extensive non-compliance with contract.
Loss of Availability	Virtual Coupling Set Up	4	3	2	3	1210	4	- Safety: Major loss of life. - Performance: Major area blocked, or main infrastructure blocked during >1 week. - Reputation: Extensive national media reports. - Compliance: Extensive non-compliance with contract.

16.4.1. Unmitigated Risk Analysis

The initial risk assessment is followed by a more detailed, so-called “Unmitigated Risk Analysis”. While the former focused on the assessment of impact, the unmitigated risk analysis proceeds by evaluating the likelihood parameter. The first step is the analysis of the Event Initiation Likelihood (EIL), where the X2RAIL-5 D11.1 (X2RAIL-5, 2023) method examines nine types of threat actors capable of triggering threats in the railway domain.

We have reassessed these likelihood criteria for each threat actor, with regards to the current SuC – VCTS. The results are presented in Table 16.5.

Table 16.4 VCTS Event Initiation Likelihood

Weights/Multiplicative factor			Consideration factor of threat actor (if an actor is not relevant, please use "0" for that specific threat actor)									
CAP	INT	TARG	1	1	1	1	1	1	1	1	1	1
1	2	3	Event Initiation Likelihood (EIL)									
			Hacker/ Cracker	Terrorist	Competitor	Government Organisation	Hacktivist	Criminal Organisation	Script Kiddy	Layman	Insider	Max EIL
			EIL	EIL	EIL	EIL	EIL	EIL	EIL	EIL	EIL	
			3	3,83	2,67	3,17	3	4	2	1,5	3,67	**4**
Delta value (δ)	1	Pessimistic EIL	3,000									
		Balanced EIL	2,98									
		Optimistic EIL	2									

There are some notable changes in these results compared to the Automatic Train Operation (ATO) Grade of Automation (GoA) 3/4 example presented in X2RAIL-5 (X2RAIL-5, 2023):

- For VCTS, "Competitors" were considered to possess higher capability, while intent and targeting were simultaneously lowered. One motivation for this being that while competitors in this sector possess extensive knowledge, they are unlikely to attack each other.
- "Terrorist" increased in intent, a motivation for this is that they likely possess a high motivation to enforce their ideological beliefs.
- "Government Organisation" increased in targeting, as this threat actor is considered to possess the most resources.
- "Script Kiddy" received a lower targeting, as this threat actor is unlikely to conduct advanced reconnaissance.

Together with assigned weights, the Excel tool utilises the capability, intent and targeting values to calculate an EIL value for each threat actor. The pessimistic EIL, which is the average (also called "balanced") EIL rounded up to the nearest integer will be the one used in subsequent calculations going forward.

After the EIL analysis, a vulnerability rationale and CVSS score is derived for each supporting asset. **¡Error! No se encuentra el origen de la referencia.** only shows the supporting asset VCTS-OB, as an excerpt of our results. The CVSS Score is normalised into "Unmitigated Vulnerability Severity" (UVS) and together with the EIL, Overall Unmitigated Likelihood is calculated as follows:

$$\text{Overall Unmitigated Likelihood} = \left\lceil \frac{\mathrm{UVS} \times \mathrm{EIL}}{4} \right\rceil \qquad [16.1]$$

The vulnerability rationale used to derive the CVSS vector is inherited from the X2RAIL-5 (X2RAIL-5, 2023) method but repurposed for this report. However, due to ongoing work on short-range communication for VCTS, they potentially need to be revised in the future. For the context of this work, it is assumed that TCMS handles this type of communication.

In the following, Overall Unmitigated Likelihood is used to calculate the Unmitigated Risk value. As displayed in Table 16.6, this value represents the threat influence of each supporting asset on their corresponding primary assets (only the results for primary asset Virtual Coupling Set Up and supporting asset VCTS-OB are presented here as an excerpt).

Table 16.5 VCTS Overall Unmitigated Likelihood (excerpt)

SA-ID	STRIDE Threat Category	Vulnerability Rationale	CVSS Vector	CVSS Score	UVS	EIL	Overall Unmitigated Likelihood
VCTS-OB	Spoofing Identity	Attacker can access VCTS-OB and spoof identity via ETCS or TCMS network + remote access interface (e.g. SSH)	AV:A/AC:L/PR:L/UI:N/S:C/C:L/I:H/A:H	8.9	3	3	2
VCTS-OB	Tampering with data	Attacker can access VCTS-OB and tamper the data via ETCS or TCMS network + remote access interface (e.g. SSH)	AV:A/AC:L/PR:L/UI:N/S:C/C:L/I:H/A:H	8.9	3	3	2
VCTS-OB	Repudiation	Attacker can access VCTS-OB and delete or modify security log or monitoring service via ETCS or TCMS network + remote access interface (e.g. SSH)	AV:A/AC:L/PR:L/UI:N/S:U/C:N/I:H/A:N	7.3	3	3	2
VCTS-OB	Information disclosure	Attacker can access VCTS-OB and steal or collect information via ETCS or TCMS network + remote access interface (e.g. SSH)	AV:A/AC:L/PR:L/UI:N/S:U/C:L/I:N/A:N	3.5	1	3	1
VCTS-OB	Denial of Service	Attacker can access VCTS-OB and steal or collect information via ETCS or TCMS network + remote access interface (e.g. SSH)	AV:A/AC:L/PR:N/UI:N/S:U/C:N/I:N/A:H	6.5	2	3	1
VCTS-OB	Elevation of Privilege	Attacker can access the VCTS-OB via ETCS or TCMS network and gain more privileges	AV:A/AC:H/PR:L/UI:N/S:C/C:L/I:H/A:H	7.9	3	3	2

Unmitigated Risk is the Impact multiplied with Overall Unmitigated Likelihood. It is a critical parameter for determining target security level (SL-T) and later allocating requirements from IEC 62443 (ISA/IEC 62443 Series of Standards, u.d.) to secure the system against identified risks. Furthermore, we have identified MITRE threats for each supporting asset, in accordance with the threat landscape (see Table 47 in (X2RAIL-5, 2023) for more details), providing a better understanding of potential threats.

Table 16.6 VCTS Unmitigated Risk (excerpt)

Primary Asset	Supporting Asset	STRIDE Threat Category	Vulnerability Type	Impact of Losing	Impact	Overall Unmitigated Likelihood	Unmitigated Risk
PA-01 Virtual Coupling Set Up	VCTS-OB	Spoofing Identity	[SPOOFING THROUGH SOFTWARE APPLICATIONS]	Integrity	4	2	8

PA-01 Virtual Coupling Set Up	VCTS-OB	Tampering with data	[SOFTWARE APPLICATIONS TAMPERING]	Integrity	4	2	8
PA-01 Virtual Coupling Set Up	VCTS-OB	Repudiation	[REPUDIATION THROUGH SOFTWARE APPLICATIONS]	Integrity	4	2	8
PA-01 Virtual Coupling Set Up	VCTS-OB	Information Disclosure	[DISCLOSING INFORMATION FROM SOFTWARE APPLICATIONS]	Confidentiality	2	1	2
PA-01 Virtual Coupling Set Up	VCTS-OB	Denial of Service	[DoS Software Applications]	Availability	4	1	4
PA-01 Virtual Coupling Set Up	VCTS-OB	Elevation of Privilege	[EoP SOFTWARE APPLICATIONS]	Confidentiality	2	2	4

As shown in Table 16.7, the second but last step in this method is to identify the maximum unmitigated risk for each STRIDE domain and security zone.

Table 16.7 Max Risk per Zone and STRIDE domain

Max Risk per Zone	S	T	R	I	D	E
OB-Z	8	8	8	4	4	8
TS-Z	8	8	8	4	4	8

The STRIDE domains are thereafter mapped to the seven foundational requirements of IEC 62443 as shown in Table 16.8, for identifying appropriate requirements to achieve a specific target security level. Each risk level also corresponds to a specific target security level (SL-T).

Table 16.8 Max SL-T per Zone and IEC 62443 FR

	IAC	UC	SI	DC	RDF	TRE	RA	SL-T Vector
OB-Z	2	2	2	2	2	2	1	{2, 2, 2, 2, 2, 2, 1}
TS-Z	2	2	2	2	2	2	1	{2, 2, 2, 2, 2, 2, 1}

Using the SL-T vector, organisations can identify and allocate requirements from IEC 62443-3-3 (for zone/system level) and IEC 62443-4-2 (for component/supporting asset level) to address cybersecurity risks.

16.5. Conclusion & Future Directions

This work presents a cybersecurity risk assessment of Virtually Coupled Train Sets (VCTS) within the R2DATO Europe's Rail project, leveraging methodologies from the Shift2Rail project X2RAIL-5 (X2RAIL-5, 2023) and aligning with IEC 62443 standards (ISA/IEC 62443 Series of Standards, u.d.). The analysis identifies critical vulnerabilities and evaluates potential threats using the Microsoft STRIDE threat model (The STRIDE Threat Model, n.d.) and CVSS exploitability metrics, demonstrating the effectiveness of a structured approach to cybersecurity within railway.

The Excel tool provided by X2RAIL-5 (X2Rail-5, 2024) is compliant with IEC 62443-3-2 and provides practical guidance for enhancing cybersecurity in railway systems. Key findings in its application highlight the importance of continuous improvement in risk assessment methodologies and the need for a detailed vulnerability severity analysis.
Future enhancements could involve more specific guidelines and examples, such as leveraging attack trees and MITRE attack techniques to generate vulnerability vectors more precisely tailored to the system in focus, as well as broader asset types which include information assets and processes. Also, aligning the threat landscape in (X2RAIL-5, 2023) with the Transport Threat Landscape for the European Union made by ENISA (European Union Agency for Cybersecurity (ENISA), 2023) would greatly increase its legitimacy. This work advances cybersecurity in railway systems, providing a foundation for future research and development to ensure safer and more reliable operations in a digital and interconnected world.

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102001 and Trafikverket (TRV 2022/46318). The project is supported by the Europe's Rail Joint Undertaking and its members.
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

17. Preliminary concepts and specifications for a self-propelled wagon

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17.1. Introduction

The transportation sector has an important role to play in achieving the goal of climate neutrality. In order to make the transport sector more environmentally friendly, freight transport needs to be shifted from road and air to rail in as many cases and quantities as is practicable. Shifting from conventional lorry transportation to rail makes it possible to save around 105 grams of CO2 per tonne-kilometre [1]. However, a better carbon footprint alone is not enough to make rail transport more attractive. The attractiveness of rail freight transport can be increased by, among other things, greater flexibility of the shunting process at the marshalling yards, more rapid responsiveness in rail freight and increased digitalization and automation of the transportation chain. In addition, the rail freight sector is a particularly cost-sensitive one, so measures to reduce costs can also further increase the attractiveness and competitiveness of rail freight in comparison to other more emissions-intensive modes. As described in [2] and [3], expenses for rail freight arise from several major factors affecting wagon operations:

- The labour-intensive process of preparing wagons for the train configuration, which involves coupling and adjusting brakes.
- Conducting manual checks before the train departs, including standard inspections and brake tests.
- Unexpected maintenance because of inadequate condition monitoring systems.
- With the shunting locomotives, only one group of wagons can be moved at a time.

Due to intense competition related to vehicle costs, there has been a drive to extend vehicle lifespans as far as possible, which, while keeping capital expenditures low, tends to lead to prolonged cycles of innovation. This disadvantage, along with the need for interoperability, results in very simple, rudimentary technology being the norm on the bulk of the current wagon fleet, and thus the need for extra manual labour for their operation and inspection.

To this end, efforts are underway to develop strategies and technologies which would provide rail freight wagons with some degree of independent propulsion and serve as a basis for further advances such as sensing, localization, digitization and automation in rail freight, thus increasing the attractiveness and capacity of rail freight and accelerating a shift to this environmentally friendly mode of transportation. As detailed in the paper, “Use cases and conceptual system specification for Self-Propelled Wagon”[4], stakeholders in industry have already expressed interest in self-propelled freight wagons (SPFW) for use in a variety of different use-cases, most obviously of course simple short-range shunting movements in closed, flat yards, but also extending to last-mile deliveries and supporting functions during mainline travel in a normal, locomotive-pulled train. These functions could include providing additional tractive effort in challenging scenarios which would otherwise require additional locomotives or lower speeds, and/or offering some proportion of regenerative braking, which would reduce noise emissions and wear significantly. In combination with advances such as the Digital Automatic Coupler (DAC), an independent propulsion capability for individual wagons stands to significantly reduce the amount of labour involved in shunting and last-mile operations.

As result of the information gathered and analyzed in the course of the stakeholder workshop and online survey described in [4], requirements for an SPFW were derived and translated into a series of specifications through analytical calculations of driving resistances and power and energy requirements. The following presents these specifications and their evaluation using a MoSCoW analysis and finally proposes a pair of preliminary system architectures for a competitive SPFW.

17.2. MoSCoW analysis and results

In order to define as best the specifications and requirements for an SPFW, a MoSCoW analysis was performed. Different sub-systems were defined, which are as follows:

- Wagon construction and other sub-systems
- Traction system
- Braking system
- Battery system
- Data management and control system.

Under each sub-system, functions and requirements are proposed and evaluated according to the MoSCoW method as “Must have”, “Should have” or “Could have” (there were no results that fell under the category W for “Won’t have”).

To summarize the results, a SPFW must be able to work both when the wagon is coupled to a train or uncoupled and independent, not add unnecessary mass to the wagon and have minimal maintenance requirements. Then, it should, given its comparatively large battery and regenerative capacity, be able to supply energy for the goods being transporting, for instance in order to power refrigerated trailers or containers. In order for an SPFW to carry out its functions while keeping capital costs low, it should be possible to retrofit a broad variety of existing wagons with minimal effort. A SPFW must be equipped with a battery system and the battery’s thermal management should be capable of heating and could be capable of cooling. Self driving should be also available, at least as an expansion of basic abilities and in shunting operations within marshalling yards. Turning to the “could have” category, an SPFW could have an obstacle detection system to be able to prevent collisions, with this being a prerequisite for operation outside of controlled environments such as marshalling yards. It could also have a loading and unloading capabilities and an adjustable platform to accommodate different types of loads such as intermodal loading units (ILU’s). A data management and control system must support train run functions and train operation modes (TOM). A human-machine interface (HMI) should be installed to enable the remote control of the SPFW.

17.3. MoSCoW interpretation

A central takeaway from the MoSCoW analysis is that there are different possible embodiments of the concept of an SPFW which address the needs and wishes expressed to different degrees and with different focuses. For example, concerning the traction system, a boosting capability must be available in order to help the locomotive at maximum speed, around 120 km/h, and also to support the distributed power. Furthermore, given the complexity, cost and labour which would be involved in plugging in and charging thousands of SPFWs regularly, it was agreed that the drive system must be able to “feed itself” through regenerative braking at appropriate times. This braking, in order to be effective, must be able to operate at all speeds which the wagon will experience. However, during last-mile operations, requirements diverge with regard to the tractive effort expected of an SPFW. While certain use-cases only require short-distance travel on level ground, others demand longer ranges on the order of 10 km and the ability to climb significant grades. Thus, much depends on where the SPFW will be in operation, and two potential scenarios present themselves with regard to the concrete specifications needed:

a) Maximization of attractiveness through consistent minimization of costs by concentration on the core applications of shunting, boosting and regenerating, or

b) Maximization of the range of potential applicability of the product in last mile applications through longer range and greater tractive effort.

17.4. Traction system requirements

All rail vehicles, including SPFWs, are subject to fundamental effects and forces while driving, some of which are depicted in Figure 17.1. In the cases being considered, a drive system for an SPFW should be dimensioned according to the forces it is likely to encounter in the scenarios it is being designed for. The primary difference between the two scenarios listed above lies in the question of whether the SPFW should be able to travel longer distances in more challenging conditions likely to be encountered in last mile operations, or if the focus should be on shunting, boosting and regenerating.

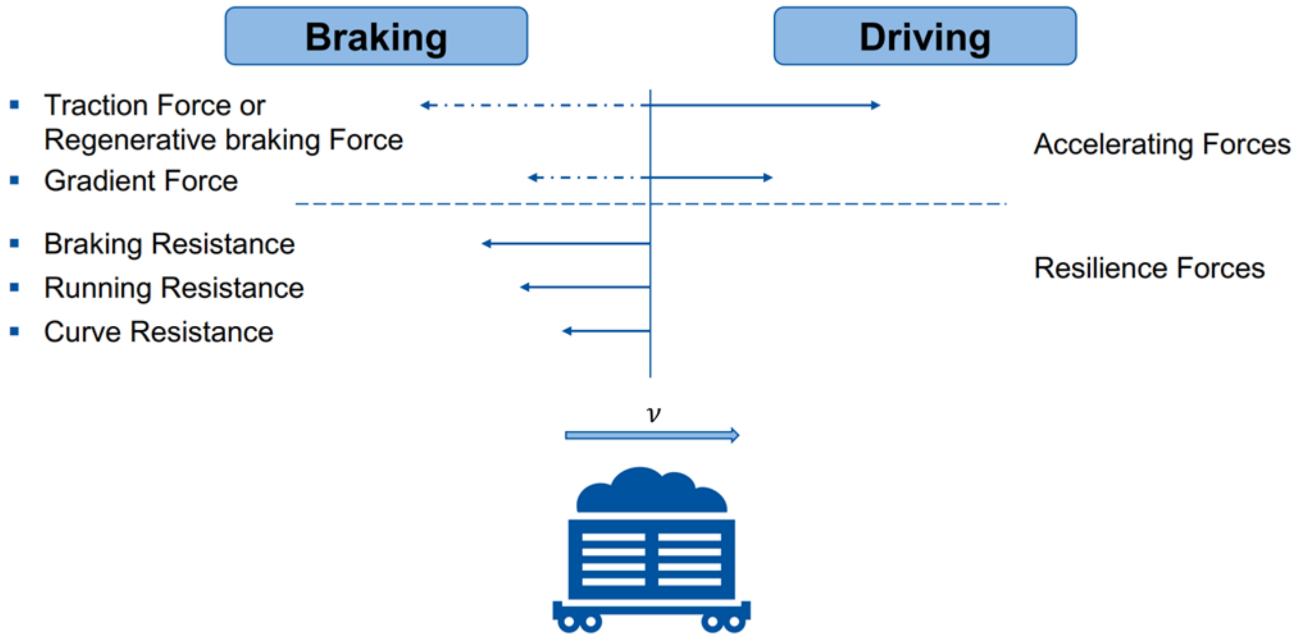

Figure 17.1 Driving forces acting on an SPFW, as depicted in [2]

To obtain an estimate of the powertrain requirements for different use cases, specific powertrain requirements (requirements per tonne of vehicle mass) as a function of speed, gradient and curve radius were studied in [5] using a simple point mass analysis of a wagon and empirical formulas for the resistance forces illustrated in Figure 17.1. The tractive force required to overcome rolling, curving and gradient resistances per tonne as a function of speed are presented in Figure 17.2. The rolling and curving resistances are doubled at zero speed (start from standstill). It can be observed that a worst-case scenario can easily add up to a requirement of around 400 N/tonne of tractive force. Using existing electric freight trains as an example, however, it appears that 150-200 N/tonne of tractive force is most often sufficient in practice as it is rare to start from standstill in a 100 m radius curve at 2% gradient. For existing lines, the specific tractive force for freight trains in operation should provide a reasonable reference for the SPFW even though there could be differences in the operational cycles that could motive different tractive force requirements. E.g. self-propelled wagons could see more start and stop cycles. The maximum tractive effort that can be provided by a single SPFW axle is assumed to be around 40 kN (corresponding to 0.2 adhesion coefficient at 20 tonnes axle load). A single driven axle should therefore be sufficient to propel up to two wagons, but more driven axles need to be considered for larger consists.

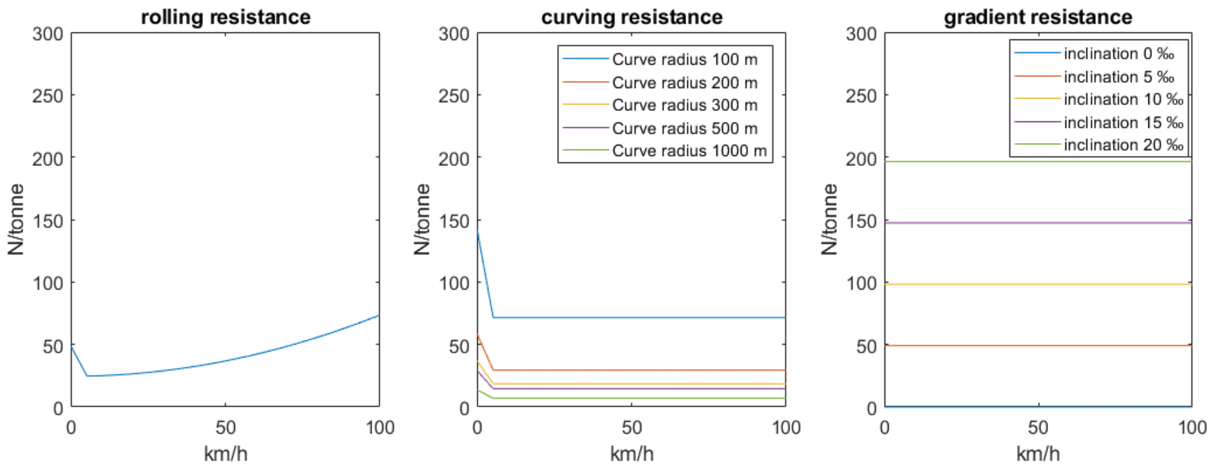

Figure 17.2 Rolling resistance, curving resistance and gradient resistance in Newtons per vehicle tonne as a function of speed for different vehicle running conditions

Normalized powertrain requirements for tangent track as a function of speed and gradient are presented in Figure 17.3. The results concern tractive force, power, energy expended per km and battery mass needed per km to store the expended energy. The numbers assume an ideal powertrain system and do not account for losses or effective operating ranges of batteries etc. It can naturally be observed that the expected speed and gradient ranges will have a strong influence on the powertrain requirements for SPFW. As the present results are specific quantities per vehicle tonne they can be easily scaled to give a starting point on the powertrain specification for different use cases. Example results also including curving resistance are included in [5].

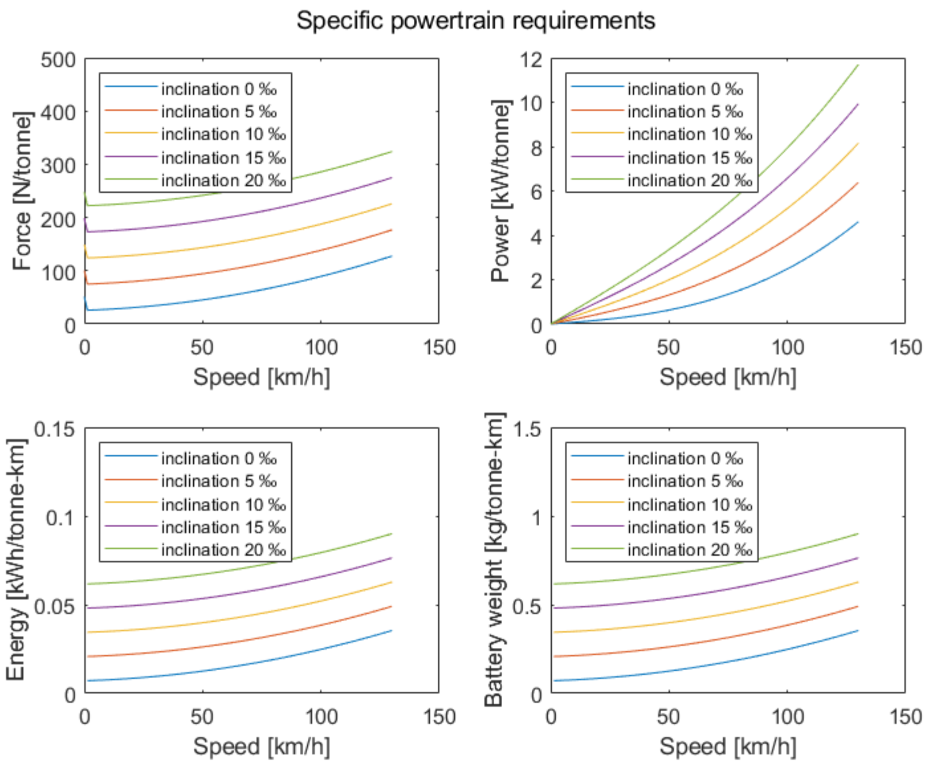

Figure 17.3 Specific force, power, energy and battery weight requirements for an electric self-propelled wagon for varying speeds and gradients on tangent track

17.4.1. Scenario a)

This scenario is being analysed through a use case defined by Renfe and CEIT to substitute shunting operations in a private yard. The objective of the use case would be to integrate a traction, battery and braking system into an existing wagon so it can carry out loading and unloading operations in a 700 m track in around 10-15 minutes, with no slope gradient and a load of 80 tons. Future tests of the SPFW could be performed in this same yard to validate the simulation results.

The SPFW should operate between 7 km/h and 20 km/h to fulfill the time requirements, considering maximum accelerations up to 0.25 m/s2. Considering these parameters and the overall characteristics of the wagon used for the use case a peak torque of 3000 Nm and a peak power of 30 kW would be necessary. Due to the available volume and in order to simplify the cooling system of the motor, a two-motor approach (one per axle) is being studied in order to reduce the required power density per motor. A higher power density could mean introducing a liquid cooling system, what would increase the complexity of the retrofitting.

Due to the fact that the goal operation time for the SPFW is very short and the regeneration time during the train regular operation is significantly higher, the capacity of the batteries must be enough to cover one trip, around 2 kWh for the studied scenario taking into account a safety margin. However, to be able to meet the power requirements without overstressing the battery a higher capacity would be needed, and a study of suitable commercial batteries for the application is being carried out.

17.4.2. Scenario b)

For scenario b), being analysed at the DLR, it also becomes necessary to consider the conditions likely to be encountered in last mile operations. Last mile operations can vary drastically, from simple trips of several hundred metres on relatively flat, straight track, as in the scenario a), to trips of many kilometres with significant inclines and curves.

In order for the wagon to be useful in a meaningful proportion of the cases it is likely to encounter, it is important to make a reasonable estimate of what distances, inclines and curves are typical. The stakeholder survey described in [4] asked specific questions regarding these characteristics, and the values given in the responses led to a series of basic scenarios in which it was decided that a fully loaded SPFW should be able to stop and start. In order to fulfill these challenging scenarios, calculations in [2] showed that a tractive effort of approximately 30 kN would be necessary, in particular in order for a 90-tonne wagon to start from a standstill in an 80m curve with a 1.25% gradient. These parameters can vary, of course, with starts on steeper inclines being possible with less mass or greater curve radii. To maintain a speed of 25 km/h under most conditions, as well as provide a meaningful amount of regenerative braking at high speeds, a motor power of at least 75 kW was found to be sufficient [2].

Further analyses of representative shunting and last mile scenarios in [2], as well as cross-checking with the survey results described in [4] showed that approximately 18 kWh of energy storage would cover the requirements for a large majority of cases, even taking battery degradation and safety margins for reserve power into account. Smaller batteries would suffice for some cases, however the 75 kW of power out of or into an 18 kWh battery already represents a C-rating of over four, and exceeding this for more than short bursts would likely lead to accelerated battery aging and/or necessitate expensive and complicated battery cooling system. For this reason, a larger, less stressed battery could in fact lead to a simpler and longer-lived system with better potential lifecycle costs.

Further considerations

As a system is developed with the goal of meeting these requirements, a mechanical system architecture needs to be considered which can fulfill that goal in the most efficient way possible. In general, as developments in many sectors such as overseas shipping have shown, a single, large system (such as a container ship's engine, or even the ship itself) is often more cost-, energy- and mass-efficient than many small ones. While this initially might be seen as an argument against SPFWs, the functional advantages of SPFWs likely outweigh any disadvantages in many use cases, and modern technologies in electric drivetrains and batteries, when distributed over a large number of wagons, could contribute to an increase in the energy efficiency of the transportation chain. However, within an SPFW itself, the rule mentioned above does in all probability hold; thus, a solution which concentrates the traction and storage systems into a small number of units is likely to be optimal. With that in mind, it is likely to be advantageous to concentrate the drivetrain onto one or two wheelsets in an SPFW.

Another means of minimizing the changes necessary to wagons themselves is by concentrating the functions and technology required into the bogies to the greatest extent possible. Figure 17.4 shows such a possible layout. For the analysis of Scenario a), a direct-drive solution is being developed, removing the heavy gearbox and coupling the motor directly to the axle, simplifying the layout and minimizing drag. Scenario b), with its high torque requirements on the other hand, necessitates the use of a gearbox in order to climb steeper grades, but can possibly use a lighter, faster turning motor. In any case, one such bogie could enable wagons to be upgraded with all of the advantages described above through little more than the exchange of one bogie for another like that depicted in Figure 17.4.

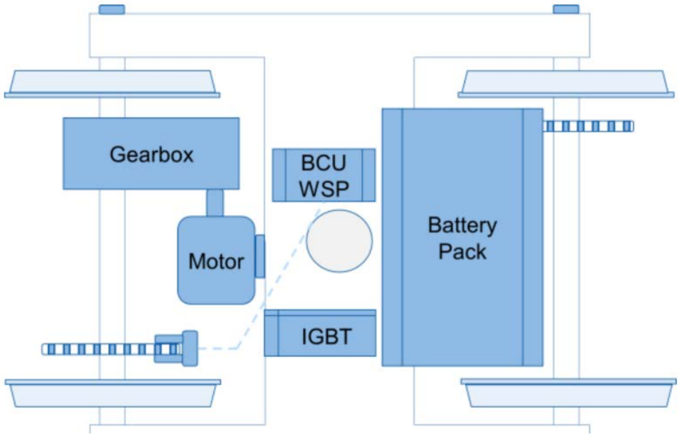

Figure 17.4 Conceptual layout of a fully-integrated self-propelled bogie, with all necessary systems for converting a conventional wagon to an SPFW, including a brake control unit (BCU) and wheel slide protection (WSP) [2]

Conclusion

Self-propelled wagons represent one of the key technologies needed to make the freight sector more attractive. SPFWs can serve a wide variety of use cases, among them the scenarios presented here, many of which pose different challenges and requirements with regard to the concept and technical specifications of the vehicles and their drivetrains. One pair of possible configurations is presented above; one a highly efficient direct drive, the other a highly capable geared drive system. Components can either be mounted to the wagon or concentrated in the bogie. However, in order for any of these concepts to live up to their potential of increasing the attractiveness and competitiveness of rail freight, it is important that they do so without adding unnecessary cost and complexity to the system as a whole. The use of standard parts and conventional materials where possible can be an important means of controlling costs as new functions and capabilities are added to future wagons.

Rail freight is currently on the cusp of several major advances, among then the introduction of the DAC. The DAC itself is an important enabler of many innovations in rail freight, including meaningful automation through self-propelled and ultimately self-driving freight wagons. As these advances are rolled out throughout the European fleet and technologies related to energy storage, power electronics, sensing and computing continue to become more robust, capable and accessible, the time has come for freight wagons to make a leap, from passive masses of steel, to intelligent, powerful, independently mobile participants in rail freight transportation.

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List of Abbreviations

SPFW	Self-Propelled Freight Wagon: a revenue wagon designed for transporting goods and capable of moving under its own power.
DAC	Digital Automatic Coupler: a centre-buffer coupler intended to replace traditional chain and side-buffer couplers in European freight traffic.
ILU	Intermodal Loading Units: standardized shipping units such as containers or swap-bodies, designed for rapid intermodal transfers.
TOM	Train Operation Modes
CEIT	Centro de Estudios e Investigaciones Técnicas de Gipúzcoa
DLR	Deutsches Zentrum für Luft- und Raumfahrt
C-rating	Capacity rating: the power flowing through a battery divided by its capacity, used as a measure of the relative load being placed on a battery or its cells
IGBT	Insulated-Gate Bipolar Transistor: an electronic component forming the basis for the variable frequency drive control of an electric motor
BCU	Brake Control Unit
WSP	Wheel-Slide-Protection

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Funded by the European Union

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102009. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

18. An Innovative Non-Destructive Method using Ka Band Microwaves for Railway Inspection

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18.1. Introduction

Crack detection in metallic structures is critical across various industries due to its impact on safety and performance. Service loads, environmental stresses, and manufacturing irregularities can cause both surface and subsurface cracks, compromising structural integrity. In railway rails, the complex loading conditions during operation can cause significant defects, such as head cracks and wear from friction, which require immediate attention to avoid structural failures [1][2][3].

The inspection and maintenance of railway infrastructure are fundamental to ensure the safety and efficiency of rail transportation. Early detection of cracks in rails, typically caused by rolling contact fatigue or welding failures, is particularly crucial for preventing accidents or costly repair work. In this context, cracks in tracks with a depth greater than 4 mm and/or a length exceeding 30 mm are considered severe and require immediate corrective action. If the crack depth exceeds 5 mm, rail replacement is necessary. These cracks often originate from welding failures or rolling contact fatigue, and early detection can prevent serious accidents and high maintenance costs [4][5][6][7].

Numerous studies have developed non-destructive testing and evaluation (NDT&E) techniques to detect and assess cracks in metallic structures. Standard techniques include visual inspection, dye penetrant testing, ultrasonic testing, eddy current testing, magnetic particle testing, and radiography. Additionally, non-standard methods such as microwave, and millimeter-wave techniques have shown significant advancements in sensitivity and resolution [8][9][10]. Far-field techniques, such as synthetic aperture radar (SAR) in the K and Ka bands, have proven effective in detecting covered or exposed cracks at long distances [6][11][7][12]. Conversely, near-field techniques using rectangular and circular waveguides have shown great potential in detecting and characterizing cracks, even under covering conditions. These techniques allow for the measurement of changes in the complex reflection coefficient (S11 parameter), providing valuable information on crack geometry [13][14][15][16].

The study shown in this publication aims to disclose the preliminary findings performed by CEIT's team towards an autonomous rail inspection method using microwaves to detect and characterize cracks. The main hypothesis is that, by measuring the S11 parameter, waveguides operating in the Ka band can provide accurate information on the presence and severity of cracks in steel rails. This approach, shown in Figure 18.1, will enhance safety and reduce maintenance costs by identifying track defects. The validation of this method could revolutionize current railway maintenance practices and establish new industry standards.

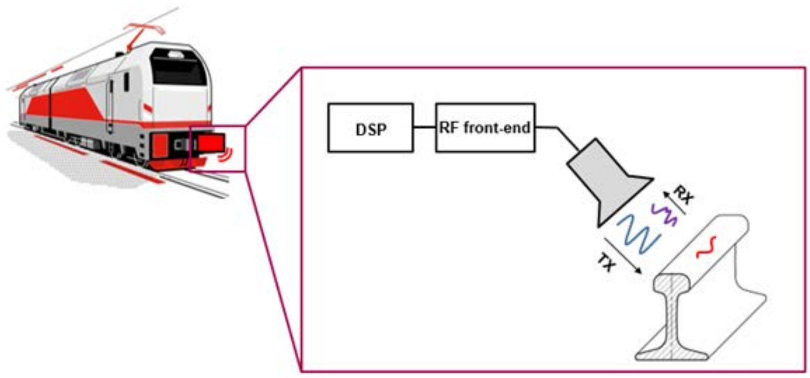


Figure 18.1 Railway inspection using microwaves

The study presented in this publication focuses on interpreting signals obtained through a waveguide operating in the Ka band, aimed at a metal plate made of F114 steel, a more standard version of steel and similar material as train rails (R260). The waveguide selected for this experiment measures the S11 parameter and allows the detection of cracks in the metallic structure by means of a specific processing of the raw signal, as seen in Figure 18.2.

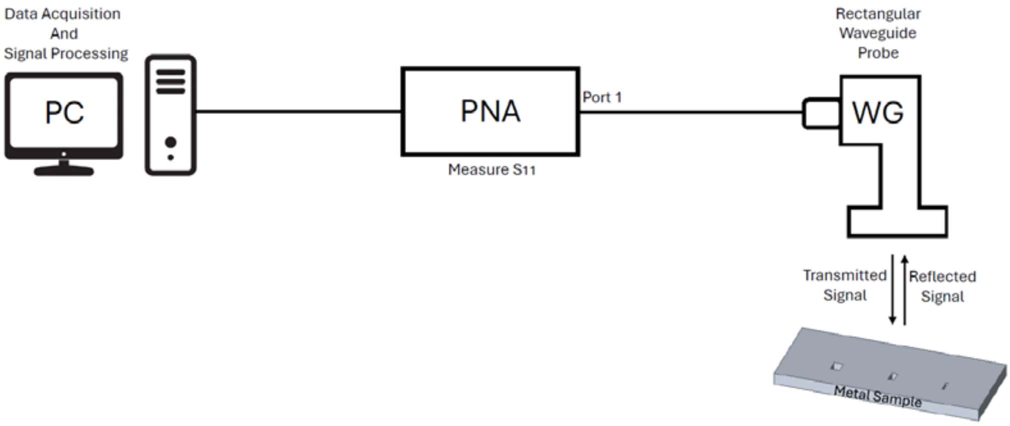


Figure 18.2 Schematic diagram of the measurement setup.

18.2. Method

The study design was structured in several phases. Initially, a thorough analysis of industry needs and existing literature on the application of microwave signals for non-destructive testing of metallic surfaces was conducted. This analysis helped define the specific requirements for the inspection system. Subsequently, relevant literature on microwave and millimetre-wave detection techniques was reviewed. This research helped identify best practices and applicable technologies for detecting cracks in railway infrastructure. An iterative approach was then adopted, comprising several stages: system requirement identification, state-of-the-art review, test protocol definition, development of a laboratory testbed for practical experiments, electromagnetic simulations, signal processing, and proof-of-concept testing. Each stage was essential for continuous refinement and system effectiveness.

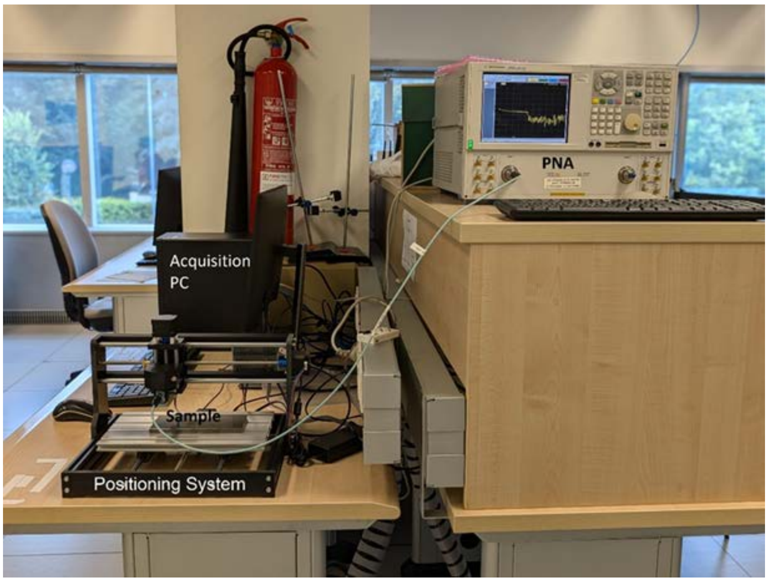


Figure 18.3 Experimental setup

In the practical phase of the study, the laboratory testbed was assembled to validate the effectiveness of the system developed in the earlier stages. This experimental setup, as shown in Figure 18.3, involved the use of a rectangular waveguide to irradiate microwave signals in the Ka band (26.5 - 40 GHz). A PNA E8364B network analyser was employed to measure the S11 scattering parameters, which indicate the amount of signal reflected by the inspected surface. To ensure precise control over the distance and irradiation angle relative to the rail surface, a modified VEVOR CNC 3018 Pro positioning system was implemented to mount the waveguide, allowing position adjustment along the x, y, and z axes. F114 steel sheets with laser cuts of different widths to emulate cracks, along with another without cracks, were placed on the positioning system surface for testing under controlled conditions.

18.3. Measurement and Data Processing

Both manual and automatic measurements were carried out using the PNA and the positioning system. The manual measurements helped identify the frequencies of interest where significant changes to the magnitude and phase of the S11 could be observed, specifically 33 GHz, 33.25 GHz, and 36 GHz. Subsequently, a systematic scan was performed on the steel sheets, taking measurements every 0.1 mm along predefined paths, as shown in Figure 18.4.

Once the frequencies of interest were identified, a U-shaped scan was conducted on the initial steel sheet, as seen in Figure 4, taking measurements every 0.1 mm along the yellow and red lines and omitting measurements along the blue line. A total of 2600 measurements were taken in this scan, which took approximately 2 hours. This process, although initially quite time-consuming, can be simplified as the system evolves; at this stage, a comprehensive approach was sought to ensure accuracy.

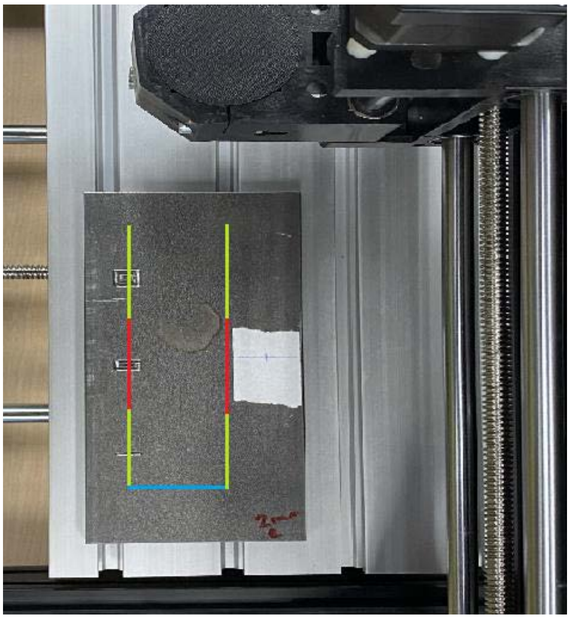


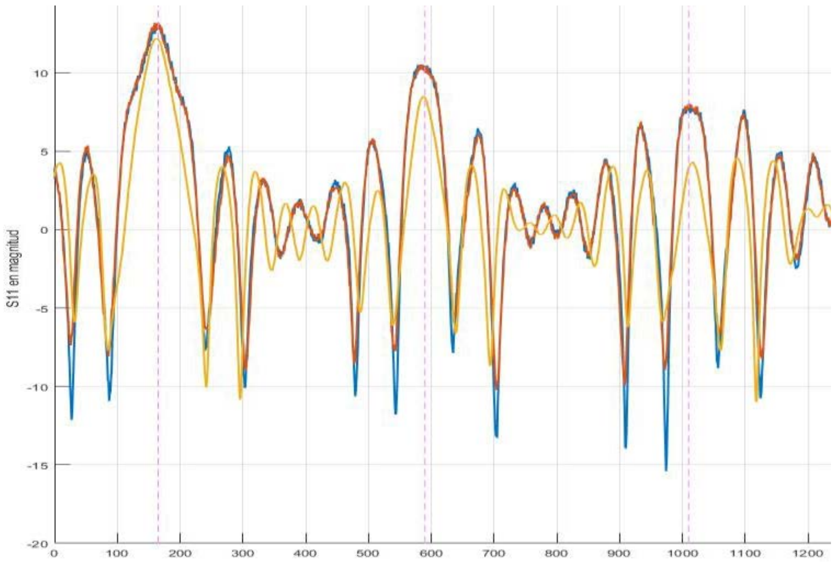
Figure 18.4 Route followed by the waveguide when performing the measurements. Left path with cracks and right path without cracks

The obtained data was processed to identify cracks by analyzing the variations in the magnitude and phase of the different S11 measurements using MATLAB. The measured S-paramenter files were stored in formats compatible with this software and processed to extract crack characteristics. Additionally, the results were graphed, and a detailed analysis of the magnitude and phase of the S11 parameter was conducted, allowing for precise crack identification.

18.4. Results

The main preliminary findings of the study confirm the effectiveness of rectangular waveguides in the Ka band for detecting surface defects in railway. Significant variations in the magnitude and phase of the S11 parameter in the presence of cracks validate the capability of this technique to identify and characterize cracks of various sizes. The optimal frequencies identified for crack detection were 33 GHz, 33.25 GHz, and 36 GHz, each showing distinct variations in the magnitude and phase of S11.

(a)



(b)

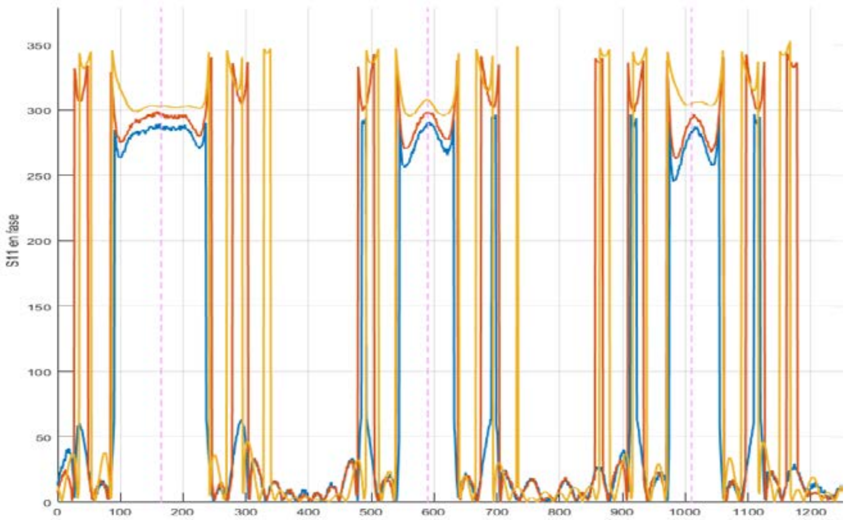


Figure 18.5 (a) Amplitude and (b) phase results of S11 at 33 GHz (blue), 33.25 GHz (orange) and 36 GHz (yellow) along the route.

In Figure 18.5, the results of the S11 amplitude and phase at the selected frequencies are presented for each position of the measurement route. The graphs show clear patterns around the cracks, which are crucial for their identification. To eliminate intrinsic variations of the steel and isolate the characteristics of the cracks, relative reflectance parameters were analysed. The results reveal consistent patterns in the S11 phase, with plateaus at the centre of the cracks and peaks at the sides, facilitating precise crack identification.

A crack detection algorithm was developed based on these findings, using changes in the magnitude and phase of S11. This algorithm identifies and sizes the plateaus to determine the presence of cracks through three key steps: identification of points of drastic rise and fall using derivatives, measurement of the area under the curve between these points, and verification that the area meets a certain threshold for the three selected frequencies.

Finally, Figure 18.6 shows the results of the sample analysis with the developed algorithm. The obtained curves indicate positive zones for the presence of cracks only when all three selected frequencies show consistent results. This significantly reduces false positives and improves crack detection accuracy.

The implications of these findings are significant for the precise detection of cracks in train rails. The described methodology not only improves accuracy in identifying cracks but also reduces the possibility of false positives, which is crucial for efficient and safe railway infrastructure maintenance. Future work should focus on automating and optimizing this process for large-scale applications, enabling continuous and real-time monitoring of the rails.

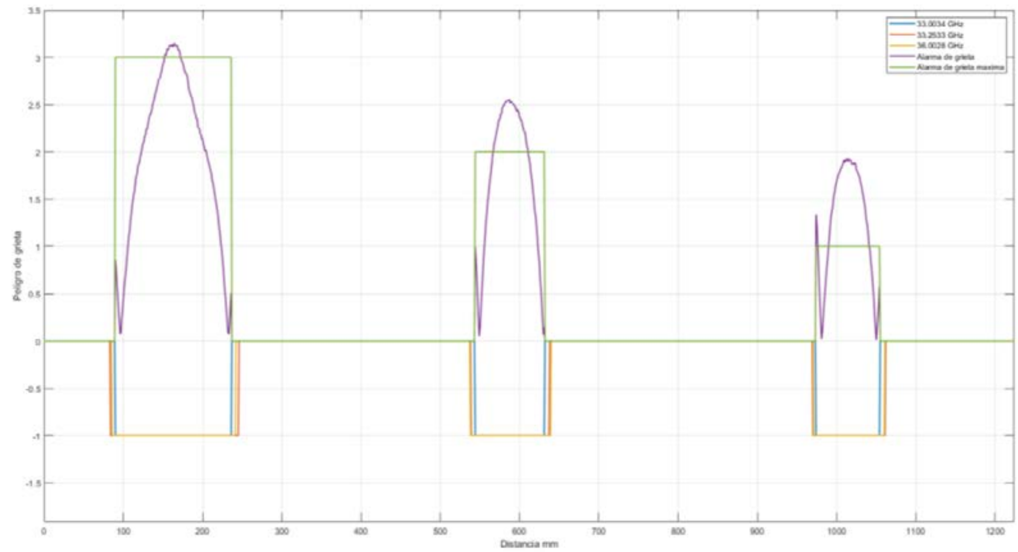


Figure 18.6 Output signals of the crack detection algorithm.

18.5. Conclusions

The study presented in this paper demonstrates the effectiveness of using rectangular waveguides operating in the Ka band for detecting and characterizing cracks in steel rails. The key findings indicate that variations in the magnitude and phase of the S11 parameter are accurate indicators of the presence of cracks, allowing for the identification of defects of various sizes. The applied methodology not only improves the accuracy of crack detection but also reduces the possibility of false positives, which is crucial for the safe and efficient maintenance of railway infrastructure.

The practical implications of this study are significant. Implementing an autonomous inspection system based on microwave technology can transform current railway maintenance practices. By identifying cracks early and accurately, safety can be enhanced, and maintenance costs reduced by preventing extensive and costly repairs.

For future research, it is recommended to automate and optimize the detection process for large-scale applications. This will include developing more advanced and robust algorithms for real-time data processing, as well as improving positioning and scanning systems. It would also be beneficial to explore the application of this technology in other types of metallic infrastructures, extending its use beyond the railway sector. With these advancements, microwave-based inspection technology could become an essential tool for predictive maintenance and asset management in various industries.

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List of Abbreviations

Non-Destructive Testing and Evaluation (NDT&E)
Synthetic Aperture Radar (SAR)
Precision Network Analyzer (PNA)
Computer Numerical Control (CNC)

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This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº101101966.The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

19. An Integrated ETD Prediction System for Yards and Terminals

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19.1. Background

Europe is striving to reach its ambitious targets of establishing railways as the backbone of freight transportation to fulfill the CO_2 emission targets by 2050. Utilizing current rail freight capacities, creating seamless operational platforms, and managing rail freight services with innovative solutions are among the plans that Europe follows (Shift2Rail Joint Undertaking, 2020).

A part of Shift2Rail projects attempted to develop integrated models between yards and the network to coordinate and optimize their interactions. Developing Yard Prediction Model (YPM) started in Shift2Rail FR8HUB project to predict yard departure status (Minbashi, Bohlin, Palmqvust, & Kordnejad, 2021) and extended in FR8RAIL III to predict yard departure and arrivals in sequence (Minbashi, Sipilä, Palmqvist, Bohlin, & Kornejad, 2023) combining with network simulation model PROTON developed in Shift2Rails PLASA and PLASA II projects (Zinser, o.a., 2019).

Europe's Rail is moving one step further in enhancing the reliability of rail freight services by integrating yards, intermodal terminals, and networks. Integrated yards and intermodal terminals with railway networks are required to guarantee reliable and predictable rail freight operations and attract more diverse types of clients to railways. Yard and intermodal operations differ due to the differences between single wagonload transport and intermodal transport. However, the processes for preparing and dispatching trains are similar, which provides for developing a departure prediction model applicable for both yards and terminals. At the FP5-TRANS4M-R project, we are developing an integrated departure prediction model for both yards and intermodal terminals. We aim to develop a predictive model based on machine learning algorithms that is applicable by yards and terminal operators, as well as, infrastructure managers.

Predictive models applying machine learning algorithms could be a solution for fast and accurate departure prediction from yards and terminals. In fact, data-driven approaches using machine learning algorithms have recently been applied to predict freight train delays in intermodal transport. These studies have mainly focused on freight train punctuality in terms of ETA prediction due to the importance of ETAs on reliable shipment delivery and predictable transshipment processes. A comparison between different algorithms in (Pineda-Jaramillo & Viti, 2023) concluded that random forest is the most accurate algorithm for predicting freight train ETAs. Influential parameters on intermodal ETA prediction were investigated in (Barbour, Mori , Kuppa, & Work, 2018). Studies also showed that the departure status from the origin yard (Pineda-Jaramillo & Viti, 2023) and departure delay from the origin terminal (Balster, Hansen, Friedrich, & Ludwig, 2020) impact the ETA prediction. Delayed departures from the intermodal terminal may lead to containers missing their connections and large waiting times for being assigned to the next train, which is not fully booked (Balster, Hansen, Friedrich, & Ludwig, 2020). A similar situation can happen in yards, leading to wagons missing their connecting train and delayed deliveries. Delayed departures may also impact the network's punctuality of other freight and passenger trains. Therefore, an Estimated Time of Departure (ETD) prediction system can substantially assist in single wagonload, intermodal transport, and network operations by increasing the predictability and reliability of freight operations.

19.2. Method

The method to develop ETD prediction systems for yards and terminals is a data-driven prediction approach based on supervised machine learning. Supervised machine learning models receive known input and output data from past operations and learn the relations between various input features and the output directly from the data. After finding these relations and the hidden patterns in the data, the models can receive input data to predict the future output that has not occurred yet. There are various algorithms to implement machine learning models; the selection of the algorithms depends on the application and the scope of the models. For the application of the yard/terminal departures. The selected algorithms are tree-based: decision trees, gradient-boosted trees, and random forests.

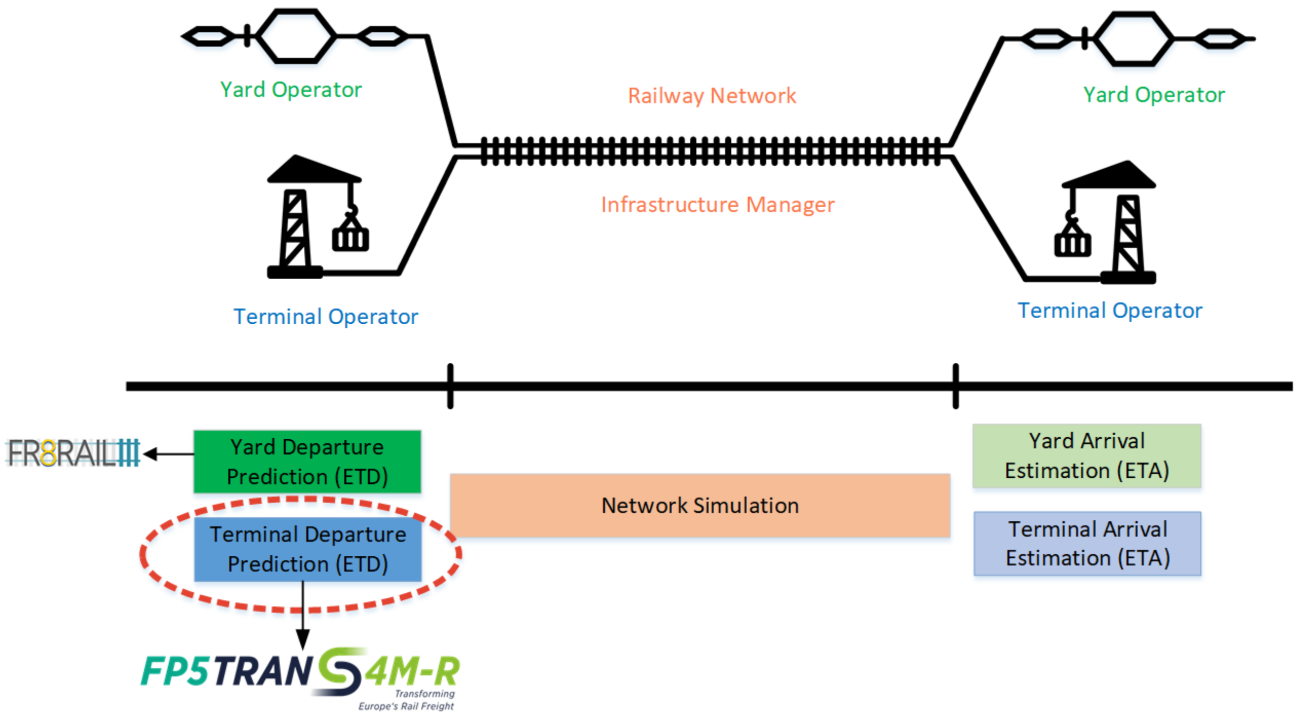

Figure 19.1 The predictive framework for Integrating yards, terminals, and the network

The structure of a decision tree is similar to a tree – with a root at the top – nodes, branches, and leaves at the bottom. The tree is built by recursively branching the data into subsets at each node based on the value of input features. This branching continues until no further branch is possible. Regression trees are built to predict continuous values, which in this case are departure deviations – deviations from the scheduled departure time.

Two more advanced ensemble versions of decision trees – gradient-boosted trees and random forests— are two other selected algorithms. The ensemble versions combine multiple trees to achieve a more robust model that has higher accuracy level. A random forest is a collection of decision trees in which each decision tree is trained on a subset of the original dataset and might perform well on that part of the dataset and overfit (a situation when the model is trained on very detailed data and will not be able to perform well when it is given new test data) on different parts of the data. Therefore, combining this collection of trees will decrease the risk of overfitting of the model by averaging the results of the collection of trees and maintaining the predictive performance of the model. Gradient boosted trees is an ensemble tree model that is built sequentially correcting the errors of the previous trees and increasing the predictive performance of the model sequentially. At each iteration, a new decision tree is added to the model which is trained to reduce the error level of the ensemble of all previous trees.

The algorithms for the yard ETD are developed in KNIME Analytics Platform 4.6.1 (Berthold, o.a., 2008). The hyper-parameter tuning on tree depth (maximum number of levels in a decision tree) and number of trees (the total number of tress in an ensemble mode) is applied using hyper-parameter optimization loops within the KNIME Analytics Platform. Tuning tree depth is important because it reduces the risk of underfitting and overfitting of the decision trees. The number of trees in the ensemble models provides enhanced stability, generalization ability of the model.

The model also applies global feature importance using the gain metric to evaluate the importance of each parameter on the final predictions. Finally, the model performance is evaluated by comparing the predicted values and the actual ones by conventional metrics: mean absolute error (MAE), mean squared error (MSE), root mean squared error (RMSE), and mean signed difference (MSD).

In a broader application, the departure predictions for yards and terminals will be integrated into network simulation for further application of ETA estimation or ETA planning, or capacity planning as can be seen schematically in Figure 1.1. A demonstrator of this application will be run on a case study of Nordic countries (Sweden and Norway) between Malmö and Alnabru.

19.2.1. Case study

Malmö yard and Malmö intermodal terminal are selected for the model development. Both are located on the Scan-Med corridor, which is important for the reliable connection of Scandinavia with the south of Europe for rail freight transportation. The case study will be extended from Malmö to Alnabru in Norway.

19.2.2. Data

The data for training and testing the model contains one year of operational and scheduled data for the Malmö yard and three years for the Malmö intermodal terminal. It is worth mentioning that access to rail freight data is difficult due to less interest among rail freight operators in an attempt to protect their commerciality and customers' privacy. Any data related to customers, the type of transported goods, the yard/terminal efficiency of the operations at the yard/terminal, and resources (staff, locomotives) seem sensitive for the yard/terminal operators to share and not easily shared. The features extracted from the operational and schedule data for the Malmö yard are listed as below:

Schedule features: departing train number, departure hour, departure weekday, departure month, minimum wagon dwell time, maximum wagon dwell time, number of wagons, number of arriving trains connected to a departing train, maximum planned weight, and maximum planned length.

Operational features: maximum operated weight, maximum operated length, minimum/mean/maximum arriving deviation from the schedule of the arriving trains connected to a departing train, and maximum wagon dwell time.

The selected features for the modeling do not reveal any commerciality of the operators' business and can be easily shared between the yard/terminal operator and the infrastructure manager. Features for the terminal side of the model are similar, however, the data granularity comprises two other levels than wagons: wagon-group and container levels.

19.2.3. Implementation and application

The integrated yard and terminal ETD model is under implementation with the latest version of the KNIME Analytics Platform 5.3 (Berthold, o.a., 2008). The yard ETD was originally implemented in KNIME Analytics Platform version 4.6.1; therefore, the operability of the model with the new version of the platform is being evaluated and upgraded. The terminal ETD is under implementation from the scratch with KNIME Analytics platform 5.3. The user interface (UI) for the yard/terminal operators provides an interactive dashboard and it is implemented on the KNIME Modern UI of the KNIME analytics platform 5.3. The tower manager at yard/terminal can insert features of the departing trains for which they need ETD and receive the ETD as a predicted value or the possible value range as a box plot to have a broader margin to make decisions for any required re-scheduling of the wagons or operations inside the yard/terminal. The ETDs can be requested for one train or a group of trains for a whole day and according to the ETDs, the tower manager can re-plan the operations inside the yard/terminal accordingly. The interactive dashboard will be similar to any operational software the tower managers use, so they will not require any further coding, AI knowledge or prerequisite computer background to be able to work with the ETD system. Additionally, the ETDs are also visualized through a decision tree diagram. The tower managers can control the visual decision tree diagram to see which features with which value led to a certain ETD. Thus, the results are more visual, interpretable, and transparent for the yard/terminal operators.

19.2.4. Limitations

Current development of the integrated yard and terminal ETD prediction system is on using the data from Sweden and the Scandinavian context of freight train operations between Sweden and Norway. The system attempts to use features that are general and achievable also in other European countries. However, there may be certain operational situations that impact the model performance and are rather more common for the Swedish context than other countries, which need to be tested and evaluated in case applying the model for other European countries is the scope. For example, a large number of freight trains depart early in Sweden (over 60%), which means the model has an outstanding capability in predicting also this type of departures, which will not be important in another European country.

Another limitation is regarding the features in the data that are used for training the models. Adding more features regarding the yard/terminal resources, weather forecasts, or yard/terminal efficiency factors may give further depth to the prediction capabilities and models' performance. In addition, the models are trained on data for one to three years of data. For implementing any data-driven, especially machine learning models, the more data the better generalizing performance of the models for future predictions.

19.3. Results

19.3.1. Model performance

A short summary of the results for the yard ETD is shown in Table 1.1. The model has the best performance with random forest algorithms with an R-squared of 92%. The model predicts the value of departure deviation on average less than three minutes, and for large deviations, it predicts them on average with less than 11 minutes of deviations. Random forests have shown the highest performance for ETDs for freight trains, which is in conjunction with previous literature on ETAs for freight trains (Barbour, Samal, Kuppa, Dubey, & Work, 2018; Balster, Hansen, Friedrich, & Ludwig, 2020). This may be due to the fact that random forest have robust performance to the outliners – large delays in this case – which is very common both for departures and arrivals. Therefore, random forests show a better performance in both applications. Additionally, previous research in Shift2Rail (FR8RAIL III, 2022) discussed the high correlation between departures and arrivals that leads to correlations between ETDs and ETAs. Punctuality of freight train departures impact the punctuality of their arrivals to the final yard/terminal. Vice versa, punctuality of arrivals to the yard/terminal impact the punctuality of freight train departures from yard/terminals. Additionally, there are similar features in training the ETD model and previous models for ETA, which may impact the similar high performance of random forests.

19.3.2. Feature analysis

The analysis for global feature importance results showed the most influential predictors from the schedule and the operational data. The most influential features of the schedule are the maximum planned length, departure weekday, the number of arriving trains connected to a departing train, and maximum wagon dwell time. The respective features from the operational data are related to the arrival deviations of the arriving trains that their wagons are connected to a departing train. Maximum and mean arrival deviations were the most influential features of the operational data. The more the arriving trains arrive according to their schedule, the less the departing wagons would be rescheduled. Consequently, departing trains will stick to their schedules. This also shows that it is beneficial to have access to highly accurate ETAs because having ETAs gives the agility and time for the operators to reschedule the wagons and trains in advance to mitigate delays and rescheduling in the yard.

Model	R-Squared	Mean Absolute Error (min)	Mean Squared Error	Root Mean Squared Error (min)	Mean Signed Difference
Base Line (Median)	-	19	1584	40	-
Simple Decision Tree	0.86	2.6	200.38	14.15	0.79
Gradient Boosted Trees	0.89	2.8	158.5	12.6	0.08
Random Forest	0.92	2.9	117.13	10.83	0.12

Table 19.1 Model performance evaluation for Malmö yard departures

19.4. Conclusion

This paper presents the implementation of the ETD prediction system for yards and terminals from "WP 28 Intermodal Prediction" from the FP5-TRANS4M-R project in the EU-Rail's program. The integrated yard and terminal departure prediction with network simulation will enhance rail freight services in terms of predictability and reliability. Applying machine learning models for integrated yard and terminal prediction is one of the use cases under development in FP5-TRANS4M-R. The results from the yard ETD for the developed tree-based models have an outstanding performance in the prediction of predicting departure deviations, with the best performance of the random forest algorithm with 92% accuracy. The yard ETD also shows that the maximum planned length of the departing trains and the arrival deviations of the connecting trains are the most influential parameters for predicting departures. This research is ongoing on implementing and integrating the terminal ETD into the yard ETD.

For the future, it would be interesting to expand the model by adding features regarding the yard/terminal resources, such as locomotive availability, locomotive delay, personnel shortage or delay. It would also be interesting to have features regarding the operational efficiency at the yard/terminal, for example, any idle or waiting times that might delay the containers or wagons along the operations and impact the departure prediction. Motivating the operators by the benefits of adding these parameters to the models may reduce the sensitivity of the data sharing in rail freight operations and benefit the involved actors using such advanced predictive tools.

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List of Abbreviations

CO_2: Carbon Dioxide
ETA: Estimated Time of Arrival
ETD: Estimated Time of Departure
MAE: Mean Absolute Error
MSD: Mean Signed Difference
MSE: Mean Squared Error
RMSE: Root Mean Squared Error
YPM: Yard Prediction Model

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102009. The project is supported by the Europe's Rail Joint Undertaking and its members.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

20. A framework for GNSS-based solutions performance analysis in an ERTMS context

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20.1. Context - Progresses in GNSS-based solution introduction in rail applications

GNSS (Global Navigation Satellite System) is now used in most of our travels and each of our smartphone apps. Most of the usages are not safety-critical. But Europe identified GNSS for more applications and to be integrated in rail in general as part of the toolset to help railway to contribute to reduce transport carbon footprint. To increase the use of trains in European transports, railways must improve their attractiveness for passengers and freight, but also increase reliability, availability and efficiency by reducing capital expenditure and operational costs. GNSS is part of the global digitalization scheme of freight that aims to offer added value to the clients knowledge of accurate time of arrival, continuous monitoring of transport conditions (temperature, humidity...).
But a major challenge will be to reach stringent applications and in particular, GNSS is today seen as a realistic and serious game changer for the future of the ERTMS (European Rail Traffic Management System).
The localisation function is today performed with both odometry and balises. Odometer provides a continuous train position in time from a reference point. But as the distance delivered by the odometer shows a growing bias with distance, due to wear and wheel sliding, the use of on-track balises allows to reduce this error. Future systems will be based on on-board localisation solutions with GNSS receivers. It will allow the development of new concepts for moving blocks, virtual coupling and automation. Its use for train integrity is also investigated.
But the environmental conditions of track and surroundings configuration, i.e, tunnels, dense urban areas or vegetation often degrade positioning performance and thus its efficiency and safety. Indeed, GNSS satellites are moving and their visibility (availability and relative position from the receiver) vary with time. Moreover, for optimal performance, the system requires open sky environments, which are the cases of most of the aeronautical uses but not of train uses. Trains often circulate in areas where signal reception can be disturbed (multipath, intentional or unintentional interferences) and thus, performances degraded. If many progresses have been made in the past years to develop more robust receivers [Puccitelli, 2022], multi-sensor solutions [CLUG website] or missing tools such as Digital Maps [Crespillo, 2023], in projects such as the Shift2Rail Project X2Rail-5 or CLUG, some questions remain and in particular related to performance evaluation. How can we evaluate performances in a dynamic environment (train, satellite, obstacles)? How can we be sure that every configuration has been tested? What is the impact of a failure (inaccuracy, missed detection) on operation?
Some of these issues are addressed in the on-going R2DATO project funded by Europe's rail.

20.2. The R2DATO project and our contribution

R2DATO is a project of the Flagship Project 2 (FP2) funded under Europe's Rail. The aim of R2DATO is to take the major opportunity offered by digitization and automation of rail operation and to develop the Next Generation ATC and deliver scalable automation in train operations, up to GoA4 for 2030, to enhance infrastructure capacity on the existing rail networks. The project is coordinated by SNCF.
The FP2 R2DATO project is developing technologies in several fields of digital automated up to autonomous train operations, seeking a new paradigm in how the rail system is operated, increasing safety, flexibility, capacity, performance and reducing energy consumption and costs. The development of positioning technologies and their evaluation are part of the scope. Railenium is contributing to several tasks for SNCF. This paper will develop the concept investigated in WP34 and 35 devoted to Testing, Validation and Certification and respectively on Test Specification and architecture, then Implementation and Certification.

20.2.1. Contributions to the development of a HIL testbed for the evaluation of GNSS-based solution impact in an ERTMS testbed

As the performance of satellite-based positioning solutions varies over time and space, it is not possible to exhaustively demonstrate the performance of an on-board solution through long and costly test campaigns. Instead, this variety of scenarios can be carried out on a test bench, equipped with tools for simulating realistic signal reception conditions and sensor errors. However, today, no realistic models of these errors exist for railway environments. The challenge here is then to model them considering variations of the track surroundings and satellite positions in time.
GNSS errors are classically divided into global and local errors. Global errors are created by propagation through the atmosphere and by the system itself (orbit, clock, etc.). They are generally known and modelled, which means they can be at least partially corrected. Commercial signal simulators incorporate them. Local errors are, by definition, closely linked to the propagation environment close to the receiver and its antenna. They are therefore difficult to model. To illustrate this difficulty, let's take the example of the urban environment, widely covered in the literature due to the number of users and applications that are useful there. Signal propagation in a very dense urban environment, such as US or Japanese business districts, will differ from conventional European city centres, due to differences in building heights, street widths, presence or absence of vegetation, etc. In the Gate4Rail project, initial error models have been specifically defined for the railway environment, based on measurement campaigns [Gate4rail, 2020]. A few representative environments have been proposed (open sky, urban, forest), as well as the crossing of a few special features such as bridges and tunnels. However, these models are limited. They represent only partially the conditions encountered and are variable over time [Kazim, 2021].
With the development of Machine Learning techniques, the possibility of characterizing and classifying the receiving environment from GNSS observations appears to be interesting to characterize a line. These tools have been tested on the classification of indoor/outdoor or urban/open-sky environments [Gao, 2018], sometimes adding classes for trees and urban canyons [Feriol, 2022]. Limitations of these studies are: the learning databases are limited and unrepresentative of the railway environment; the number and choice of environment classes are also unsuitable. Finally, the error modelling step for each of the classes does not exist. Using railway data, [Tan, 2019] chose to classify environments along a Qinghai-Tibet line into three classes based on a visibility criterion: open sky/partial occlusion/severe occlusion. [Sun, 2022] uses classes closer to those of Gate4rail: open sky/urban/bridge/tunnel, based on a fairly short database acquired at the experimental site of the Beijing Academy of Railway Sciences. None of these models currently includes suburban environments, or the edges of wooded lines, for example.

20.2.2. Simulation chain

SNCF-CIM maintains an ERTMS testbed in which hard or software solutions can be tested. Our aim is to allow GNSS-based solutions to be inserted in this chain as illustrated on Figure 20.1. The Stella NGC Suite developed by M3Systems is the first element of the chain, capable of generating multi-constellation and multi-frequency GNSS signals along any scenario. A hardware GNSS-based solution shall then be interfaced with the simulator and feed the ERTMS chain with a localisation information. The goal of the work presented in this paper is to allow the Stella Suite to add specific local errors as representative GNSS pseudo-range errors before use by the GNSS receiver.
In order to assess the methodology, in a further step, one will compare real data with simulation, injecting local pseudo-range errors according to representation of the environment as represented in Figure 20.2.

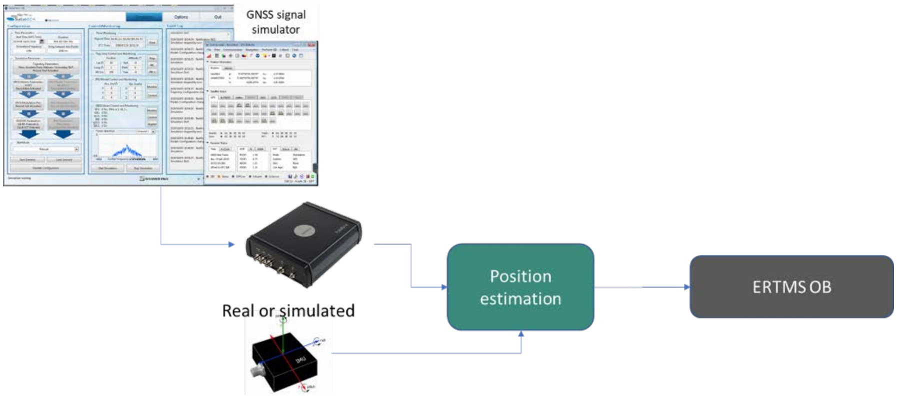

Figure 20.1 Schematic representation of the testing process

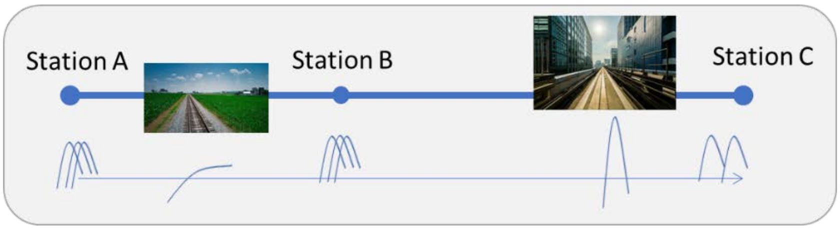

Figure 20.2 Local error simulation along a railway line according to the environment type detection

The first investigations done for the R2DATO project consist in:

- Proposing a data-driven context detection model
- Associating error models to each of the types of environments.

20.2.3. Data-driven context detection

The objective of environment classification can be twofold:

- Identify environment with semantic similarities: urban areas, streets, track with trees...
- Or identify environments with GNSS similarities: satellite visibility, pseudo-range errors...

First category is more intuitive as an operator can easily replay or describe environment and determine a series of environments encountered along a line from station A to station B. Second one may be more relevant from a GNSS view as literature still shows that “urban” for example cannot be described by a single error model anywhere on the globe.
Three main categories of features can be found in the literature for environmental classification context: signal quality variables, based on the C/N0; Constellation characterization such as satellite positions or number of satellites; pseudoranges (satellite-to-receiver distance measurements).
Our models have been trained based on several datasets. These datasets must fulfil several requirements:

- to represent train movements with multiple speeds;
- to be taken from different environment, with maximum variability: urban, open-sky, with or without trees...;
- the environments must have enough continuity (the train should spend enough time in each environment);
- to have the possibility to identify the environment a posteriori.

The last presented requirement brings the major difficulty. For each time of the train journey, we need to know the environment in which the receiver evolved. A simple solution would be to have a human operator labelling the journey from the train during the acquisition. For previously recorded data, it is necessary to use external information. For the CLUG dataset used in our study, several years have passed since the recording campaign. Data are composed of RINEX observation and navigation files, as well as a ground truth file.
A large set of Machine algorithms have been tested and compared. Only an example will be given in the following for illustration purpose. Complete analysis will be published in the coming year.
Primary environment classes are defined when the track is surrounded by a homogeneous environment (both sides of the tracks share the same environmental characteristics): Trees, Buildings, Open-sky (urban), Open-sky (rural), Bridge, Post-bridge, Station, Triage, Tunnel, Post-tunnel. Besides these classes, most of the time the two sides of the tracks do not share the same properties: for instance, one side is full of trees, and the other one is totally empty. In this situation, we define secondary classes, which are mixing of the previous ones: Mixed trees and open-sky, Mixed trees and buildings, Mixed buildings and open-sky.

20.2.4. Machine Learning process for environment separation

20.2.4.1 Machine learning general principle

The Machine Learning paradigm allows the development of complex models to perform the classification task. Starting from a large set of data with labels, the algorithm is trained to recognize this data to perform afterward the inference of the label for new unknown observations. For the GNSS application introduced in this paper, we measure the ability of the trained algorithm to distinguish between the multiple environments based on the GNSS sensor measurements only. The higher the scores reached, the better the separation of the data in their relying abstract space.

20.2.4.2 Illustration on a train journey between Fenouillet and Foix

Our exercise data consist in a two hours GNSS recording (sampling frequency of1 Hz), giving 7000 timestamps observations, based on a train commercial train journey between Fenouillet and Foix (South of France), as illustrated in Figure 20.3. From these points, a manual labelling has been performed, using external sources of information for classification of the environment. For the identification of areas with buildings, Google Earth has been employed. For the vegetation, the infrared satellite images are used (publicly available on the French national Geoportail website [Geoportail]). Many timestamps were attributed to mixed environment (for instance with two different environments: building from one trackside and open-sky from the other one). Among the 7000 observations, only 3000 could be attributed to clear environments (train station, forest, buildings or opens-sky). Due to stopping intervals of the train, the observations belonging to the class train station are nearly 2000. The features computed from the observation and given to the algorithm were the statistics (mean, minimum, maximum, variances, skewness and kurtosis) of the signal characteristics for each constellation and each frequency band, alongside geometric information and number of visible satellites. The training dataset (to train the algorithms) consists in 2000 observations. The remaining 1000 observations are kept, forming the test dataset, used for the assessment of the trained algorithms performances. For multiclass problem, a simple inspection criterion is the confusion matrix, which compare the true and the predicted labels (a perfect classification algorithm would have all the counting on its diagonal).

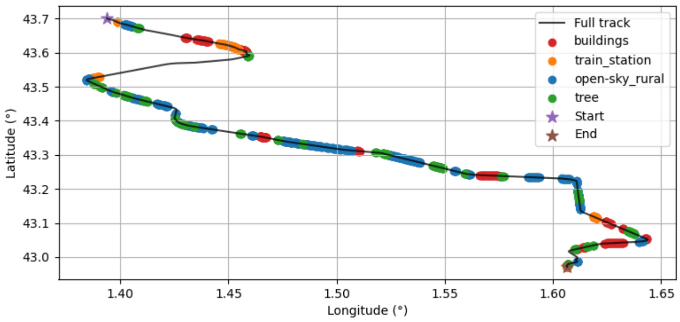

Figure 20.3 Train path from the CLUG project

20.2.4.3 Machine learning models: strengths and limitations

To investigate the complexity of the problem, two majors machine learning models have been employed: a linear one and a complex non-linear one. These models will provide information about the data distribution and the possible robustness of the results. In the context of machine learning, increasing the complexity of a model can bring dangerous issues, such as overfitting, which results in a model with poor generalization performances.
As a first experimentation, a linear algorithm is employed: a multi-class logistic regression (MLR) [Bishop, 2009] model. This algorithm is employed for its interpretability power, and the statistical interpretations induced by its learned parameters. To prevent overfitting, a L2 penalization is employed, whose hyperparameters are tuned by a 5-fold cross validation on the training dataset. In the case of GNSS data coming from the CLUG dataset, the MLR succeeded in identifying several environments with ease but failed for several ones, see the confusion matrix in fig. 4 (left part). This phenomenon highlights the limitations of the linear assumption. Separation between several environments is not perfect, here between the open-sky and the forest (tree) environments. This could indicate that in railways application, the vegetation around the track does not disturb necessarily the propagation of the signal. This inspection should be theoretically performed at different periods of the year to sustain this hypothesis.
To fully explore the possible performances accessible by a powerful machine learning technique, the XGBoost algorithm [Chen, 2016] has been tested. This model, from the family of Gradient Boosting algorithms, is able to learn a complex non-linear separation rule, at the cost of less interpretable parameters and structure. Its empirical accuracy allows a fast estimation of the maximum performances bound, see the confusion matrix in Figure 20.4 (right part). The accuracy of this model is clearly superior to the previous one. This experiment shows the difficulty of the representation of environments. Various sources of information should be included to improve the separations: images from cameras, internet exchanges, or specific maps of the ground.

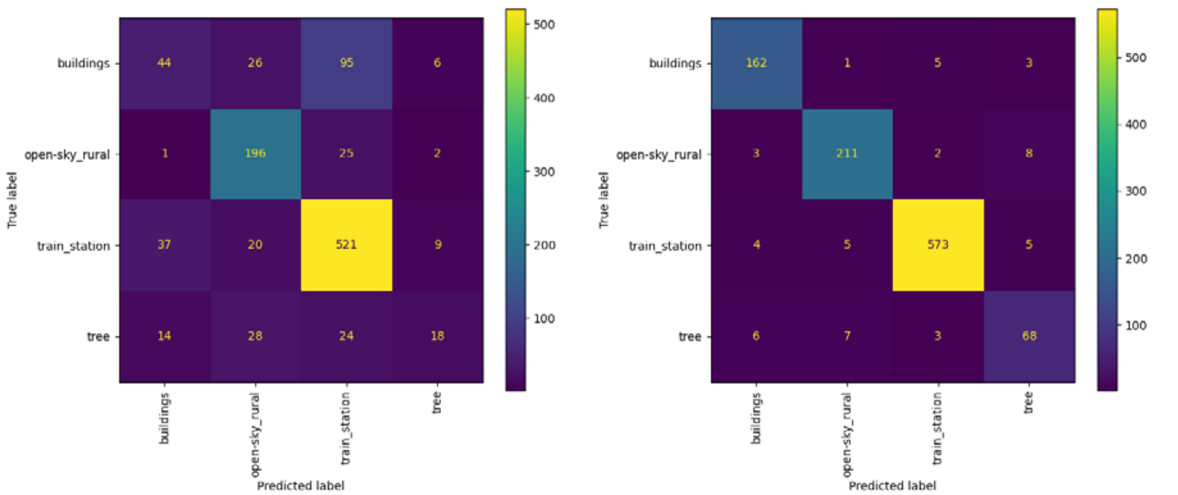

Figure 20.4 Confusion matrix for Multi-class Logistic Regression (left) and XGBoost (right)

The two aforementioned models are inspected after the training phase. Statistical indicators, as the SHAP value, allows the identification of the most important variables for environment separation. Among them, we discover the calculation of the ionospheric bias (therefore non-linear transformation of the elevation) and the direct minimums of RINEX observation (the statistical transformations seem not to have a high weight in the classification of environments). The other features should however not directly be removed, since the interaction between features is complex to model and their influence on the classification difficult to assess in the non-linear modelling. A general idea of the classification process is to learn the conditions of the environment. We do not want the algorithm to learn the spatial information (locations of the environments). The generalization property is indeed needed to perform classification in other areas.

20.2.5. Error models

The generation of a realistic local error (multipath and noise error) requires a proper knowledge of the true location of the train at each time step. This information is accessible in the CLUG dataset. From each pseudorange R_i, the following are sequentially removed: the geometric range ρ_i, the receiver δt_{rcv} and satellite clock offset δt^{sat} (and relativistic correction), the instrumental, Ionospheric I_i and Tropospheric delays Tr. Each frequency band is process independently, and the Klobuchar ionospheric model used as a standard approximation of the Ionospheric delay. The remaining quantity ε_i is considered as the error to be later reproduced.

$$R_i = \rho_i + c(\delta t_{rcv} - \delta t^{sat}) + Tr + I_i + \varepsilon_i$$

The simulation we introduce is based on a stochastic model, which assumes temporal independence between errors. A Gaussian assumption of this error allows an easy parametrization of this stochastic model. The simulation therefore involves only the generation of independent samples from the Normal distribution. However, since we expect higher errors for low elevations satellites, instead of removing the related observation, this article uses a robust estimator for the parameters of the Gaussian distributions, the Minimum Covariance Determinant [Rousseeuw, 1999]. As example on the local errors calculated for the GPS satellites in the L1 frequency band is displayed in Figure 20.5Figure 20.5 Local errors distributions for GPS satellites (L1) and fitted Gaussian laws. The robust estimator has a narrower variance than the classical estimators (empirical means and covariances): 7.7 m^2 instead of 19 m^2, since it is less biased by outlier or abnormal values.

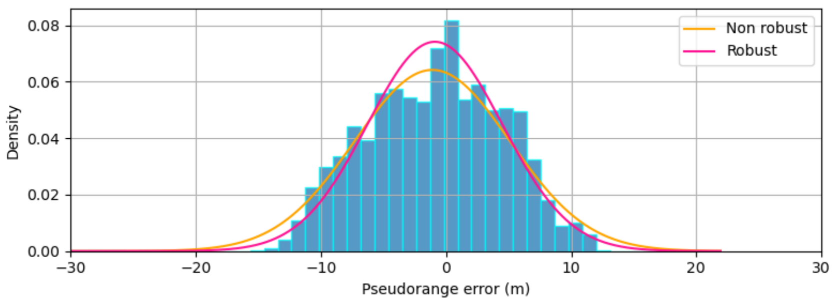

Figure 20.5 Local errors distributions for GPS satellites (L1) and fitted Gaussian laws

In the future, these models will be calculated for each environment, based on the empirical train journeys. Other quantities, such as those provided by the Code-Minus-Carrier method, could also be used instead of the single pseudoranges to provide more reliable estimates.

20.3. Perspectives

The work presented in this paper intends to continue the first concepts for GNSS-based solution evaluation in an ERTMS testbed initiated in the Gate4Rail project. The work is performed in a collaborative way with the CIM-SNCF, M3Systems and Railenium in order to add specific GNSS local errors in rail to the ERTMS testbed maintained by the CIM.
The concept is now in a proof-of-concept phase where the goal is to evaluate how realistic such a data-driven error model can be and if it can be used for performance demonstration and later safety evaluation. The different tasks in progress are: choice of the ML algorithm and its parameters in order to provide the best model; error generation along a railway run for simulation and evaluation; comparison analysis.

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List of Abbreviations

ERTMS: European Rail Traffic Management System
FP2: Flagship Project 2
GNSS: Global Navigation Satellite System
MLR: Multi-class Logistic Regression

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102001. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

21. Increase Safety in Regional Networks with Decentralization – The Autonomous Route Setting Approach

Arne Lamm, DLR, Francisco Parrilla Ayuso, INDRA, Paula Díaz Serrano, INDRA

21.1. Introduction

The rail sector is in change to improve efficiency by increasing the number of trains traveling over certain distances in less time. However, this push for efficiency comes with significant risks, particularly in safety-critical tasks that are performed manually, which increases the likelihood of human error. To mitigate these risks, the use of assistance systems is recommended, especially in regional areas where control centers oversee larger regions and cannot monitor every event with equal precision.
The main challenge is to provide support that enhances safety without interfering with the workers' tasks. One of the most critical areas where support can be provided is in route setting [1, 2]. However, centralized planning for large areas presents difficulties, especially when systems need to dynamically adjust train routes due to delays, disruptions, or to resolve potential conflicts. The complexity lies in managing future track capacities without compromising safety while ensuring a continuous flow of trains.
To address this challenge, the Europe's Rail project R2DATO aims to develop innovative approaches to achieve the goal of full automation and autonomy in rail operations. The authors propose an Autonomous Route Setting (AnRS) approach, which resolves potential conflicts in a decentralized manner, with each switch making decisions independently. If necessary, these switches can communicate with other AnRS systems in the area to effectively resolve complex conflicts. A key advantage of this approach is that it can be integrated into the existing infrastructure without requiring changes to current systems and interfaces.
In this extended abstract, the authors will introduce dependent systems, relevant roles, and then discuss the differences between automatic and autonomous route setting. They will explore the concept of autonomy, defining the criteria that characterize an autonomous system. The abstract will also summarizes anomaly detection to protect server infrastructure from unauthorized access and demonstrate how this concept can be applied to the railway sector. Finally the authors will derive the architecture for the AnRS system, explain its functionality, and show how this system could be demonstrate and tested. The abstract will close with an outlook on the next steps in its development.

21.2. Fundamentals

In the following the authors will described the systems that are directly related and associated with the AnRS approach. This chapter will describe the basics for understanding the AnRS functionality, how it can be embedded into the existing infrastructure and how it can be differed from the Automatic Route Setting (ARS). Further it will be explained how autonomy is defined and how this concept can be applied to the railway domain.

21.2.1. Traffic Management System and Automatic Route Setting

Rail networks in general have centralized control centers where signalers or computer systems manage train movements (see Figure 1). One central system is the Traffic Management System (TMS). The core components of a TMS can be broadly categorized into different key areas. Firstly, train scheduling and timetabling form the foundation, where the system plans and manages the schedules of trains, optimizing the allocation of train paths and timings to balance demand and infrastructure capacity [3–5]. This involves advanced planning tools and algorithms to ensure efficient use of tracks and minimize potential conflicts. Several control systems, communicating with trackside equipment such as signals and switches. This communication is essential for coordinating the setting of routes and ensuring that the track layout aligns with operational requirements [6, 7]. Integration with train control systems is paramount, allowing for seamless coordination between the infrastructure and trains. The system continuously monitors train positions, adjusting routes in real-time to accommodate changes in schedules, unexpected delays, or other operational factors.

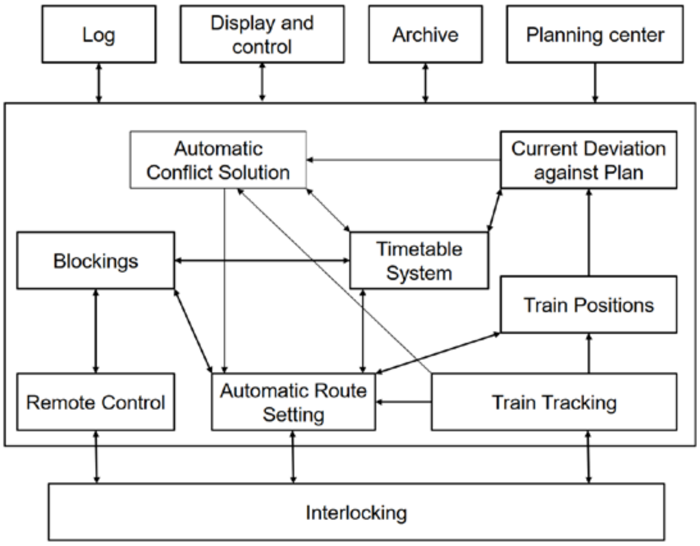

Figure 21.1 Overview exemplary architecture of a fully automated railway system [5]

Security measures are incorporated to prevent unauthorized access or tampering, emphasizing the importance of maintaining the integrity and safety of rail operations. Redundancy is also a key consideration, ensuring reliability by implementing backup mechanisms in case of system failures.
The ARS as one building block follows more of a rule-based approach in order to automate the setting of the track. This technology automates the process of determining and setting the optimal route for a train, considering factors such as the trains destination, schedule, and the current state of the rail network. The implementation of ARS plays a significant role in streamlining operations, reducing delays, and ensuring a more responsive and adaptive rail infrastructure [8]. It is a sophisticated technology integrated into rail signaling and control systems. Its primary objective is to automate the decision-making process related to route selection for trains, minimizing human intervention and optimizing the use of rail network resources [7]. However, the decision-making authority and responsibility still lies with the human being. This means that the ARS draws on existing information that is made available to the ARS and executes decisions automatically according to predefined rules. Accordingly, the ARS does not claim to be a safety-critical system, but rather to take over manual process sequences and thus relieve the signaler. The general principle is as follows. based on a timetable server, the points are triggered if the train position and timetable match. Otherwise, a warning or enquiry is communicated to the signaler via a human-machine interface (HMI) in order to resolve the conflict situation manually. The ARS can thus be embedded in the TMS as a supplement. This is intended to reduce the workload of the signaler. This process is therefore automated if no incidents or conflicts arise [9].

21.2.2. Criterias of Autonomous Systems

Planning tasks within the transport sector can be generalized across various domains and categorized into three levels [10]:

- Strategic level
- Operational level
- Control level

Strategic planning involves long-term tasks, such as network expansion and long-term timetable development. At the operational level, tasks are further divided into short-term planning and operations command [3]. In the rail sector, the control level is often referred to as the management or field level [3]. These tasks are not necessarily assigned to specific individuals but are instead associated with roles, allowing them to be distributed as needed.
At the operational level, key tasks include timetable creation, train composition, and infrastructure planning, with activities centered around disposition. These have a medium-term planning horizon. At the control level, tasks focus on train dispatching and the management of interlocking systems (both internal and external), which have a shorter planning horizon [3]. The core objective of the presented research result was to develop an innovative solution for the railway sector that aligns with the concept of autonomy, with route setting being a function that spans all levels mentioned.
Autonomy in the transport sector encompasses three key criteria [11, 12]:

1. Adaptability: The system is provided with a goal without detailed instructions on the process, allowing it to operate in changing environments with uncertain conditions. Autonomous systems are highly adaptable, modifying their behavior based on real-time data and learning from experience, unlike automatic systems that strictly follow predefined rules.
2. Independence: External intervention is not necessarily required, as autonomous systems are designed to function independently for extended periods with minimal human involvement. Automatic systems, by contrast, usually require regular oversight and intervention, particularly in unusual situations.
3. Decision-Making: Autonomous systems are capable of continuous learning and making decisions to achieve their objectives, even in unforeseen circumstances. In contrast, automatic systems are limited to executing predetermined instructions without the capacity for complex decision-making.

These criteria's highlight the key distinctions between automatic and autonomous systems, particularly in terms of independence, adaptability, and decision-making. Autonomous systems offer greater flexibility and reliability, raising important considerations around security, reliability, and trustworthiness. While both types involve automation, the level of human oversight and the system's ability to adapt and learn are the defining factors.

21.3. Autonomous Route Setting Architecture

To better understand and categorize the concept of autonomy, let's first explore the use case of anomaly detection in safety-critical infrastructure, such as server environments. Autonomous anomaly detection in these environments helps prevent hacker attacks by continuously monitoring and analyzing various data sources, including network traffic, system logs, application logs, and user behavior. The system begins by collecting this data to establish a baseline of normal activity through historical analysis. Once the baseline is defined, the system continuously monitors real-time data, comparing current activities against these established norms. Using statistical methods and machine learning algorithms, it detects any deviations from typical behavior. When an anomaly is identified, such as multiple failed login attempts or unusual network traffic patterns, the system flags the issue and alerts administrators [13–15].
In response to detected threats, the system can automatically implement risk mitigation measures, such as blocking suspicious IP addresses or isolating compromised servers to prevent further damage. The system also evolves over time by updating its models with new data and feedback, improving its ability to detect and respond to emerging threats. This proactive approach ensures that potential security threats are quickly identified and addressed, reducing the likelihood of successful cyberattacks [15].
In summary, the system operates without a precisely defined goal but learns to identify unwanted access attempts and makes decisions autonomously, without human intervention.
Several parallels can be drawn between the railroad domain and computer networks. Both involve systematically guiding and routing traffic, with critical nodes where reactive decisions must be made. In both contexts, there are established protocols for finding the optimal route to the destination, whether that be a server in a network or a station in a rail system.

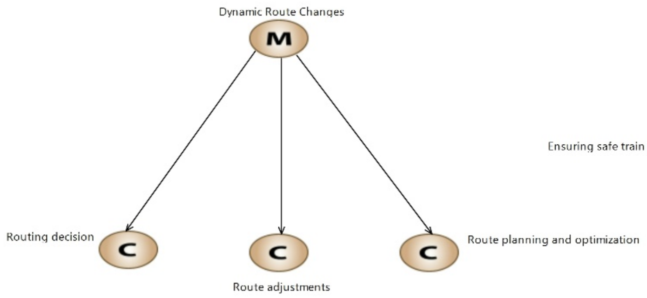

Figure 21.2 [MCB] AnRS Capabilities

The authors derived from these needs or aspects the following capabilities and missions that a route setting system should fulfill and defined the conditions for the AnRS. The authors made a system analysis, to describe the missions of Dynamic Route Changing and Conflict Resolution, identifying specific sub-capabilities that contribute to effective problem-solving. Dynamic Route Changing involves determining new routes (decision-making), adapting to changes, and permanently planning and optimizing routes under dynamic conditions. For Conflict Resolution, the key aspects include identifying conflicts, resolving them, coordinating actions, and ensuring safe train movements. During this analysis, it became evident that the distribution of tasks and the responsible actors can be distinctly separated between these two missions. Conflict Resolution primarily falls under the train dispatcher's responsibility, while Dynamic Route Changing is more within the train driver's domain.

The primary focus of the AnRS concept was ensuring that the system could seamlessly integrate with existing infrastructure and interlocking interfaces. This guarantees that the new system can be smoothly incorporated into current operations without causing disruptions. The concept also includes an operational analysis, which features scenario planning and a demonstration case study. This case study provides a practical example of the AnRS system in action, showcasing how the proposed solution functions in a real-world environment. The overall assumption is, that the decentralized AnRS system, trains and trackside equipment (such as switches and signals) communicate directly with each other to determine the best routes through a section of track. The system would operate on the basis of learned patterns that allow each component to make decisions based on real-time conditions.

Figure 2 shows a possible high-level integration of the AnRS into the existing traffic management infrastructure. The aim is to concentrate the decision-making processes and to place the AnRS as middleware between traffic management and interlocking for one specific coordination area. The coordination and cooperation on a macroscopic level will be realized as a distributed, decentralized system that enables greater flexibility and scalability. One challenge is to use the existing interfaces and continue to operate them unchanged. In doing so, the authors realize that two additional components are also required. An environment capturing unit and an information management system that ensures the correctness of the underlying database.

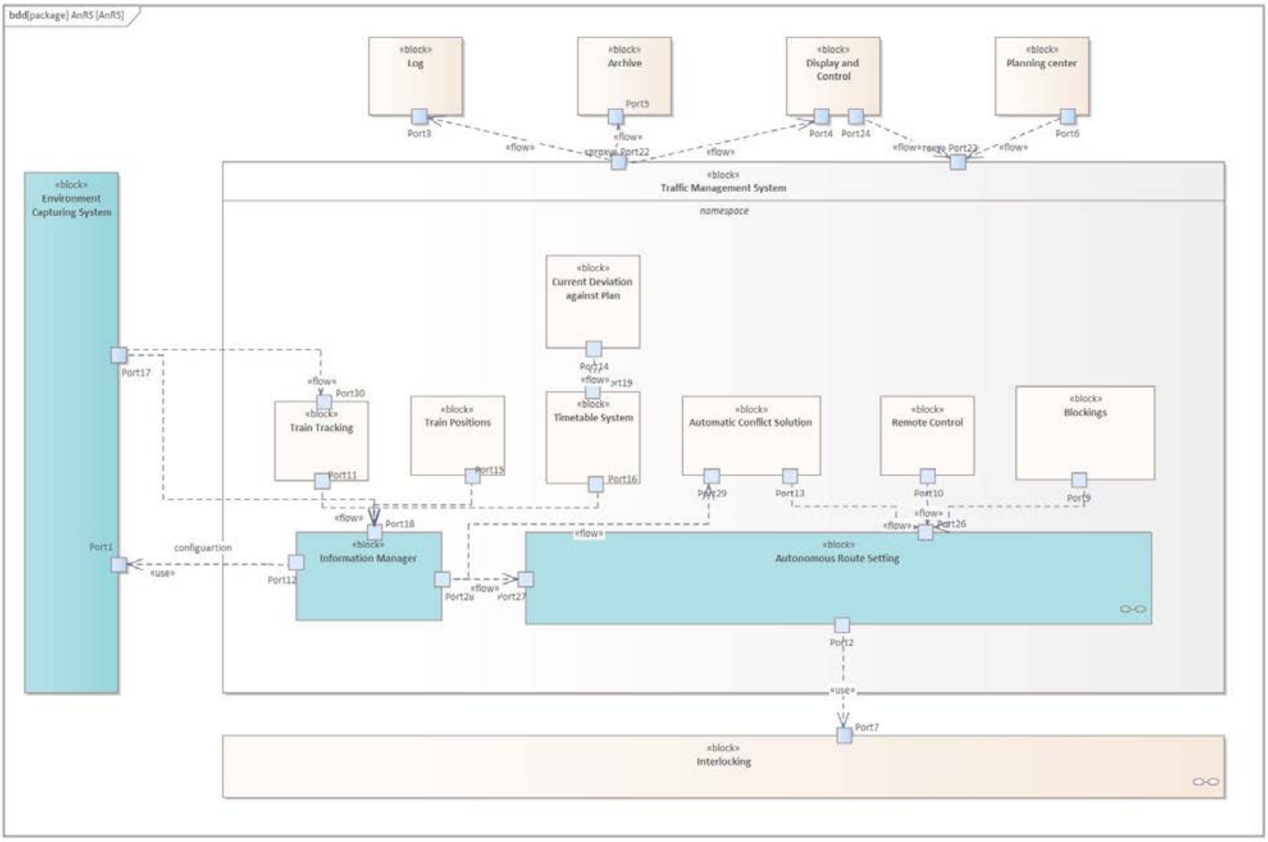

Figure 21.3 Draft overview about the AnRS integration into a fully automated railway system

Another challenge of this approach is in decentralized traffic management. In situations where no centralized control system along the line exists, each AnRS unit communicates directly with others at the edge, collaboratively establishing routes based on predefined Real Timetable Plan (RTTP) guidelines. This decentralized approach fosters agility and adaptability, allowing trains to navigate complex network configurations with ease. The integration of AnRS with RTTP also opens up opportunities for future advancements in rail transportation. By leveraging technologies such as artificial intelligence and machine learning, the system can continuously optimize routes, considering factors such as traffic patterns, weather conditions, and infrastructure capacity. This predictive capability not only improves efficiency but also enhances safety by proactively mitigating risks.
A significant advantage of the AnRS is its compatibility with existing infrastructure. By adhering to established interfaces and standards, the system can be seamlessly integrated into current setups, making it ideal for retrofitting projects—a point also considered in the concept. The integration of AI, as mentioned in the introduction, plays a crucial role in automate the decision-making within the AnRS approach. This technology enables the system to process real-time observation data, make adaptive decisions, and contribute to the overall efficiency and safety of railway operations.

21.4. Evaluation

The concept evaluation was conducted in two phases. First, the authors derived two use cases from accident reports to describe the AnRS function. Then, the authors present a setup on how the AnRS can be tested and integrated into the existing INDRA lab environment to demonstrate compatibility with current infrastructure.

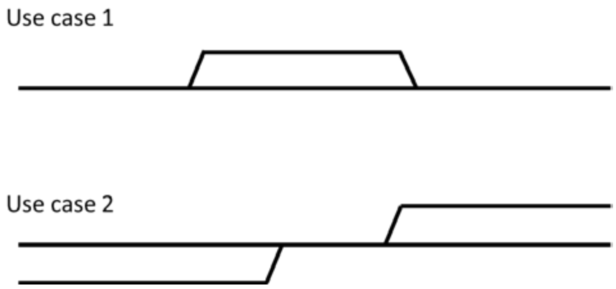

Figure 21.4 Track network of derived use cases for the concept evaluation

Use Case 1 – Passing Loop:
In a decentralized system, trains and trackside equipment communicate directly to determine optimal routes. For a single-track railway with passing loops, the system evaluates train positions and speeds to prevent collisions. It prioritizes the closest or most critical train and sets switches accordingly. If communication fails, the system defaults to a fail-safe mode, coordinating with other systems to maintain safety. This decentralized approach improves flexibility and efficiency, though reliable communication and rigorous testing are essential.

Use Case 2 – Rail Junctions:
At a rail junction where multiple tracks converge, a decentralized AnRS system manages train movements based on real-time data. The system prioritizes trains and sets switches to ensure safe passage. For complex scenarios, such as major interchanges with multiple levels, the system could coordinate both horizontal and vertical train movements. This decentralized control improves traffic flow and minimizes disruptions by optimizing decisions based on local and global cost functions.

Lab Demonstration
In figure 5 the planned demonstration and evaluation setup is designed. To show that the AnRS as a decentralized system could work, the authors planning to embed the system into a realistic simulation environment and connect it to the existing interfaces and show the approach based on the described use cases and scenarios. For the evaluation the authors have defined the following requirements to the simulation specially to perform verification and validation tasks to ensure the simulation accurately reflects real-world conditions and rigorously tests the system.

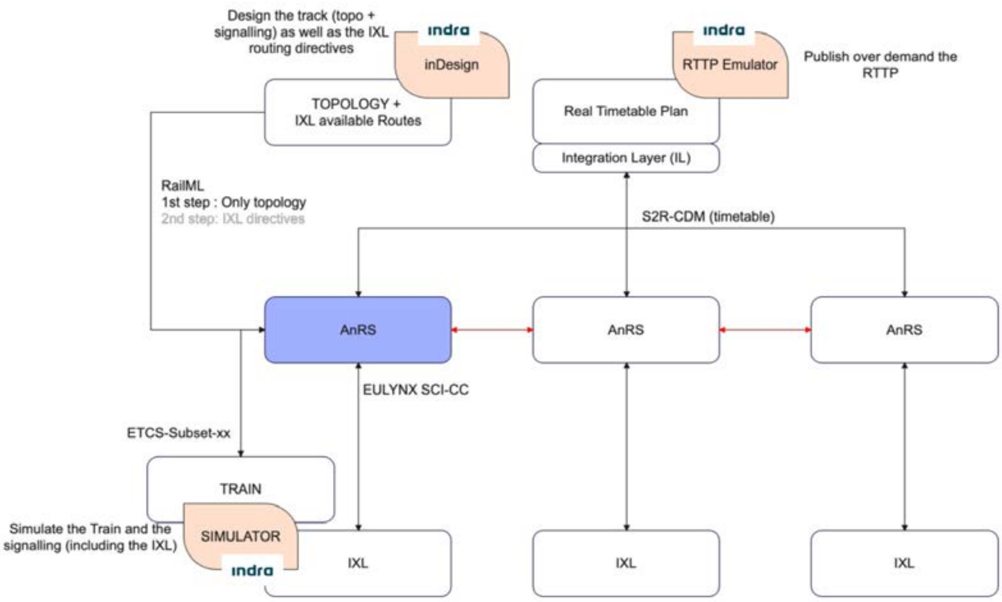

Figure 21.5 Planned Test setup for AnRS Concept - LAB Environment

21.5. Conclusion

The abstract presented the current results of the concept study for the AnRS approach. In comparison to ARS, which is a centralized system that automatically manages and controls railway routes based on predefined schedules and rules. The AnRS distributes the decision-making process across multiple autonomous nodes. Each AnRS system manages its local environment and cooperates with others to optimize routing. This system is adaptive and can dynamically adjust to changes like delays or track blockages without relying on a central command. ARS relies on pre-programmed logic to determine the best route for a train and typically requires human supervision to handle exceptions or unusual situations. Since ARS is centralized, a failure in the system can affect the entire network. In contrast, AnRS is more scalable and resilient to failures, and it operates with minimal human intervention, often using real-time data to make decisions. The future work focuses on the prototypical implementation of the AnRS approach and integrate the prototype into a realistic simulation environment.

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Funded by the European Union

Europe's Rail

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102001. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

22. Driving the Future of Automatic Train Operation: A Focus on Intelligent Driving Algorithms

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22.1. Introduction

The European Union (EU) has launched the Europe's Rail Joint Undertaking (ERJU) initiative [1], aimed at advancing efficient and environmentally sustainable mobility within rail networks through technological projects such as MOTIONAL [2], R2DATO [3], TRANS4M-R [4], FutuRe [5], among others. The R2DATO project [3], which is grounded in the X2Rail-4 project [6] and adhering to relevant standards such as the Technical Specification for Interoperability – Control Command and Signalling (TSI – CCS) [7], is focused on creating novel solutions. These solutions are designed to enable swift and economical implementation and transition of digital and automatic train operation systems.

As the rail industry moves towards autonomous driving, there is a growing emphasis on implementing Automatic Train Operation (ATO) systems up to Grade of Automation 4 (GoA 4). This transition requires harmonization between current and future rail systems and poses significant challenges in design, operation, technology, and human factors [8]. The Grade of Automation (GoA) defines the level of automation in train operations, specifying the responsibilities of drivers, train staff, or ATO systems [9]. As automation levels increase, so does the complexity of ATO systems. To address these challenges, extensive theoretical research is being conducted to design intelligent solutions that enhancing the driving functions, such as optimize speed profiles, and improve automatic tracking control, in train operations. The development of ATO solutions is an ongoing process that demands thorough theoretical investigation and extensive real-world testing to ensure these systems are both effective and adaptable to the evolving demands of railway transportation.

This work introduces the novel reference architecture for GoA 3/4 systems, developed as part of the X2Rail-4 project [6], incorporating four innovative components aimed at advancing high levels of automation. Among these, the Automatic Driving Module (ADM) stands out, as it integrates several critical functions that enable the automatic operation of trains. A key aspect of these functions is the use of smart algorithms designed to optimize speed profiles and enhance tracking speed control models to meet system requirements. To support this, this work provides a review of the various solutions and techniques employed to tackle the challenges of speed profile optimization and automatic tracking control across different railway systems.

The structure of this paper is as follows: Section II introduces the novel reference architecture developed in the X2Rail-4 project. Section III discusses the smart algorithms for driving functions. Section IV explores the opportunities and challenges faced by ATO systems. Finally, Section V presents the conclusions of this work.

22.2. Novel reference architecture for GoA 3/4 automation level

The R2DATO project [6] [3] is focused on advancing the system requirement specifications (SRS) for Automatic Train Operation (ATO) up to GoA 4, building upon and enhancing the reference architecture initially established in the X2Rail-4 project [6]. This novel architecture represents a significant evolution from the traditional architecture described in SUBSET-125 [10], incorporating both trackside and onboard systems to create a more cohesive and advanced approach to train automation.

In addition, this novel architecture includes both trackside and onboard systems. As illustrated in Figure 22.1, the upper section of the framework is dedicated to trackside components, encompassing the Traffic Management, Train Management, Train Control, Digital Map (DM), Operational Execution (OE), Mission Data (MD), and Train Data (TD).

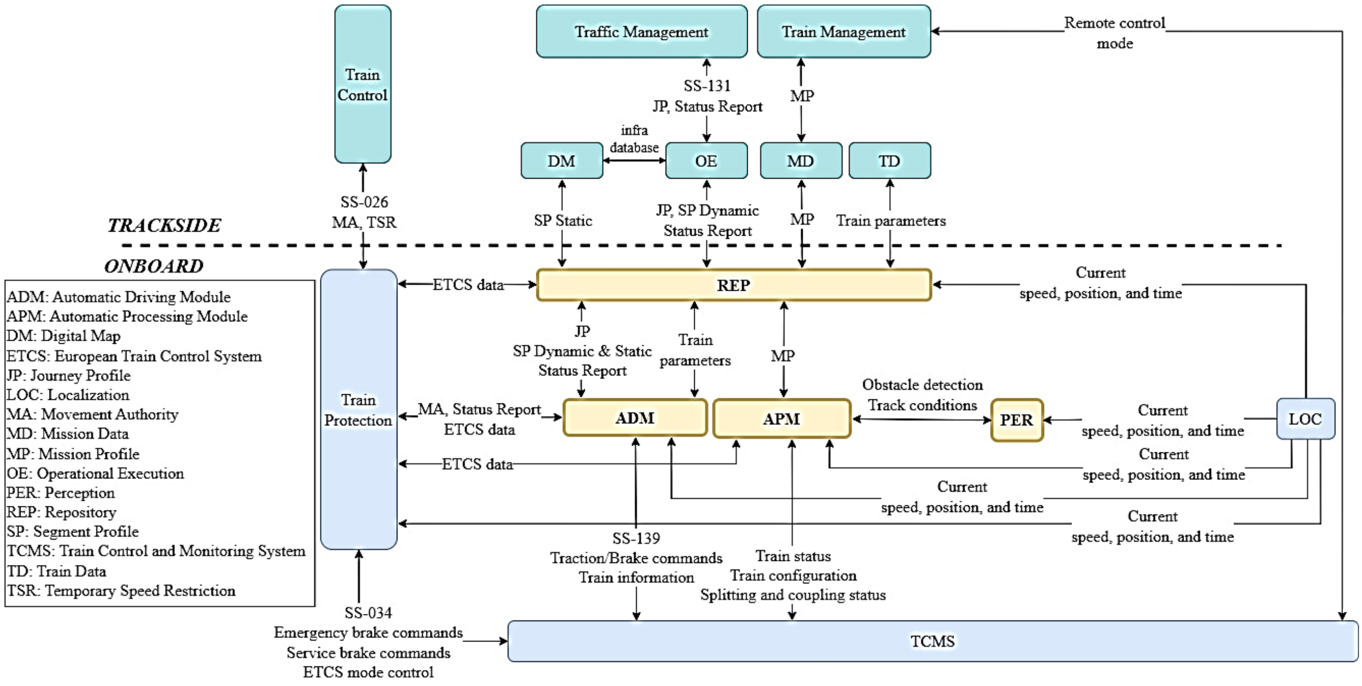

Figure 22.1 ATO up to GoA 4 - Logical reference architecture [11].

Meanwhile, the lower section of the framework focuses on the onboard components, which include the Train Protection, Localization (LOC), Train Control and Monitoring System (TCMS), and four novel GoA 3/4 components, namely Automatic Driving Module (ADM), Automatic Processing Module (APM), Repository (REP), and Perception (PER).

22.2.1. GoA 3/4 components

The new architecture introduces four key components for GoA 3/4 systems, each playing a vital role in enhancing automation capabilities. While the complete details of the other components are available in the Deliverable D5.1 WP5 GoA3/4 Specification document from the X2Rail-4 Project [11], the GoA 3/4 components are described as follows:

22.2.1.1 Perception (PER)

Serving as the "eyes" of the driver in GoA 3/4 systems, the PER module comprises a suite of onboard sensors that evaluate the physical railway environment. This onboard module enhances situational awareness, enabling the detection and recognition of static or dynamic objects, such as obstacles on the tracks or a road vehicle on an unprotected level crossing, that could impact train operations.

22.2.1.2 Automatic Processing Module (APM)

Acting as the "brain" of the driver, the APM module emulates the decision-making responsibilities of human operators, overseeing mission execution, reflexive safety actions, and responses to both train and track incidents.

22.2.1.3 Repository (REP)

This onboard module is designed to collect, check and filter data received from various trackside modules, including the Digital Map (DM), Operational Execution (OE), Mission Data (MD), and Train Data (TD). The REP module then transmits this data to the relevant onboard systems, ensuring that all onboard components operate with the most up-to-date and accurate information.

22.2.1.4 Automatic Driving Module (ADM)

Replacing the traditional ATO Onboard (ATO-OB) system, the ADM is responsible for executing the core driving functions that enable autonomous train operation. According to SUBSET-125 [10], these functions include:

- *Supervised Speed Envelope Management (SSEM)*: This function calculates the maximum permissible speed for the train, ensuring it operates within safe limits without triggering intervention by the European Train Control System (ETCS).
-
- *Automatic Train Stopping Management (ATSM): ATSM manages the speed profile required to stop the train precisely at designated stopping points.*
-
- *Time Table Speed Management (TTSM): TTSM integrates journey and segment profile data to calculate the most energy-efficient speed profile, continuously updating it based on the current position and speed of the train to optimize performance while adhering to infrastructure constraints and timing points.*
-
- *Traction/brake control: This function generates the necessary output commands to realize the tracking of the optimal speed curve, coordinating with SSEM, ATSM, and TTSM to ensure accurate and effective train control.*

22.3. Smart algorithms for driving functions

Considering the substantial advancements in the novel architecture from X2Rail-4 [6], where the ADM has replaced the traditional ATO system but maintain the SRS defined in the SUBSET-125 [10], there are numerous challenges and opportunities within ATO up to GoA 4. Nevertheless, this work specifically addresses smart algorithms due to their indispensable role in fulfilling two critical functions of ATO: optimizing train speed profiles and ensuring precise tracking control. These driving functions collectively meet the operational requirements of automation and efficiency [12].

The importance of smart algorithms in achieving operational efficiency, safety, and energy conservation cannot be omitted. In the complex environment of rail automation, where disturbances and variable conditions frequently occur, the ability to dynamically adjust speed profiles and control strategies through advanced algorithms is essential. By concentrating on these algorithms, we can better understand how to address the specific challenges of speed optimization and tracking control, which are part to the success of the future GoA 3/4 systems.

22.3.1. Speed Profile Optimization Techniques

Speed profile optimization is generally approached as an optimal control problem, utilizing advanced algorithms to determine the most efficient speed profiles for train operation. The literature reveals several techniques employed in this area, each with its unique advantages and challenges.

22.3.1.1 Analytical approaches

The issue of determining the most efficient method for controlling the movement of a train was initially raised by Milroy [13], who obtained a basic velocity profile and suggested it as an optimal strategy by applying the analytical approach known as the Pontryagin maximum principle. Similarly, Asnis [14] examines the various types of optimal trajectories that satisfy the maximum principle. On the other hand, Howlett [15] used the Pontryagin maximum principle to discover the precise optimal strategy for achieving a minimum cost journey.

22.3.1.2 Numerical methods

This type of method has relatively fewer requirements for the objective function and can make a trade-off between optimization performance and computational time [16]. Miyatake [17] introduced three numerical methods (gradient method, dynamic programming, and sequential quadratic problem) to solve the optimal control problem with constraints for finding energy-saving train speed profiles.

On the other hand, the optimal control problem for minimizing energy consumption by a train, as proposed by Ko [18], has been numerically solved using Bellman's Dynamic Programming algorithm within an acceptable computational timeframe. This method can be applied to actual complicated running conditions. Similarly, Thorlund [19] introduced a novel dynamic programming approach to find optimized speed profiles that result in reduced energy consumption.

22.3.1.3 Genetic algorithms

Genetic algorithms (GA) have been effectively utilized in coasting control optimization to determine the optimal train trajectory [20]. In his work, Chang [21] proposed a GA for determining the number of coasting points. The results of this approach demonstrated promising performance in the trade-off between journey time and energy consumption.

Similarly, Wong [22] applied a genetic solution to search for coasting points. The number of coasting points was dynamically allocated into the chromosomes, which enhanced the practical application of this approach. Söylemez [23] proposed a novel method that utilized artificial neural networks and genetic algorithms to optimize coasting points for trains.

22.3.2. Automatic Tracking Control Techniques

Once an optimal speed profile is established, the next challenge is to ensure the train can accurately follow this profile, maintaining safety and operational smoothness. Various control techniques have been explored in the literature to achieve precise tracking control.

22.3.2.1 PID controllers

The most widely used train speed control method of ATO is the PID controller, which continuously calculates the error value between the measured train speed and recommended speed, and adjusts the control command to minimize the speed tracking error over time [24]. The existing challenges in this kind of controller is how to determine the best PID coefficients considering that the parameters of train models are always affected by some external factors in daily operations, such as weather condition, normal deterioration and mechanical wear. These parameters variations will inevitably reduce the performance of PID controller if the PID coefficients are fixed [24].

To address this, some studies are developed novel solutions. One of such is the combination of fuzzy logic with PID control where the parameters of PID controller could be adjusted dynamically so to improve the performance. Ke [25] determined the speed commands of the ATO system by manipulated by the fuzzy-PID gain scheduler under acceleration, deceleration and jerk restrictions. Similarly, Yang [26] proposed a fuzzy-PID solution to meet the performance demand of the freight train control.

22.3.2.2 Sliding Mode Controllers

These controllers are recognized for their high effectiveness in various practical systems, as numerous studies have demonstrated [27], [28], [29]. Incorporating an appropriate nonlinear sliding surface in Sliding Mode Control (SMC) can ensure that the closed-loop system's state converges to a balanced point within a finite time frame [30].

Some studies focus on SMC solutions for automatic tracking control. Wu [31] focused on the control problem of precise and comfortable train operation through the use of adaptive terminal sliding mode control, introducing a novel terminal sliding surface to ensure stability and robustness. Conversely, Yao [32] applied robust adaptive sliding mode control strategies to study the position and velocity tracking control problem of trains.

22.3.2.3 Adaptative Control Methods

The controller in question is employed in high-speed applications where achieving train speed control presents a formidable challenge [12]. This is attributed to the intricate nature of the operation and the rapid dynamics of the train. In this regard, certain studies opt for the implementation of adaptive control techniques to manage the intricacy and uncertainty associated with train operation models. Yang [33] presented a mixed controller, which is synthesized through the use of linear matrix inequalities to attain the objective of speed command tracking. Conversely, Chou [34] proposed an adaptive control system for heavy-haul train applications, which is adaptive to various optimization objectives, including energy consumption, velocity tracking, and in-train force.

22.4. Opportunities and challenges

The escalating demand for railway transport and the constraints of existing infrastructure present a widening gap that necessitates increased research and development in ATO systems. To progress ATO systems, it is imperative to delve into several key research areas that concentrate on devising more sophisticated solutions that bolster safety, efficiency, and adaptability. Future enhancements in ATO systems may involve the creation of advanced algorithmic solutions for optimizing speed and tracking control, integration of real-time data and the perception technologies. While this work focuses on three specific challenges for ATO systems, it is important to acknowledge that there are many more areas requiring attention to fully address the complexities of modern railway operations.

22.4.1. Machine learning for driving functions

Future research should focus on enhancing optimization strategies by incorporating hybrid methods that combine advanced optimization algorithms with machine learning techniques [35]. This approach has the potential to produce superior results in determining optimal train speed profiles. One promising avenue is the application of reinforcement learning, an artificial intelligence technique that trains systems to control environments by maximizing performance over time [36].

Unlike conventional deep learning approaches, which typically depend on pre-existing datasets [37], reinforcement learning employs a process of trial and error to enable systems to learn and make decisions autonomously. This method has been applied in recent studies to address challenges in optimizing train speed profiles and automatic tracking control across different railway systems. To address the speed curve optimization problem for urban metro trains, Yin [38] proposed two intelligent train operation algorithms, one based on an expert system and the other on reinforcement learning (RL).

In contrast, Ning [39] presented a novel train trajectory optimization approach for high-speed railways that utilizes the deep deterministic policy gradient method to generate optimal train trajectories through offline training based on the agent interaction with the trajectory simulation environment. On the other hand, Chen [40] proposed an automatic driving control method for urban rail trains based on the Deep Q Network algorithm.

22.4.2. Integration real-time data

Given that disturbances can arise unexpectedly, it is challenging for ATO systems to adjust timetables and generate new speed profiles in real time [41]. However, integrating real-time data into ATO systems presents a significant opportunity to enhance both safety and efficiency. By dynamically adjusting speed profiles in response to current conditions such as weather, train status, delays, and track conditions; ATO systems can become more responsive, resilient, and better equipped to handle the complexities of modern rail operations [42]. Recent research has extensively addressed the challenges of integrating real-time data into ATO systems. For instance, delays in the Chinese high-speed railway network, caused by issues with rolling stock, pantographs, and catenaries, constitute approximately 20% of total delays [43]. To mitigate these delays, a neural network-based delay prediction model has been developed by Huang [43], which captures the interactions between trains and stations, as well as weather-related factors, to enhance the accuracy of delay forecasts. On the other hand, a model for rescheduling final trains has been proposed by Kang [44], focusing on optimizing timetables by minimizing train running and dwell times, especially in response to operational disruptions.

22.4.3. Perception systems

Integrating advanced perception systems can significantly improve the ability to detect and interpret a wide range of environmental and operational conditions, leading to smoother, safer, and more efficient train operations. This advancement is made possible through the adoption of cutting-edge sensor technologies, sophisticated machine learning algorithms, and robust real-time data processing capabilities. Recent research highlights the critical need to enhance perception systems within the railway sector by exploring innovative technologies.

For instance, Staino [45] developed a deep learning-based approach for detecting and classifying railway signals, which represents a significant step forward in signal recognition. In a different vein, He [46] introduced a novel deep learning-based system for detecting obstacles on rail transit routes. This system improves the accuracy of identifying small and irregular obstacles in real-world rail environments without compromising speed or adding to model complexity.

22.5. Conclusions

The current work highlights a novel reference architecture for GoA3/4 from the X2Rail-4 Project, which comprises four innovative components such as Repository (REP), Perception (PER), Automatic Processing Module (APM), and Automatic Driving Module (ADM). The objective is to bring attention to the capabilities of ATO up to the GoA4 system requirements specification, a subject that has been comprehensively explored in recent years.

Furthermore, this work delved into the operational functions of ATO systems, with a particular focus on methods, approaches, and techniques for addressing train operation challenges. Typically, these challenges are addressed by implementing optimized speed profiles and train speed controllers. The incorporation of smart algorithms, particularly those utilizing artificial intelligence and machine learning, presents a substantial opportunity to improve the accuracy, efficiency, and safety of train operations.

Finally, the future of ATO systems hinges on addressing several key opportunities and challenges. This work highlights three critical areas for future exploration: the enhancement of optimization strategies through machine learning, the integration of real-time data to improve system responsiveness, and the advancement of perception systems to ensure safer and more efficient operations.

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List of Abbreviations

ADM	Automatic Driving Module
APM	Automatic Processing Module
ATO	Automatic Train Operation
ATSM	Automatic Train Stopping Management
CCS	Control Command and
DM	Digital Map
ERJU	European Rail Joint Undertaking
ETCS	European Train Control System
EU	European Union
GA	Genetic Algorithm
GoA	Grade of Automation
LOC	Localization
MD	Mission Data
OE	Operational Execution
PER	Perception

REP	Repository
RL	Reinforcement Learning
SMC	Sliding Mode Control
SRS	System Requirement Specification
SSEM	Supervised Speed Envelope Management
TCMS	Train Control and Monitoring System
TD	Train Data
TTSM	Time Table Speed Management
TSI	Technical Specification for Interoperability

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Funded by the European Union

This project is under the scope of the Europe's Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement nº 101102001. The project is supported by the Europe's Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe's Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

23. **EU-RAIL FP1 / Multimodal Integration** B2B Financial Services as a Key Asset for Rail Integration with Other Mobility Modes

Laurent Bellet (Hitachi Rail RCS France SAS)

23.1. Introduction

The need to develop mobility in urban, sub-urban areas, as well as at state and European levels is ever more demanding; a growing population and people from all walks of life require public and private transportation solutions. The development of railway adoption is key for moving towards sustainable mobility at a large scale. Even if cities and main lines are the most profitable segment for mobility providers, there is a need to provide solutions and connect railway with other mobility modes in rural areas where the car remains the main mode of transportation. Developing efficient and sustainable transport offers is not only a matter of providing more infrastructure, but also of making existing ones more attractive and convenient to use. The potential contribution of the digital transformation to the development of an efficient mobility includes breaking silos between private and public transportation, integration and interoperability of all mobility means, easy and secure payment/validation for mobility, developing convenience and accessibility in mobility hubs and other connecting areas, adapting the delivered service to passenger demand and managing disruptions.

Multimodal integration is not achievable without the cooperation between Mobility Providers. To favour this cooperation, MOTIONAL (eurail-fp1 (europa.eu)) proposes the improvement and development of B2B platforms and services in the areas of Sales, Distribution, Financial services and Traffic information. Key technical features associated with these business objectives include cross-operator and cross-mobility support and the compatibility with SaaS deployment, as well as the usage and enhancement (when applicable) of standards.

23.2. Revenue repartition, a key B2B service for intermodal transport

Status Quo. Referring to sales and distribution in the land passenger transport industry, there are several solutions and standards allowing to manage global and cross selling, especially for railways: TAP-TSI (Telematics Applications for Passenger Service TSI | European Union Agency for Railways (europa.eu)), OSDM (OSDM | Open Sales and Distribution Model) standards and models allow managing cross selling and there is a move to extend mobility modes in scope beyond railways. MaaS platforms provide also such services in the form of a 'one-stop-shop' approach.

However, there are no or limited cross-accounting solutions allowing us to redistribute the revenue collected at retail channels. Even if the use of ledgers can support revenue management, the resulting financial flows are usually not automated and with limited reactivity.

The expected service can be identified as 'Clearing and Settlement'. The general objective is to make the market smoother and more efficient by centralizing financial flows and hence preventing participants from making transfers to each party with which they have transacted.

The following drawing gives an overview of challenges and targets.

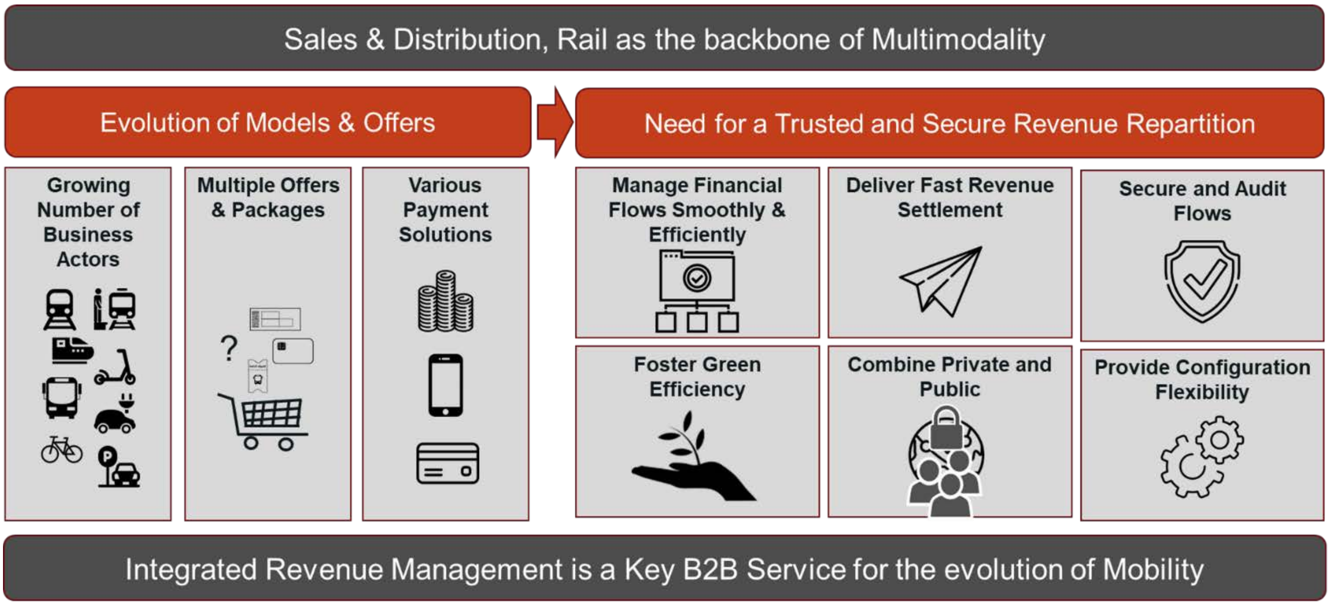


Figure 23.1 Overview of challenges and targets

Clearing and settlement is the general process by which an organization acts as intermediary body between trading parties, apportions the revenues when applicable and settles accounts. This intermediary body is usually called ‘Clearing House’. ‘Clearing Houses’ are commonly used in Stock Market and to promote national and international trade. Even if this is at a smaller scale than trading “Clearing Houses”, mobility may require clearing and settlement functionalities to apportion and settle the revenue between participants.

Apportionment is the business logic for re-distributing the revenue. There can be many rules such as the distribution of the price of an inter-modal product based on agreed percentages (e.g. bus-train pass apportioned at 40% to bus operator and 60% for train operator), dynamic distribution based on the use of the service (i.e. apportionment at the expiration of the product), post-payment apportionment based on distance. Also, there can be fees charged on the paid amounts to reward the Retailers.

The settlement is the transfer of funds between creditor and debtor entities. The frequency of the process is usually adjusted according to the business needs. Frequency should not be too low as to remain fair to all participant cash flow positions but shall not be too high to minimize the administrative work.

The below figure gives a high-level illustration of apportionment and settlement. The blue arrows are elementary apportionments resulting from a booking of from the consumption of the services. Those elementary settlement are then aggregated for settlement.

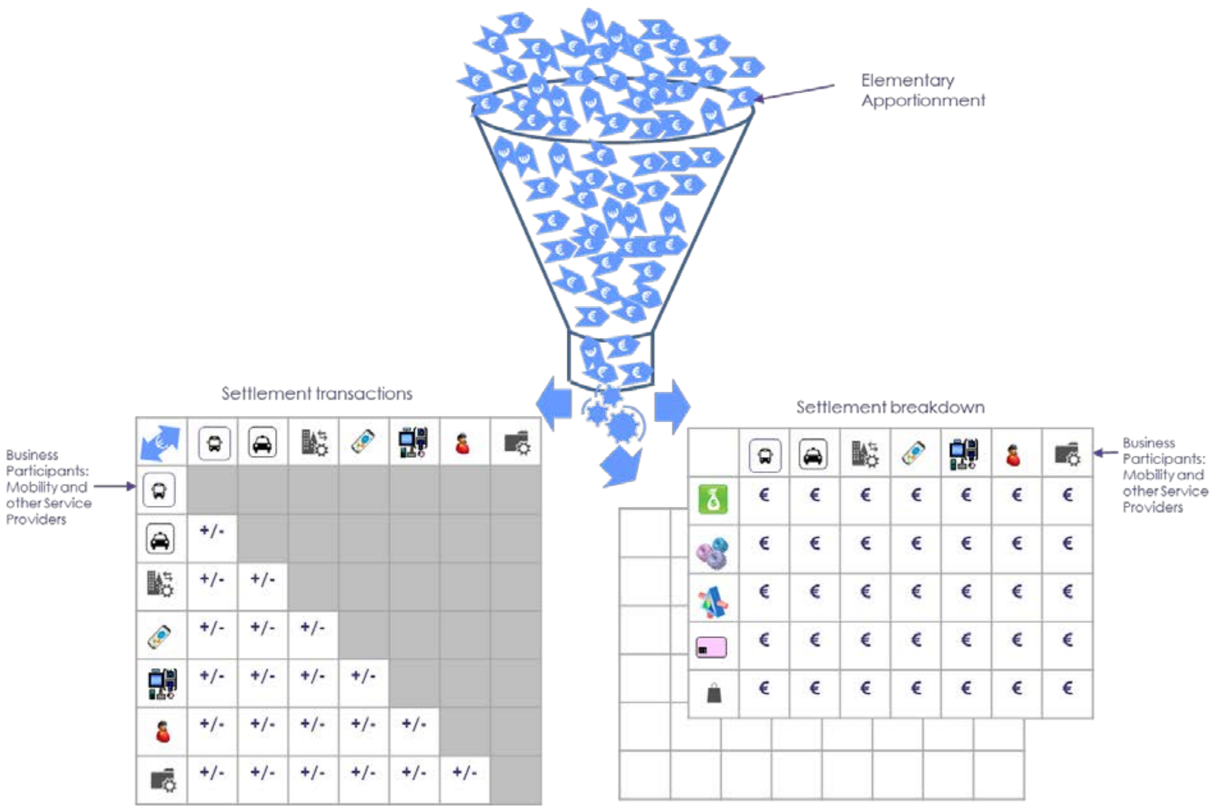


Figure 23.2 Apportionment and Settlement illustration

Apportionment and Settlement is a key feature within the context of multimodal integration. The below figure is a simplistic illustration of the ecosystem.

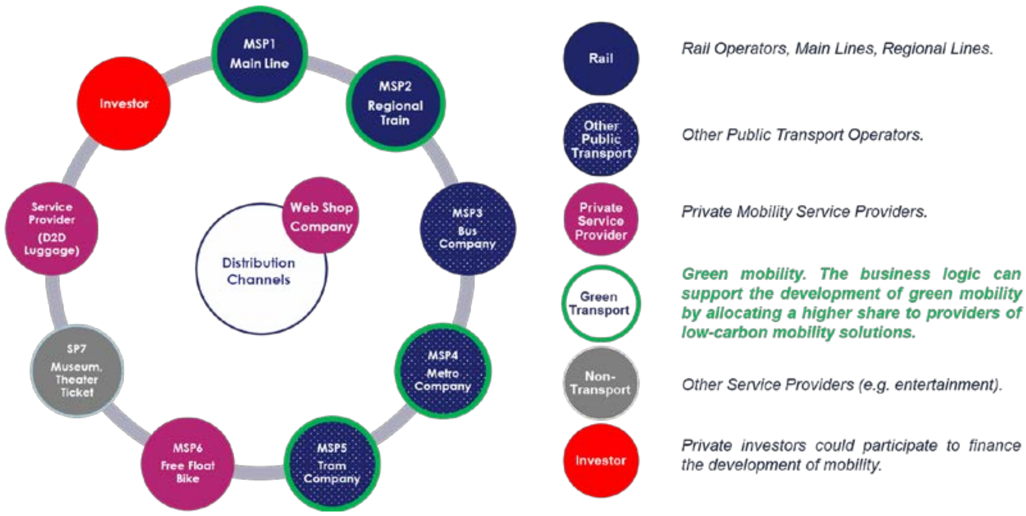


Figure 23.3 Business participants (example)

Public and private mobility providers of many types can join the ecosystem. Inter-operability leads to financial transfers between business players including private and public companies. Also, private investors could be part of the game to finance the development of mobility. And the business logic can help to the development of green mobility by apportioning a higher share to low carbon mobility solution providers.

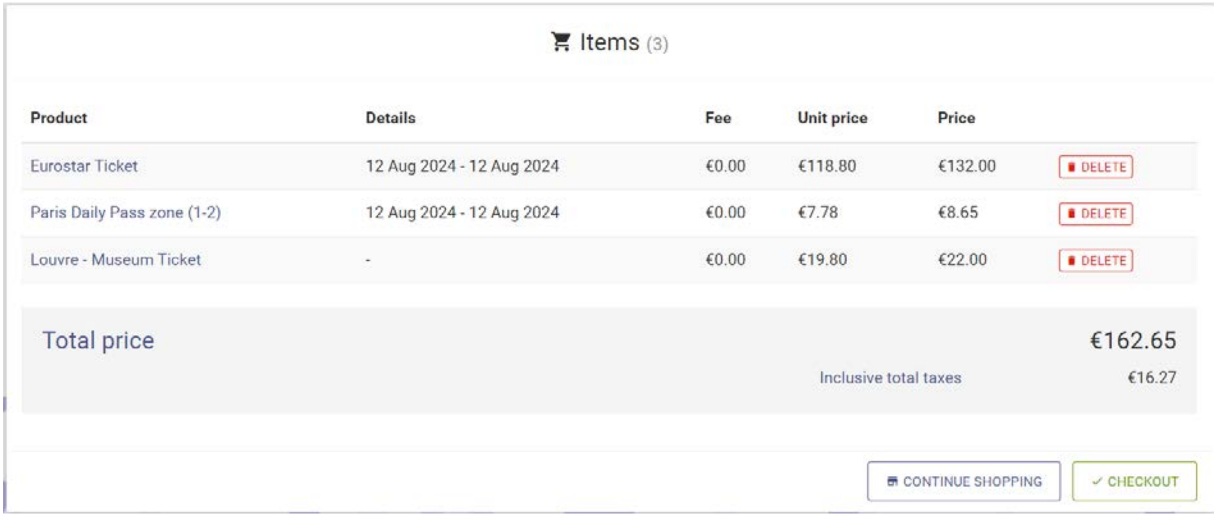
Small private players will surely expect to have the monies they earned settled into their account as soon as possible. Small players are usually managing cash accounting instead of accrual accounting and a delay in settlement would impact their ledger. Therefore, by providing a fast settlement process, the solution will even attract small business players for whom negative cash flow is a serious issue.

23.3. A typical journey

The following shows a test case implemented within the context of MOTIONAL development phase. Note that this is purely simulation.
The scenario consists of the following 'Combo':

- A Eurostar Ticket from Amsterdam to Paris Nord.
- A Paris daily ticket (Zones 1, 2)
- An Adult Museum Ticket

Purchase of Eurostar Ticket, Paris daily pass and Museum ticket is carried out on a Web Shop.



Product	Details	Fee	Unit price	Price	
Eurostar Ticket	12 Aug 2024 - 12 Aug 2024	€0.00	€118.80	€132.00	DELETE
Paris Daily Pass zone (1-2)	12 Aug 2024 - 12 Aug 2024	€0.00	€7.78	€8.65	DELETE
Louvre - Museum Ticket	-	€0.00	€19.80	€22.00	DELETE

Figure 23.1 Cart at the Web Shop

Following the check-out, sales transactions are processed, and the collected amount is apportioned to service providers

	Apportionment context	Apportionment name	Validity end date	Product price
⌄	Product	O/D Thalys	August 12, 2024 11:59 PM	€132.00

Rules

Rule "Commission for retailer and product owner"

Payer account	Payer	Payer role	Amount	Payee role	Payee	Payee account
liabilities	SELECTOUR	Product retailer	€122.76	Product owner	Thalys	liabilities
liabilities	SELECTOUR	Product retailer	€6.60	Product retailer	SELECTOUR	assets
liabilities	SELECTOUR	Product retailer	€2.64	Product owner	Thalys	assets

Liabilities after rule
Thalys
€122.76

	Apportionment context	Apportionment name	Validity end date	Product price
⌄	Product	Navigo Jour - Zone (1-2)	August 12, 2024 11:59 PM	€8.65

Rules

Rule "Commission for retailer and product owner"

Payer account	Payer	Payer role	Amount	Payee role	Payee	Payee account
liabilities	SELECTOUR	Product retailer	€0.43	Product retailer	SELECTOUR	assets
liabilities	SELECTOUR	Product retailer	€0.18	Product owner	IDFM	assets
liabilities	SELECTOUR	Product retailer	€8.04	Product owner	IDFM	liabilities

Liabilities after rule
IDFM
€8.04

	Apportionment context	Apportionment name	Validity end date	Product price
⌄	Product	Louvre - Museum Ticket	August 13, 2024 9:53 AM	€22.00

Rules

Rule "Special le Louvre - Commission for retailer and product owner"

Payer account	Payer	Payer role	Amount	Payee role	Payee	Payee account
liabilities	SELECTOUR	Product retailer	€1.10	Product retailer	SELECTOUR	assets
liabilities	SELECTOUR	Product retailer	€20.90	Product owner	LE LOUVRE	assets

Figure 23.2 Individual Apportionment

Apportionment rules are configurable in this test case, there is a fee attributable to the Retailer (in this test case Selectour).

Then, and typically at the end of the day, there is a settlement between participants resulting in fund transfers. For clarity, there is a unique sale in the settlement here, but in the real world this would include all sales performed during the day.

Settlement movements

Payer account	Payer	Amount	Payee	Payee account
liabilities	SELECTOUR	€20.90	LE LOUVRE	assets
liabilities	SELECTOUR	€8.13	SELECTOUR	assets
liabilities	SELECTOUR	€0.18	IDFM	assets
liabilities	SELECTOUR	€8.04	IDFM	liabilities
liabilities	SELECTOUR	€2.64	Thalys	assets
liabilities	SELECTOUR	€122.76	Thalys	liabilities

Figure 23.3 Settlement

The following screenshot gives an overview of account balances.

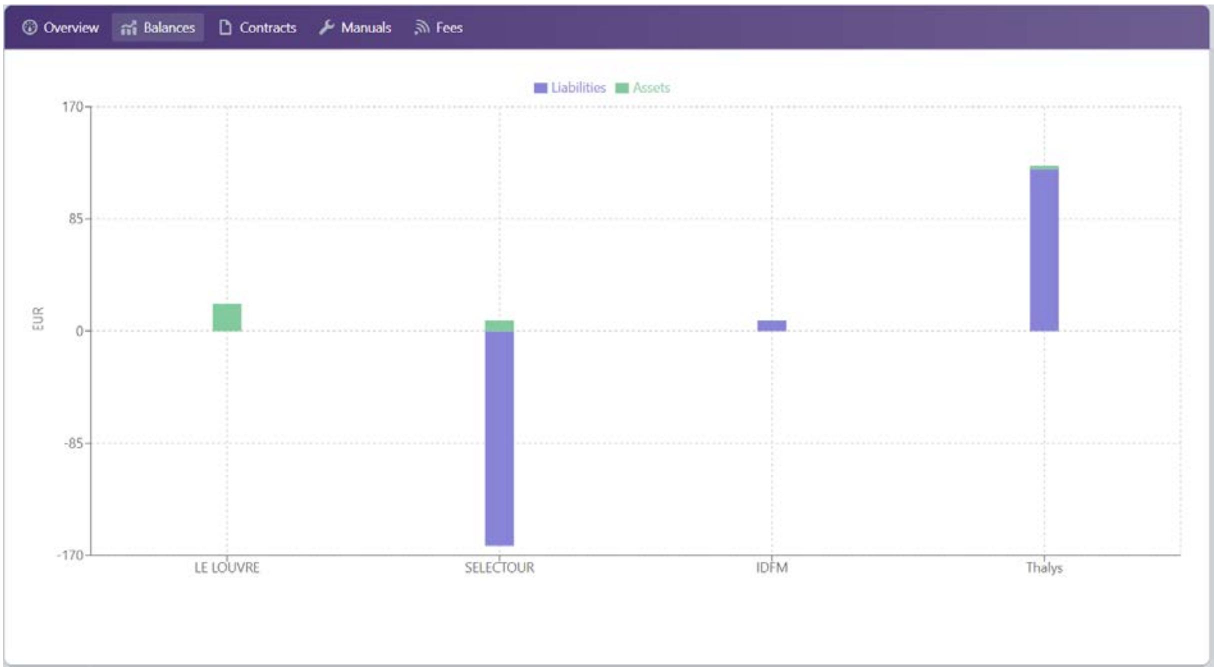


Figure 23.4 Balances

23.4. Conclusion

B2B Integration is key
The development of railway adoption is key for moving towards sustainable mobility at a large scale. Developing efficient and sustainable transport offers is not only a matter of providing more infrastructure, but also of making existing ones more attractive and convenient to use. Connecting Rail with other mobility modes in urban, sub-urban and rural areas, breaking silos between private and public transport, providing seamless journeys to end customers, solving the First Mile Last Mile burden, .. All of that will enhance Rail attractiveness. Multimodal integration is not achievable without the cooperation between Mobility Providers.

B2B Financial Services as a Key Asset for Rail Integration with Other Mobility Modes
MOTIONAL Financial Platform, focused on apportionment and settlement of revenues between mobility providers, retailers, and third parties helps at making Smart Mobility Smoother and More Efficient. Whether it’s a prepaid multimodal mobility product or a pay-as-you-go journey, the solution ensures seamless revenue distribution among

all business participants. This is a significant step towards simplifying revenue apportionment for multimodal mobility journeys across Europe, benefiting citizens and businesses alike.
We’re proud to be at the forefront of this evolution in mobility, making travel more efficient and equitable for everyone involved.

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Laurent Bellet works as system architect at Revenue Collection Systems (RCS), a Hitachi Rail business line delivering world class solutions for automatic fare collection, free flow road tolling, car parks, fleet management and road traffic control.
Laurent started his career working as a software engineer for companies especially in space technology and then moved to the transportation industry. He participated in the design and deployment of major intermodal fare collection systems in EMEA and APAC regions.
Laurent joined Shift2Rail within the context of IP4 Projects in 2018 and integrated EU-RAIL FP1 MOTIONAL in 2022 as work Package leader.

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Funded by the European Union

This project is under the scope of the Europe’s Rail JU and the EC Framework Programme for Research and Innovation, under grant agreement n°101101973. The project is supported by the Europe’s Rail Joint Undertaking and its members. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Europe’s Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

Posters

- Cybersecurity Risk Assessment of Virtually Coupled Train Sets, Aria Mirzai, RISE Research Institutes of Sweden
- What is the code of this wagon?, Melissa Tijink, University of Twente
- Enhancing Pedestrian Safety in Multimodal Transport through Pod-Based Transfers: An Ontological Approach, Reguieg Seddik, Gustave Eiffel University
- ESEP4Freight: Initial Approach to Smart Contract Generalization in Freight Logistics, Francisca Rosell, Eurecat
- Remaining useful life of an optimal topographical ground rail surface via Classical & Quantum Neural Network, Alfredo Serafini, Luleå University of Technology
- Repair of wheel and rails by additive manufacturing, Itziar Ruiz, CEIT

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