Deliverable 1.1

State of art in the railway domain of PhDs EU-RAIL

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1 Executive Summary

This deliverable provides a comprehensive state-of-the-art overview across multiple research domains that underpin the PhDs within the EU-Rail project. The aim is to highlights the integration of the technological, social, operational, and educational perspectives necessary for the transformation and the sustainability of the European railway system. Each chapter addresses a distinct PhD research theme while collectively contributing to a harmonized vision of railway innovation aligned with EU priorities such as the European Green Deal, digitalization, and gender equality.

PhD 1 “Innovation Implementation in Railways” outlines the crucial role of railways in achieving the EU’s decarbonisation goals, emphasizing the sector’s high energy efficiency. However, gaps in life cycle analysis, certification standards, and long-term data remain. Future research is expected to close these gaps by developing integrated methodological toolkits and harmonized regulatory frameworks.

PhD 2 “Gender Equality in Rail” analysis the rail sector in terms of gender imbalance. While progress has been noted in awareness and policy commitment, implementation remains inconsistent. A systemic approach involving education, organizational change, and leadership accountability is necessary for structural change.

PhD 3 “Education and Training” focus on skills gap that threatens the sector due to demographic shifts and rapid technological evolution. Current curricula often lag behind industry needs. AI-driven evaluation methods and harmonized, dynamic programs are recommended to ensure adaptability and workforce readiness.

PhD 4 “Rail-Enabled Urban Logistics” studies the urban logistics facing an increasing environmental and efficiency challenges. Rail-based solutions, including micro-hubs and multimodal strategies, show promise. However, policy, economic, and infrastructure constraints hinder widespread adoption. The study calls for more integrated urban transport planning.

PhD 5 “Fast Night Train Operations” focus on night trains that are regaining relevance amid sustainable travel trends. However, regulatory, operational, and comfort-related challenges persist. The analysis identifies opportunities to enhance international interoperability, ticketing platforms, and onboard services to make night trains a competitive alternative.

PhD 6 “Bridge-Train Dynamics Normative Framework” explores safety and comfort of train operations on bridges. Normative models and empirical standards are needed to guide infrastructure design. The study promotes a coordinated approach combining structural engineering, traffic dynamics, and regulatory evolution.

PhD 7 “Human Factors in Digital Command Systems” as the shift to digital communication in railway control demands user-centered design, the study emphasizes human factors, cognitive load management, and system usability. It proposes iterative development informed by field studies to enhance safety and effectiveness.

PhD 8 “Economic Impact (KPI) of Rail Research” expands the KPI-based assessment framework by linking technical innovations to societal outcomes. Through econometric modeling, it quantifies impacts like modal shift and carbon savings. The work aims to enhance EU-Rail’s strategic evaluation tools and policy alignment.

PhD 9 “Inclusion for Individuals with Intellectual Disabilities” studies how the accessibility in rail remains unequal, especially for those with cognitive disabilities. The study highlights the importance of lived experience, ethical design, and staff training. It advocates for inclusive standards and participatory design methods.

PhD 10 “ICT Platforms for ERTMS Systems” as reliable and interoperable Traffic Management Systems (TMS) are essential for digital rail operations, the research discusses the current limitations of ERTMS/ETCS Level 3 and proposes architectural improvements for future system compatibility and reliability.

The **conclusive remarks** of this deliverable are that the railway sector still requires major innovation to modernize infrastructure, foster decarbonisation, and address persistent gender inequality across workers, potential workers, and users. Education and training remain outdated and fragmented, slowing the development of a future-ready workforce, while opportunities lie in urban logistics, night train operations, and sustainable last-mile solutions. Data-driven governance, KPI monitoring, and interoperable ICT platforms are also highlighted as key enablers of progress. As these are PhD projects, the work will continue to evolve, already resulting in 10 publications, and this deliverable provides a multidisciplinary foundation that identifies gaps and guides future research in support of the EU-Rail vision for a connected, green, and inclusive rail system.

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
AI	Artificial Intelligence
AF	Application Framework
ATP	Automatic Train Protection
ATO	Automatic Train Operation
ATO-OBU	Automatic Train Operation - On Board Unit
ATO-TRK	Automatic Train Operation - Trackside Unit
BTM	Balise Transmission Module
CMD	Common Data Model
DMI	Driver Machine Interface
DB	Deutsche Bahn
ETCS	European Train Control System
ERTMS	European Rail Traffic Management System
EU	European Union
EU-Rail	Europe's Rail Joint Undertaking
FRMCS	Future Railway Mobile Communication System
GoA	Grade of Automation
GSM-R	Global System for Mobile Communications – Railway
HTD	Hybrid Train Detection
ICT	Information and Communication Technology
IL	Integration Layer
IoT	Internet of Things
JU	Joint Undertaking
KPI	Key Performance Indicator
LEU	Lineside Electronic Unit
MA	Movement Authority
OBU	On Board Unit
OPTIMA	Operational Platform Testbed for Integrated Mobility Applications (name of a project)
RBC	Radio Block Centre
S2R JU	Shift2Rail Joint Undertaking
TMS	Traffic Management System

TIMS	Train Integrity Monitoring System
TSI OPE	Technical Specifications for Interoperability – Operation and Traffic Management
UTO	Unattended Train Operation

3 Objective/Aim

The objective of this deliverable is to depict a first state of the art in railway domains where the PhDs are taking place: Innovations implementation, Gender equality, Education and training, Rail enabled urban logistics, Fast night train operations, Bridge-train dynamics normative, Human factors in digital command, Economic impact (KPI) rail research programs, Inclusion & accessibility of individuals with intellectual disability, ICT platforms for reliable and interoperable ERTMS systems.

4 Background

The PhDs EU-Rail project aims to foster collaboration and innovation in the European railway sector by consolidating a scientific community and conducting research through 10 PhD positions. The project is closely aligned with the goals of the EU-RAIL Joint Undertaking (EU-Rail) and the involved industry partners. The research topics cover a range of areas, such as supporting the implementation of rail technical innovations for decarbonization, promoting gender equality in the rail industry, exploring new education and training methods, enabling rail-based urban logistics, improving fast night train operations, studying the dynamic stability of trains over bridges, enhancing safety-relevant communication in the railway system, calculating societal KPIs of rail research programs, the railway inclusion and accessibility for individuals with intellectual disability and ICT platforms for interoperable and reliable ERTMS systems.

The present deliverable D1.1 *State of the art in railway domain of PhDs EU-Rail* provides with a credible, substantial and original state of art in the railway fields concerned by the ongoing PhD research activities. by offering a rich literature review and research topic refinement from each PhD candidate in conducting a propaedeutic preliminary thorough literature review in their respective fields.

5 Innovations Implementation in Railways

5.1 Introduction

The topic of railway innovation is highly relevant within the framework of European transport strategies. Sustainable development and the decarbonization of transport are among the European Union's (EU) top priorities, driven by the commitments of the Paris Agreement and the ambitious targets of the European Green Deal. These initiatives emphasize the urgent need to reduce greenhouse gas emissions (GHGs), with transport traditionally being one of the largest contributors to CO_2 emissions (European Union Agency for Railways, 2024; International Transport Forum, n.d.).

Rail transport holds a unique position in this transition: its inherent energy efficiency compared to other land-based transport modes makes it a crucial lever for achieving a greener transport system (Ahsan et al., 2023; Wen et al., 2025; Chamaret et al., 2023). Within broader EU frameworks, such as the European Green Deal and the "Fit for 55" package, the overarching goal is to cut emissions in the transport sector by approximately 90% by 2050 (European Union Agency for Railways, 2024; International Transport Forum; Flammini et al., 2020).

For the railway sector, meeting these targets requires a multifaceted approach. Key measures include expanding track electrification, advancing hydrogen and battery technologies, embracing digitalization, and implementing intelligent traffic management systems. Infrastructure modernization is equally important, including the development of hydrogen refueling stations and smart energy supply and recuperation systems (Depature et al., 2023; Marjani et al., 2025; Zhao et al., 2024).

The motivation behind these efforts is clear: reducing harmful emissions, alleviating road congestion, and improving the speed, reliability, and comfort of transport for both passengers and shippers (Ahsan et al., 2023; Wen et al., 2025; Chamaret et al., 2023; European Union Agency for Railways, 2024). By embracing these innovations, railways can become a cornerstone of Europe's sustainable and connected transport future.

5.2 Methodology

This analysis presents a literature review to determine the current state of implementation and use of innovations in rail transport aimed at decarbonisation. Its purpose is to give a comprehensive picture of the latest decarbonisation technologies in the railway sector, with a particular focus on transport-sector emissions reduction. The object of the study is the assessment of the impact of decarbonisation innovations on the efficiency of rail transport. To evaluate the effectiveness of these innovations, methods from the MCDM group will be used: AHP, OPSIS, or PROMETHEE, as well as the integrated LCA-MCDM approach.

The study follows an integrated methodology that begins with a review and analysis of existing scholarly publications, statistical data and regulatory documents related to lowering carbon emissions in transport through innovation. It focuses on vehicle design, fuel types, operations, infrastructure, traffic management and transport technologies. The review identifies research gaps and compares emissions from diesel rail traction.

Specifically, publications on rail-transport innovation from the past five years were surveyed – a timeframe chosen to capture state-of-the-art technologies and because research on transport decarbonisation has accelerated only recently, peaking in 2023–2025. The review covers scientific articles, academic works, European and national research projects, and initiatives developed by key actors in the rail sector. This approach provides an accurate picture of the status of innovative technologies in rail transport. The analysis highlights obstacles, challenges and gaps that require further research and improvement, as well as directions for practical implementation.

The main objective of PhD1 research is to develop systemic recommendations and identify effective mechanisms and technical solutions that would accelerate the decarbonization process of railway transport, while simultaneously taking into account the requirements of the "European Green Deal," the latest technological trends (hydrogen and battery-powered trains, energy recuperation systems, digital platforms), as well as the specifics of the institutional and economic environment (EU financial instruments, national modernization programs, regulatory barriers) , (Bijgaart, I. van den, Lindman, Å., Löfgren, Å., & Söderholm, P. (2022), Matura, A., Singh, R. K., & Kumar, R. (2025), European Union Agency for Railways. (2024), International Transport Forum). Additionally, it involves analyzing various development scenarios that consider the rapidity of innovation adoption, the availability of "green" electricity, and possible structural shifts in the transport balance.

In the analysed section, a structured review of literature and best practices related to rail decarbonisation was conducted. This review adopts a descriptive approach to group and synthesize existing knowledge, identify trends, highlight areas requiring improvement, and develop a comprehensive understanding of the researched topic. Based on preliminary inquiries, a set of keywords was formulated to guide the search for relevant information.

The main keywords used in the analysis included: "innovation," "rail transport," "decarbonisation," "transport safety," "environmental impact," "sustainable mobility," and "European Green Deal." The literature search was conducted in the Web of Science, Scopus, and Google Scholar databases, using various combinations of these keywords, primarily in English, but also in Ukrainian.

The reviewed materials included: (1) analytical reports by the International Energy Agency (IEA) and the International Union of Railways (UIC); (2) peer-reviewed scientific publications on hydrogen-powered, battery-electric, and hybrid traction systems; and (3) evaluations of pilot projects implemented in European countries such as Germany, France, Italy, and the Netherlands. Key sources representing these categories include (Ahsan, N., Hewage, K., Razi, F., Hussain, S. A., & Sadiq, R. (2023), Chamaret, A., Mannevy, P., Clément, P., Ernst, J., & Flerlage, H. (2023), European Union Agency for Railways. (2024), Marjani, S. R., Motaman, S., Varasteh, H., Yang, Z., & Clementson, J. (2025), Mandegari, M., Ebadian, M., & Saddler, J. (2023), Zhao, L., Chen, H., & Wang, Y. (2024))

To form the theoretical foundation of the research, a literature review was conducted, in the course of which more than 50 scientific articles published in leading databases (WoS, Scopus, ScienceDirect, Google Scholar) over the last decade were analyzed. These publications cover the topic of railway transport decarbonization, discuss the latest achievements in the field of hydrogen and battery technologies, and also address issues of electrification and energy recuperation systems.

5.3 Results

The research analyzed in this section highlights a broad spectrum of approaches to decarbonizing railway transport, addressing both freight and passenger operations across multiple contexts. Hernandez et al. (2024) provide a comprehensive evaluation of decarbonization options for freight rail, integrating economic, environmental, and operational considerations. Their work underscores the critical role of the freight sector in overall greenhouse gas (GHG) emissions and the urgency of identifying optimal strategies to reduce its carbon footprint.

Complementing this perspective, Ahsan et al. (2023) examine the evolution of rail transport as a key instrument for achieving global GHG reduction goals. They demonstrate that, despite the high emissions associated with road transport, rail already offers one of the lowest carbon footprints among land transport modes. Their study compares different traction systems, from conventional diesel engines to hybrid hydrogen-battery locomotives, highlighting pathways for further emission reductions.

China's state policies promoting sea-rail intermodal transport (SRT) are analyzed by Li et al. (2024), illustrating how strategic interventions can lower carbon emissions through integrated logistics solutions. Similarly, Zhang et al. (2024) explore the modernization of the UK rail network, focusing on scenarios for a complete diesel phase-out via electrification or hydrogen fuel cell trains, providing both a theoretical foundation and practical guidance for engineers pursuing a low-carbon rail system.

Optimizing operations is another key avenue for decarbonization. Tian et al. (2024) show that improvements in route planning and train load factors can substantially reduce emissions while maintaining or enhancing transport performance. Marjani et al. (2025) combine train dynamics modeling with engine simulations to evaluate the environmental and operational impacts of transitioning from diesel to hydrogen-powered intercity trains, capturing detailed insights into fuel consumption and pollutant emissions under various operating conditions. Zhao et al. (2024) further emphasize the potential of hydrogen fuel cell rolling stock, noting its advantages in reducing reliance on costly electrification infrastructure, especially in remote areas.

Regional rail transport also presents opportunities for cleaner energy adoption. Kapetanović et al. (2024) assess five powertrain configurations—ranging from hybrid and battery-electric systems to biodiesel and hydrogen—demonstrating the versatility of technological solutions for replacing diesel traction. Beyond powertrain innovations, Nampalli (2024) illustrates the role of artificial intelligence (AI) and deep learning in enhancing infrastructure maintenance and operational efficiency, indirectly contributing to decarbonization through energy savings and reduced downtime. Flammini et al. (2020) further extend this perspective with the RAILS project, integrating AI, IoT, and sensor networks to optimize infrastructure management and traffic planning, thereby lowering energy consumption and emissions through smarter operations.

Together, these studies paint a detailed and multidimensional picture of decarbonization in railways, spanning technological innovation, operational efficiency, and strategic policy interventions. The results highlight that reducing the sector's carbon footprint is not solely a matter of adopting new traction systems, but also of integrating data-driven management, optimizing logistics, and modernizing both infrastructure and operational practices.

The following gaps were identified:

- human and organizational resource constraints;
- limited evidence base for the effectiveness of decarbonisation solutions;
- financial mechanisms have been studied only fragmentarily;
- lack of a unified methodological approach for evaluating innovations; and
- neglect of regional specificities.

According to IEA data, from 2010 to 2022, CO_2 emissions from railway transport fluctuated within the range of 86 – 103 million tons per year (Fig. 1). The decrease to 85.62 million tons in 2020 is explained by restrictions related to the COVID-19 pandemic (International Energy Agency. (2023)). However, in 2021 – 2022, a gradual recovery in transport activity was observed, leading to a partial increase in emissions. Special attention should be paid to the IEA forecast for 2030 under the Net Zero (NZE) scenario, according to which the volume of CO_2 emissions in the railway sector could drop to 63.22 million tons. Figure 1 illustrates the significant potential of railway transport for further reducing the carbon footprint, in particular by scaling up electrification, actively implementing hydrogen technologies, and gradually transitioning to innovative logistics models (Marjani, S. R., Motaman, S., Varasteh, H., Yang, Z., & Clementson, J. (2025), Vaccaro, R., Maino, F., Zubaryeva, A., & Sparber, W. (2024), Mandegari, M., Ebadian, M., & Saddler, J. (2023), Kapetanović, M., Núñez, A., van Oort, N., & Mijnders, R. (2024)). Accordingly, in the NZE scenario, railway transport is regarded as one of the key areas of decarbonization within EC strategies aimed at reducing emissions and achieving climate neutrality (European Union Agency for Railways. (2024), International Transport Forum).

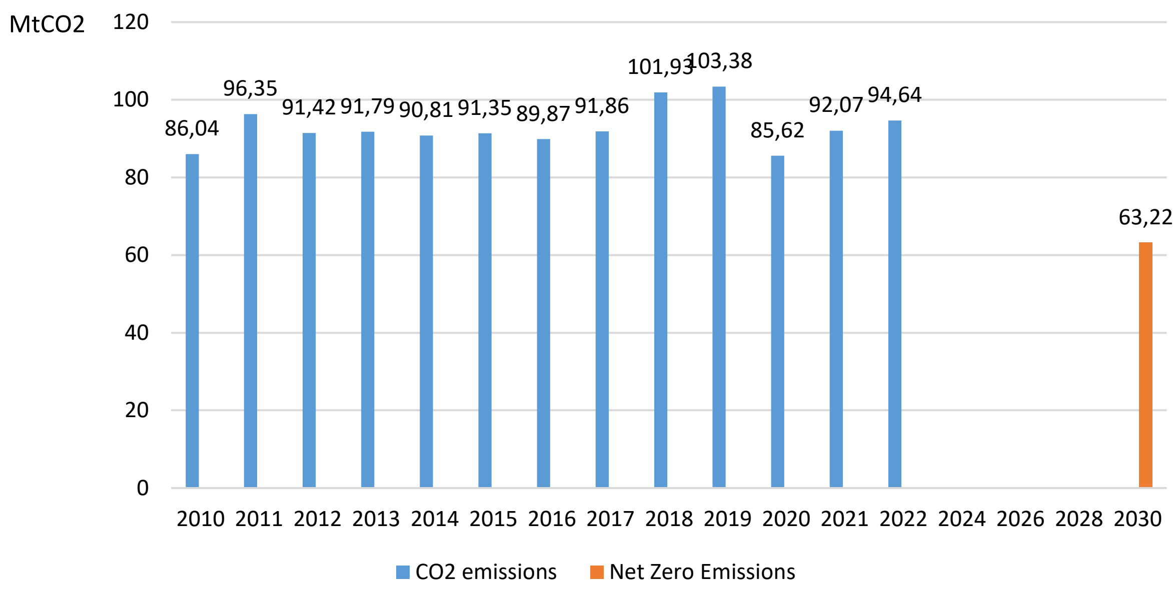

Figure 1-CO2 emissions from rail in the Net Zero Scenario, 2010-2030 ((International Energy Agency. (2023).

To process and structure the large volume of information, systems analysis and content analysis methods were applied, involving the search for cross-cutting themes, comparison of results from various pilot projects, and identification of the most effective technical solutions and management measures (Hernandez, A., Ng, M. T. M., Siddique, C., Durango-Cohen, P. L., Mahmassani, H. S., Elgowainy, A., Wang, M., & Zhou, Y. J. (2024), Ahsan, N., Hewage, K., Razi, F., Hussain, S. A., & Sadiq, R. (2023), Wu, C., Le Vine, S., & Sivakumar, A. (2025), Nampalli, R. C. R. (2024)..

As part of the literature and practice review presented in this section, the analysed sources were divided into three functional categories: first, peer-reviewed academic publications that elaborate theoretical frameworks—ranging from mathematical models and scenario analyses to experimental investigations of hydrogen, battery-electric and hybrid rail technologies; second, practice-oriented materials, including official project reports produced under Shift2Rail and Europe's Rail Joint Undertaking (ERJU) as well as technical documentation from Alstom, Siemens, Stadler and joint studies with *Ukrzaliznytsia*, which collectively provide granular data on capital and operating costs, environmental performance, return-on-investment profiles and implementation challenges; and third, regulatory and technical standards such as UIC guidelines, directives of the European Commission and ISO/EN norms that define the legal, safety and interoperability requirements for deploying innovative traction systems, particularly hydrogen-powered rolling stock. This tripartite classification made it possible to structure the review coherently and reveal consistent patterns that cut across scientific, technical and regulatory domains relevant to contemporary rail-decarbonisation initiatives (Table 1).

Table 1- Source groups used in the literature review

№	Group of sources	Examples / Sources	Primary purpose in the research
1	Academic publications	Peer-reviewed articles from WoS, Scopus, ScienceDirect, Google Scholar (e.g. Ahsan, N., Hewage, K., Razi, F., Hussain, S. A., & Sadiq, R. (2023).)	Theoretical background, scenario analysis, modelling approaches
2	Scientific project reports and applied cases	Shift2Rail documents, ERA environmental reports, Alstom, Stadler, Ukrainian Railways, OECD (e.g. European Union Agency for Railways. (2024).)	Practical implementation, case studies, cost analysis, impact evaluation
3	Technical standards and regulatory documents	UIC publications, ISO & EN standards, EU directives (e.g., Flammini, F., Vittorini, V., & Lin, Z. (2020).)	Regulatory framework, certification, safety and environmental compliance

The classification of sources reflects the multi-dimensional structure of the research, integrating theoretical frameworks, real-world implementation cases, and regulatory requirements relevant to the decarbonisation of railway transport. As a result of the conducted study, the following gaps were identified: limitations in human and organizational resources; a restricted evidence base regarding the effectiveness of decarbonisation solutions; financial mechanisms have been examined only fragmentarily; the absence of a unified methodological approach for evaluating innovations; and the neglect of regional specificities.

Based on this literature review, four main areas of innovation in the railway sector have been identified (Fig. 2). Railway innovations will be assessed using generally defined criteria.

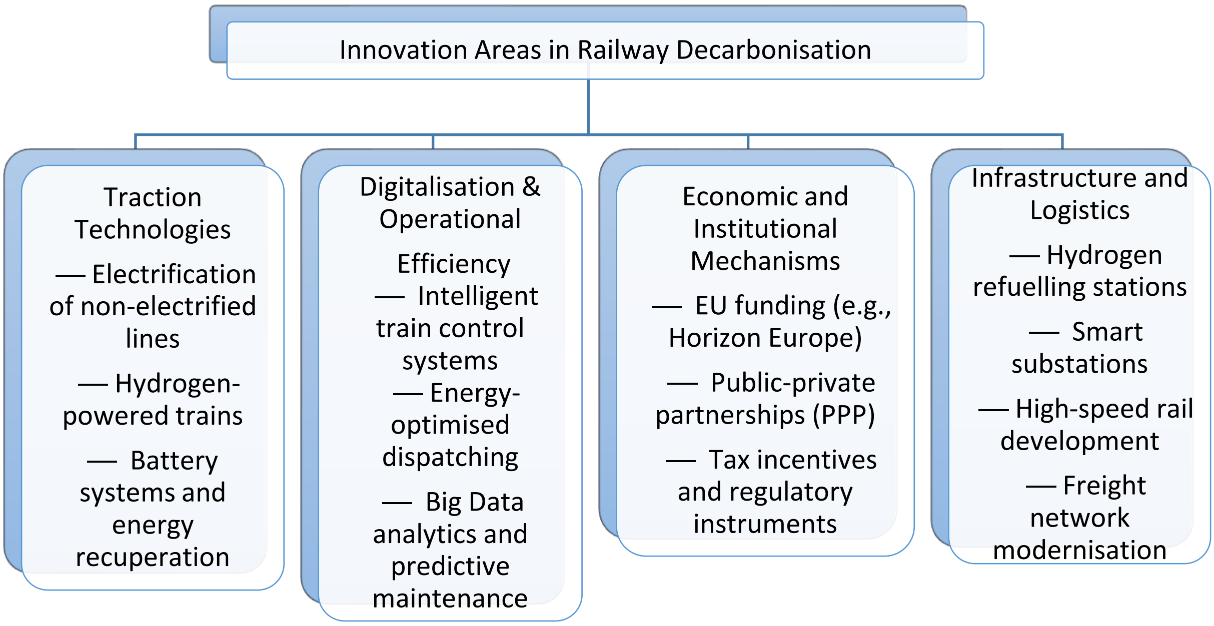

Figure 2-Main areas of innovation in the railway sector

Primarily, it concerns traction technologies, which include the electrification of non-electrified sections, the development of hydrogen trains, and the implementation of battery systems (in particular, advanced energy recuperation solutions) (Depature, C., Dégardin, F., Riezu, I., Agnus, F., & Juston, M. (2023); Ahsan, N., Hewage, K., Razi, F., Hussain, S. A., & Sadiq, R. (2023; Marjani, S. R., Motaman, S., Varasteh, H., Yang, Z., & Clementson, J. (2025); Zhao, L., Chen, H., & Wang, Y. (2024); Riezu, I., Juston, M., Leguéré, R., Dalbavie, J.-M., & Vulturescu, B. (2023), Chang, A. S. F., & Kalawsky, R. S. (2025)). The second direction involves digitization and movement optimization: intelligent train control systems, dispatching and scheduling with energy efficiency in mind, as well as the use of Big Data and analytics to improve reliability and convenience in transportation (Wu, C., Le Vine, S., & Sivakumar, A. (2025), Nampalli, R. C. R. (2024), Flammini, F., Vittorini, V., & Lin, Z. (2020)). The third block covers economic and institutional mechanisms: EU financial instruments such as Horizon Europe, government incentives, public-private partnership schemes, and tax or regulatory measures (Bijgaart, I. van den, Lindman, Å., Löfgren, Å., & Söderholm, P. (2022, Matura, A., Singh, R. K., & Kumar, R. (2025)., Gopal, M., & Dutta, A. (2024), Gopal, M., & Dutta, A. (2024)). Finally, the fourth direction pertains to infrastructure and logistics solutions (multimodal transport hubs, development of a network of hydrogen filling stations and "smart" power substations, scenarios for the construction of high-speed lines, and efficient freight connections) (Wen, Y., Liu, Y., Sheng, L., & Yu, Z. (2025), Li, S., Wu, J., Jiang, Y., & Yang, X. (2024), Yuan, J., Peng, L., Zhou, H., Gan, D., & Qu, K. (2024), Kapetanović, M., Núñez, A., van Oort, N., & Mijnders, R. (2024)).

As part of the research work conducted within the framework of the PhD1 dissertation, a scientific article indexed in the Scopus database was prepared and published under the title "Decarbonizing Strategy of Ukrainian Transport Sector" (Decarbonizing Strategy of Ukrainian Transport Sector" (Intelligent Transport Systems: Ecology, Safety, Quality, Comfort.. The study is aimed at developing a comprehensive approach to reducing carbon emissions in the transport sector, with a focus on the role of railway transport as a key element of sustainable development.

Based on the results of the literature review and ongoing projects in European countries, several general trends can be identified that shape the development of innovation in the context of railway transport decarbonization.

To compare alternative projects, five criteria have been defined: technical-technological, environmental, implementation duration (time), economic, and social resource.

The first, there is active electrification of non-electrified lines: despite significant capital expenditures, electrification remains one of the most effective paths toward reducing greenhouse gas emissions, especially when combined with the implementation of smart grids, energy recuperation systems, renewable energy sources, and advanced substations (Depature, C., Dégardin, F., Riezu, I., Agnus, F., & Juston, M. (2023); Ahsan, N., Hewage, K., Razi, F., Hussain, S. A., & Sadiq, R. (2023); Chamaret, A., Mannevy, P., Clément, P., Ernst, J., & Flerlage, H. (2023)).

According to IEA data, from 2010 to 2020, the main energy sources for railway transport remained diesel fuel and electricity, particularly in regions with insufficient electrification (Fig. 3). The Net Zero scenario for 2030 envisions a significant reduction in diesel's share in favor of electricity, hydrogen, and biofuels. At the same time, overall energy consumption increases, indicating not a reduction in transport volumes, but rather an energy transformation (Marjani, S. R., Motaman, S., Varasteh, H., Yang, Z., & Clementson, J. (2025), Mandegari, M., Ebadian, M., & Saddler, J. (2023)).

Achieving NZE targets requires a transition to carbon-free traction systems, the use of green energy, and the development of the corresponding infrastructure presented in Figure 3.

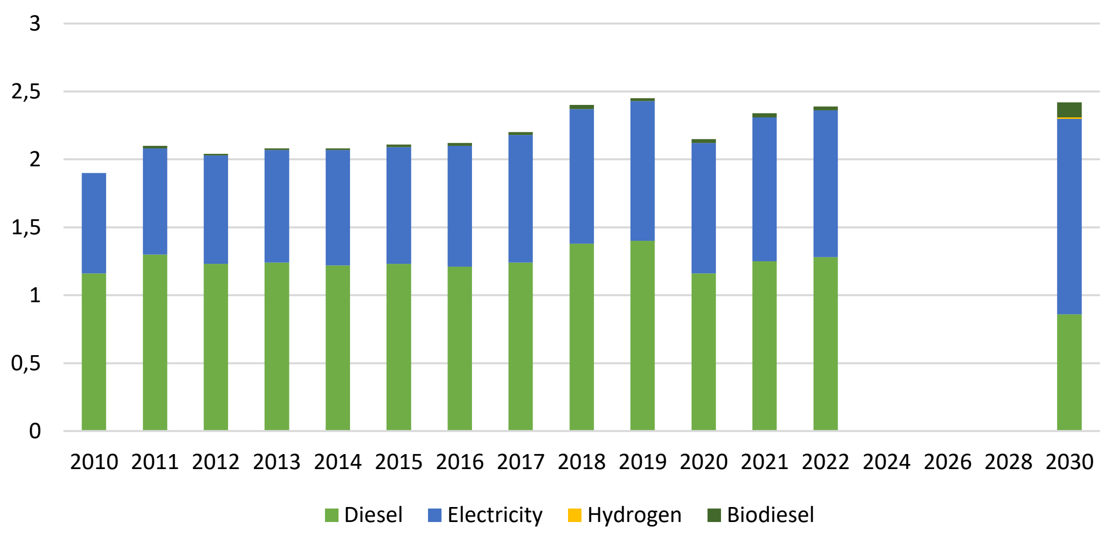

Figure 3-Energy consumption by fuel type in rail, NZE scenario

Secondly, hydrogen and battery technologies are increasingly being adopted for serving remote or low-traffic routes, where full electrification is economically unfeasible. In such cases, hydrogen locomotives or hybrid trains (hydrogen + batteries) are being used more frequently, which is particularly justified in regions with access to green electricity (Zhao, L., Chen, H., & Wang, Y. (2024)).

Lastly, digitization is becoming a crucial factor in enhancing energy efficiency, as automated train operation (ATO) systems, Big Data analysis, and AI applications make it possible to optimize speed profiles, reduce unproductive stops, and efficiently utilize regenerative braking (Nampalli, R. C. R. (2024)).

Finally, there is a growing integration of railways with other modes of transport (road, port services, etc.) aimed at creating a unified logistics network, which has an additional "green" effect by encouraging the shift of freight flows from roads to rail (Li, S., Wu, J., Jiang, Y., & Yang, X. (2024)).

Railway transport already demonstrates the lowest energy consumption per passenger, a trend further reinforced by the implementation of digital solutions as is shown in Figure 4 (Ahsan, N., Hewage, K., Razi, F., Hussain, S. A., & Sadiq, R. (2023)).

An important case is the Coradia iLint project (Alstom), where hydrogen trains have been operating successfully in Germany since 2018, achieving zero CO_2 emissions when powered by green hydrogen (Zhao, L., Chen, H., & Wang, Y. (2024)). France's SNCF is testing both hydrogen and battery systems on regional lines while continuing large-scale electrification, aiming to reduce emissions approximately 25% by 2030. In the Netherlands, Nederlandse Spoorwegen has conducted all passenger transport using electricity from renewable sources since 2017 and is exploring the use of battery solutions on partially electrified routes (Chang, A. S. F., & Kalawsky, R. S. (2025)). Meanwhile, Ferrovie dello Stato Italiane (Italy) is developing the concept of "Green Hubs", featuring charging stations for battery trains and hydrogen refueling points at key nodes (Wen, Y., Liu, Y., Sheng, L., & Yu, Z. (2025)).

It has been identified that among the most significant obstacles are infrastructure complexity and the high capital costs associated with the construction or upgrading of networks, including the installation of overhead contact lines and hydrogen facilities. Economic barriers are reflected in the still relatively high costs of hydrogen and battery technologies, as well as the lack of concessional financing or grant programs to support their implementation (Gopal, M., & Dutta, A. (2024)). Additionally, there is a shortage of unified standards for hydrogen trains across different European countries, which complicates the certification process and the approval of new technologies. Equally important is the issue of personnel qualification, as the deployment of innovations requires new skills and knowledge in the fields of fuel cells, batteries, and AI, along with overcoming organizational resistance within the traditionally conservative railway sector (Abdulghani, T., & Winkler, H. (2025)).

Most studies dedicated to hydrogen and battery innovations rely mainly on pilot data or short-term experiments, and therefore there is a lack of empirical evidence regarding the long-term economic viability of such systems (Depature, C., Dégardin, F., Riezu, I., Agnus, F., & Juston, M. (2023)). There is also a shortage of comprehensive research that would compare various financial instruments (such as subsidies, green bonds, concessional loans) and their impact on the pace of railway decarbonization (Mandegari, M., Ebadian, M., & Saddler, J. (2023)).. In addition, life cycle assessment (LCA; hereinafter referred to as LCA) methodologies in the context of hydrogen and battery technologies lack a unified approach: there are still open questions regarding the "cleanliness" of hydrogen (depending on the energy sources used), and insufficient attention is paid to socio-economic factors and behavioral aspects on the part of operators and passengers (Li, S., Wu, J., Jiang, Y., & Yang, X. (2024)).

The identified gaps and challenges highlight the need for comprehensive models and a multidisciplinary approach (Tian, A.-Q., Wang, X.-Y., Xu, H., Pan, J.-S., Snášel, V., & Lv, H.-X. (2024)). The first and foremost, it is advisable to develop a unified methodological toolkit (e.g., Multi-Criteria Decision-Making (hereinafter referred to as MCDM), LCA) that would allow for comparing decarbonization technologies (hydrogen, batteries, biofuels, additional electrification) within a common analytical framework. The second direction involves expanding LCA studies to evaluate the full life cycle — from component production and processing to operation and disposal. In addition, there is a need to integrate forecasting models (e.g., ARIMA, neural networks) with expert-based methods (Delphi) to develop adaptive scenarios, as well as to create Digital Twins for real-time monitoring and optimization. Finally, the socio-economic dimension is of great importance: implementing innovations requires assessing acceptance among transport sector staff and passengers, as well as developing reskilling strategies and business incentives through various forms of public-private partnerships (Bijgaart, I. van den, Lindman, Å., Löfgren, Å., & Söderholm, P. (2022)). In this way, the foundation is laid for systemic transformation in the railway sector, aligned with European decarbonization strategies.

Based on the research conducted, it can be concluded that railway transport has high potential for contributing to European climate goals. Key directions toward achieving "green" performance indicators include: large-scale electrification, the active development of hydrogen and battery solutions, increasing levels of digitization and automation, and the creation of a supportive institutional and financial environment (through government support, EU grants, tax incentives) (Matura, A., Singh, R. K., & Kumar, R. (2025)). However, a number of problematic areas remain — including the high cost of innovations, the lack of unified regulations for hydrogen rolling stock, imperfect life cycle assessment methods, and organizational and personnel barriers (Riezu, I., Juston, M., Leguéré, R., Dalbavie, J.-M., & Vulturescu, B. (2023)).

The findings obtained have formed the methodological foundation for the continuation of the PhD research, enabling the selection of a comprehensive approach that combines modelling, regression analysis, MCDM methods, SWOT analysis, and Delphi surveys (Hernandez, A., Ng, M. T. M., Siddique, C., Durango-Cohen, P. L., Mahmassani, H. S., Elgowainy, A., Wang, M., & Zhou, Y. J. (2024)). In addition, several priority areas for further development have been identified:

- integrated models that consider environmental, economic, and technical factors;
- development of scenarios with varying rapidity of technology adoption and availability of green energy;
- and preparation of concrete recommendations for national railway operators and potential investors.

Stimulating hydrogen and battery projects involves the active implementation of pilot tests of hydrogen locomotives on low-traffic sections and the initiation of a network of hydrogen refuelling stations and green electrolysers in cooperation with energy companies (Zhao, L., Chen, H., & Wang, Y. (2024)). Digitalization and automation should be expanded through the implementation of AI algorithms, Big Data platforms, and IoT technologies for infrastructure monitoring and preventive maintenance. In the financial and economic domain, it is advisable to develop public-private partnerships, implement concessional loans and green bonds for the modernization of rolling stock and the creation of environmentally oriented infrastructure. Given the lack of a unified regulatory framework for hydrogen and battery systems, it is necessary to harmonize standards and certification procedures at the EU level, as well as to develop national railway decarbonization strategies aligned with the provisions of the European Green Deal. In the context of the human factor and workforce training, it is recommended to initiate educational programs and retraining courses that cover the specifics of new traction technologies and digital systems, and to establish cooperation between universities and manufacturers in order to accelerate the implementation of innovations in the railway sector (Abdulghani, T., & Winkler, H. (2025)). Overall, a systemic approach that considers technical, economic, and social aspects would ensure a significant reduction in emissions and strengthen the competitive advantages of railway transport in the near and medium term, laying the foundation for comprehensive modernization programs at both the national and European levels (Chamaret, A., Mannevy, P., Clément, P., Ernst, J., & Flerlage, H. (2023)).

Even within the framework of a sustainable development scenario that accounts for technological shifts across all sectors, rail transport maintains the lowest level of emissions, underscoring its strategic role in achieving climate goals (International Energy Agency. (2023)).

The analytical component of this PhD research enriches the scientific discourse on rail-transport decarbonisation by fusing theoretical constructs, empirical evaluations of demonstrator projects and a systematic appraisal of regulatory frameworks within a single methodological architecture; building on a structured literature review and case-based synthesis, it advances a tripartite typology that links innovation trajectories, institutional support mechanisms and systemic constraints pertinent to the EU's green rail transition, thereby moving beyond the prevailing scholarship — which typically isolates specific technologies or reports on discrete pilot schemes — and instead revealing cross-cutting patterns that span technical, economic and legal dimensions of the field (Zhang, R., Hanaoka, T., Hu, M., Xu, Y., Xue, J., Liu, J., & Sun, Q. (2024)).

By integrating a literature review, analysis of EU strategic documents, and statistical data (in particular, from the IEA), the research lays the groundwork for the development of comprehensive decision-making tools. The proposed typology of innovation directions and the identified scientific gaps create prerequisites for further studies using life cycle assessment (LCA) approaches, MCDM methods, and scenario planning, enabling a more holistic evaluation of railway decarbonization prospects (Tian, A.-Q., Wang, X.-Y., Xu, H., Pan, J.-S., Snášel, V., & Lv, H.-X. (2024)).

In the context of Ukraine's integration into the European climate policy framework, the results of the study acquire particular practical value, as the implementation of hydrogen locomotives, the development of multimodal transport, and the large-scale electrification of high freight-density sections represent realistic pathways capable of simultaneously reducing emissions and increasing the efficiency of the transport system.

Building on the synthesis of EU policy documents and international case studies, the study delineates a set of actionable measures for Ukraine's rail-sector decarbonisation: gradual deployment of hydrogen traction on non-electrified lines; expansion of multimodal logistics hubs; formulation of regional decarbonisation strategies tailored to existing infrastructure conditions; implementation of targeted training programmes for technical personnel; nationwide public-awareness campaigns on low-carbon transport; and mobilisation of international climate finance through public-private partnership schemes.

The proposed measures, based on EU experience and global practices, include analysis of electrification levels, assessment of hydrogen technology potential, and the development of regional decarbonization strategies, while the creation of training programs for specialist preparation and the promotion of environmental initiatives among citizens ensure the sustainable development of the railway sector. The involvement of international funding sources, the expansion of public-private partnerships, and effective institutional synergy enables Ukraine to confidently advance toward a low-carbon transport system in line with the European Green Deal criteria (European Commission, 2019).

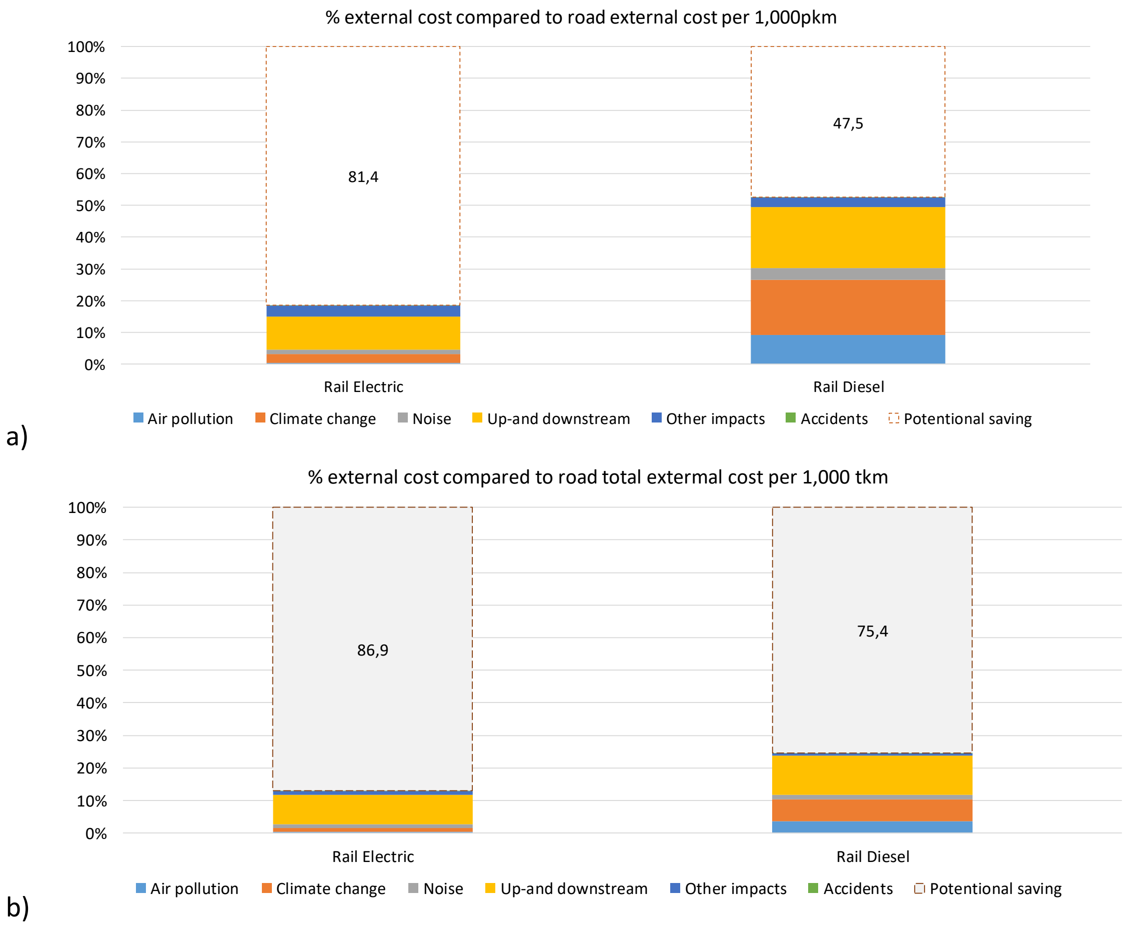

Figure 4-External costs in freight and passenger transportation, %

According to the Fig.4 data, railway transport demonstrates the lowest external costs among all land and air transport modes, making it a key candidate for large-scale environmental modernization.

The structured analysis of scientific sources, methodological frameworks, and existing research trajectories represents a completed stage of this deliverable. However, due to the dynamic nature of the field, the continuous monitoring of emerging publications will remain important throughout the PhD research process.

The existing body of literature and practical reports underpinning this dissertation clearly delineates a number of systemic gaps that hinder the formation of a comprehensive decarbonisation strategy for the railway sector, namely:

1. A single integrated methodological toolkit that simultaneously covers full LCA, MCDM and socio-behavioural factors—and thus enables correct comparison of electrification, hydrogen, battery and biofuel traction—has not yet been created (Hernandez, A., Ng, M. T. M., Siddique, C., Durango-Cohen, P. L., Mahmassani, H. S., Elgowainy, A., Wang, M., & Zhou, Y. J. (2024)). Existing studies employ fragmented metrics (g/km CO_2, NPV, TCO); their assumptions about energy pricing, battery degradation or hydrogen “cleanliness” are inconsistent, preventing consolidation into a unified scenario analysis.
2. Long-term empirical data on the operational reliability and cost trajectory of innovative technologies are lacking. Pilot projects with hydrogen and battery trains (iLint corridors in Germany, SNCF regional lines, NS demonstration runs) so far cover only 3–5 years (Riezu, I., Juston, M., Leguéré, R., Dalbavie, J.-M., & Vulturescu, B. (2023)), which is insufficient to assess fuel-cell degradation, battery-replacement costs or H_2-infrastructure upgrades over the entire life cycle.
3. Regulatory, certification and power-system issues remain unresolved. Safety and interoperability standards for hydrogen rolling stock differ markedly across EU member states; no common “fast-track approval” procedures or mutual recognition of certificates exist, forcing manufacturers to undergo repeated testing (Marjani, S. R., Motaman, S., Varasteh, H., Yang, Z., & Clementson, J. (2025)). At the same time, studies that quantitatively assess how large-scale electrification and high demand for “green” H_2 will affect the balance of renewable energy sources, peak loads and the need for energy-storage systems are lacking (International Energy Agency. (2023)). Risk management is a separate “grey zone”: response protocols for H_2 incidents and other criteria are still described in detail only in companies’ internal standards rather than in unified technical regulations (Yuan, J., Peng, L., Zhou, H., Gan, D., & Qu, K. (2024)).
4. Financial-economic and human-resource aspects are examined only superficially. Despite frequent references to green bonds, Horizon Europe grants and public-private partnerships, the literature lacks comparative assessments of which instruments actually shorten project pay-back periods (Matura, A., Singh, R. K., & Kumar, R. (2025)) Moreover, models for workforce reskilling and methods for managing resistance to change during the introduction of AI platforms and digital twins are missing (Abdulghani, T., & Winkler, H. (2025)., Flammini, F., Vittorini, V., & Lin, Z. (2020)).
5. The evidence base for energy savings from ATO, big-data dispatching and predictive maintenance is limited to isolated simulations; large-scale “before-after” measurements are scarce (Wu, C., Le Vine, S., & Sivakumar, A. (2025)., Wu, C., Le Vine, S., & Sivakumar, A. (2025).). The impact of shifting freight flows among railways, ports and roads on external costs—CO_2, noise, congestion – has been insufficiently studied (Li, S., Wu, J., Jiang, Y., & Yang, X. (2024), Ou, Y., Zheng, J., & Liang, Y. (2024)).

Finally, the specific conditions of Ukraine and Europe are virtually absent from the predominantly “Western-European” scenarios: wartime risks, low electrification levels on certain sections, a different energy mix and the price volatility of H_2 and electricity remain outside sensitivity models (Hernandez, A., Ng, M. T. M., Siddique, C., Durango-Cohen, P. L., Mahmassani, H. S., Elgowainy, A., Wang, M., & Zhou, Y. J. (2024)., Zhang, Y., Tian, Z., Jiang, K., Hillmansen, S., & Roberts, C. (2024)., Li, S., Wu, J., Jiang, Y., & Yang, X. (2024)., International Energy Agency. (2023)). Overcoming these gaps therefore requires interdisciplinary synergy: a unified LCA + MCDM framework, long-term monitoring of pilots, harmonisation of standards, in-depth power-system analysis, financial experiments, as well as workforce-training programmes and large-scale digital pilots with transparent evaluation of their environmental and economic impact.

5.4 Conclusion and discussion

As a result of the conducted review and literature analysis, it was established that, although significant progress has been made through European projects and institutional initiatives promoting innovation in the transport sector, the current state of infrastructure and existing technological solutions still require substantial efforts to overcome barriers, foster innovation, and ensure the successful implementation of technological advancements in railways. These efforts are crucial to advancing decarbonisation initiatives within the transport sector.

At the next stage of the dissertation, a comprehensive research framework is planned that will encompass simultaneously:

1. A comparative analysis of the organisational models of Ukrzaliznytsia and LTG, with emphasis on the role of R&D units, innovation-management mechanisms and funding sources;
2. Primary data collection from ongoing hydrogen and battery pilots in Germany, France, the Netherlands and Lithuania, followed by calibration of an integrated LCA-MCDM model for three development scenarios—baseline, electrification and hydrogen-digital;
3. Identification of safety barriers, regulatory-certification and power-system bottlenecks, and the development of a roadmap for their elimination through H_2-infrastructure standardisation, expansion of energy-storage systems and demand-response mechanisms;
4. Economic calculation of CAPEX/OPEX and relevant financial instruments (green bonds, grants, public-private partnership schemes) for each scenario over the 2030–2050 horizon;
5. Preparation of a set of policy recommendations aligned with the CERRE and Fit for 55 roadmaps, addressed to the governments of Ukraine and partner countries as well as to key stakeholders, including the Lithuanian Ministry of the Economy, LTG, Ukrzaliznytsia and passenger and freight customers.

The expected outcome is a practically oriented railway decarbonisation programme supported by quantitative models, financial evaluation and harmonised safety and certification standards.

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6 Gender Equality in the Railway Sector

The railway industry, traditionally male-dominated, has seen a notable underrepresentation of women in various roles, including engineering, operations, maintenance, and leadership positions. The elaboration of this state of the art aims to understand the current situation of gender equality in the railway sector, reviewing the academic production that has been generated on this topic over the last ten years. Based on this review, women's experiences are analysed from three different perspectives: as workers, as potential workers, and as users. The review has made it possible to identify the main problems that limit the presence of women in this industry, as well as to detect actions and initiatives that can help to achieve a more diverse, fair and inclusive sector.

Recently, there is a growing emphasis on increasing the participation of women and promoting gender equality within the sector. Despite this, women remain underrepresented in the rail industry, comprising only 12.8% of the workforce in the sector (Sum4all, 2023). To address the current imbalance, initiatives such as the 1st Women in Rail Award (European Commission, 2022) and the EU's Gender Equality Strategy 2020-2025 (European Commission, 2020) are being implemented. These initiatives aim to provide support and networking opportunities, as well as to promote the industry as an attractive career choice for women. The Australasian Railway Association (ARA, 2023) has launched a Women in Rail Strategy to support the continued increase in female representation in the industry. There are also initiatives that seek to improve knowledge about women's employment in the railway sector and identify the obstacles that exist to reduce the gender gap. For example, the report 'Women on the Railway'[1], launched by the Fundación de Ferrocarriles Españoles (Spanish Railway Foundation) (FFE, 2024). In 2023, the Sustainable Mobility for All Consortium launched the "Gender Imbalance in the Transport Sector: A Toolkit for Change," providing guidance and resources for mainstreaming a gender-sensitive approach in transportation (SuM4All, 2023). The UIC, a global railway organization, supports initiatives like the TRAIN 2B EQUAL project, fostering best practices, peer learning, and elevating ambitions for women in rail services (UIC, n.d.). These efforts reflect a growing recognition of the importance of gender diversity and the need to create a more inclusive and equitable work environment within the rail industry. The expert group report from the European Commission emphasizes breaking the glass ceiling and recommends public communication to attract young talent and promote female employment in the Rail Supply Industry, highlighting its role in addressing societal challenges (European Commission, 2019).

The industry needs diverse skills, and there is a recognition that recruiting and retaining women is fundamental to the sector's financial and environmental resiliency (Sum4all, 2023). The involvement of women in the rail industry is crucial for fostering diversity of thought, creativity, and human capital, which are essential for the sector's success and innovation (Sum4all, 2023). Several women have made significant contributions to the rail industry, advancing state-of-the-art technologies and playing leadership roles in engineering and design (Lester, 2023). Reducing the gender gap in the workplace is a central issue in today's political and social agenda. Despite this, some sectors, such as the railway industry, remain deeply male-dominated and present various barriers that hinder women's access and retention. Although different efforts have been made to improve female representation in the railway sector, there are still few women in it, occupying positions traditionally associated with women and with difficulties in accessing leadership positions, thus demonstrating the persistent difficulty of access and professional development.

[1] Original title: "MujerES en el Ferrocarril"

6.1 Methodology

This analysis conducts a literature review to determine the current state of the art on the gender gap in the railway sector. The objective is to generate a holistic view of the current situation of women in this industry, encompassing their roles as workers, potential workers and users.

To achieve this, a qualitative methodology has been implemented. Specifically, a review of the published literature related to women in the railway sector produced from 2014 onwards has been carried out. This review employs a descriptive and narrative approach to group and synthesise the available knowledge, identify trends, as well as aspects to be improved and generate a global vision of the analysed issue. This type of review was chosen because it allows the selected articles to be grouped according to the meaning of their results, thus organizing the information in a coherent and meaningful way. In addition, it allows inquiring into a wide variety of topics, approaching the situation from different angles and with different levels of completeness (Guirao Goris, 2015). In this way, an update on the most relevant aspects in an evolving area, such as the presence of women in the railway sector, is achieved.

As mentioned in the paragraph above, a search of relevant literature produced over the last decade was conducted. This timeframe has been selected to provide the most contemporary overview of the situation. The review includes the analysis of scientific publications, academic papers, European and national research projects, and initiatives developed by key entities in the railway sector. This approach has facilitated the understanding of the status of women in these fields. The analysis has identified the progress made, areas needing further advancement, and aspects that require enhancement. Due to the limited academic production focused specifically on this issue in the railway sector, it was decided to extend the review to those texts found that focus on the transport sector, as a parallelism between the gender gap in both industries is perceived.

The search process was structured around an initial set of questions related to the situation of women in the railway sector. These questions were categorised into the three main groups mentioned previously. To achieve the general objective, the following main three research questions are established to cover the key aspects to be analysed:

- What are the main barriers and opportunities for the participation and professional development of women currently working in the railway sector?
- What factors influence the decision of young women, students and potential workers to choose or reject the railway sector as a career option?
- What factors most influence women's travel patterns and mobility decisions when using railway services?

Based on our questions, a set of keywords was obtained to conduct research for relevant information related to the topic. The main keywords used in the analysis were "women", "rail", "railway", "gender", "gender gap", "public transport" and "transport".

The text search was performed in the Web of Science and Scopus databases using boolean combinations of these keywords, in both Spanish and English. Once the main search in these databases was completed, the process was repeated in online search engines, including Google Scholar to avoid 'missing cases' out of the study. In this case, only the combinations of words that gave the highest number of results in the first part of the search were used. This process allowed us to gather information that had not been detected at the outset.

The following selection criteria were applied to select the material that was analysed. The texts that were selected had to be written between 2014 and 2025. The documents had to be written in English or Spanish and had to be focused on the railway sector specifically or the transport sector in general, but with special reference to railways. Papers from other areas of transport that are closely related to the railways, such as metro or tramways, were also reviewed. To determine whether the situation of women is repeated in similar areas, studies focusing on other areas of the transport sector, such as buses or bicycles, and related industries, such as car repair shops, are also reviewed. The publications selected for review had to address at least one of the three areas of interest. In total, 68 documents were reviewed.

The exclusion criteria established for the selection of texts are detailed below. For consistency with the timeframe, all documents published before 01-01-2014 were excluded, as well as informative texts without institutional backing or clear authorship. Research that referred to the railway sector but did not include a gender analysis or did not mention the situation of women in that context was not considered. It was decided to exclude documents that were not fully accessible and whose available information, such as the abstract or table of contents, did not allow for a proper evaluation. All studies with a focus on the global crisis caused by COVID-19 were excluded, as they analyse an exceptional short-term period that is not considered representative of the overall situation. When finding documents with duplicate data or very similar content, which has been particularly common in reports generated by institutions, priority was given to the most recent versions.

To complement the data obtained, an analysis of initiatives and reports developed by key entities in the railway sector was also conducted. The selection of these actions was made based on their relation to the objective of the study and their direct focus on the presence, inclusion and needs of women in the railway sector in one of the three areas analysed. First, the main railway entities at national (Spain) and European level were identified, using official sources such as the International Union of Railways (UIC) membership portal and the Board of Trustees of the Spanish Railway Foundation (FFE). In addition, professionals from the railway sector, including companies such as Siemens Mobility, were contacted for assistance in identifying key organisations and initiatives. Following a review of all identified documents, only those addressing gender issues and the situation of women railway workers that had been developed from 2014 to the present were selected for further consideration. Initiatives without a clear focus on gender issues, or those lacking institutional backing, were excluded to ensure the consistency and rigor of the analysis. In total, 10 documents were reviewed.

6.2 Results

WOMEN AS WORKERS

The review has shown that there is widespread gender inequality in the railway sector. Women are poorly represented in this segmented a male-dominated sector and face various difficulties in terms of access, retention and promotion. The following section examines the situation of women in this industry, analysing their level of participation and the benefits of ensuring gender equality in the work environment.

Research conducted by academia and various railway organisations demonstrates that the transport sector is predominantly male dominated, with the railway sector being no exception. In Spain, for example, women constituted 27.9% of the workforce in railway-related sectors in 2023 (Fundación de los Ferrocarriles Españoles [FFE], 2024). Focusing exclusively on the primary railway entities in Spain, the female workforce in the same year was 20.4% female (FFE, 2024). To provide some context, it is noteworthy that the total percentage of women in the Spanish workforce was 47.31% (Instituto Nacional de Estadística [INE], 2023).

This situation is comparable to other European countries, where similar situations can be observed. The countries with the highest numbers of female transport workers are Latvia, Cyprus and France, with around 30% of the workforce being female. Conversely, the lowest percentages were recorded in Malta, Greece and Romania, at around 15% (Fraszczyk & Piip, 2019). From a global perspective, it has been reported that within the global transport, storage and communications workforce, the proportion of women in employment is only 16% (Dominguez Gonzalez et al., 2023).

Women working in the railway sector are not equally represented in all areas of work. This sector is deeply segmented, both horizontally and vertically (Mejia-Dorantes, 2019). In passenger operators (public, private, regional and metropolitan), freight operators and large companies in the railway industry, women mainly occupy public-facing positions related to administration, ticket sales and revision, and customer service (FFE, 2024), as well as catering and cleaning (Dominguez Gonzalez et al., 2023). Keeping women in these positions traditionally accepted by society limits their access to other areas of the industry that are still dominated by a male presence. An example of this is that only 1.5% of female workers are engaged in railway driving in Spain. This low number is repeated in other European countries such as France (5%), Norway (5%) or the United Kingdom (5.2%) (Ballesteros Doncel & Maira Vidal, 2019).

Segmentation is also evident in the holding of leadership positions. According to Wright in the panel The Glass Ceiling, senior management can be classified into three categories: senior executives led by the CEO (C-Suite); line managers, who manage a core business division within the company and move up as CEO; and, at the same level as these, executives who manage a specific business function or department that serves all operating divisions, such as HR, Communication or Marketing (2025). Historically, women in executive leadership positions have been in the latter group (Wright, 2025), which means they are often excluded from the high-decision-making positions.

The Community of European Railway and Infrastructure Companies (CER) observes a slow but progressive trend change. Its sixth annual report (2020) shows that between 2012 and 2018, female participation in management positions in the European rail sector increased from 17.6 % to 20.9 %, with rises at all levels: top executives (+7.2 %), middle management (+3.0 %) and team leaders (+1.8 %) (Community of European Railway and Infrastructure Companies [CER], 2020). However, this progress remains fragile. In Spain, for example, the proportion of women in top positions fell sharply from 21.9 % in 2021 to 13.8 % in 2023 (FFE, 2024). While the report does not explore the causes of this decline, it would be very relevant to understand them to determine if they align with the causes of exclusion identified by the academy.

The under-representation of women in senior positions is a major obstacle to closing the gender gap in the railway sector. The lack of leadership figures limits the existence of female role models. This makes it difficult for other women to project their professional careers in the industry and reinforces the perception that this is a sector 'for men' (Mejia-Dorantes, 2019), as women, not being represented, feel out of place. The absence of female leaders affects both female employees and female clients. Given the low presence of women in top decision-making positions, companies are unaware of their specific needs and therefore unable to implement measures that are truly adapted to them and improve their situation (Dominguez Gonzalez et al., 2023). In this way, a vicious circle is generated between the low representation of women in the sector and the lack of an adequate gender perspective in the planning and management of transport infrastructures (Mejia-Dorantes, 2019). Research shows that there is a positive correlation between the presence of women in leadership positions and an increase in the number of women entering the workforce (Ng & Acker, 2020). One of the main reasons for this is that women in such positions are aware of the structural barriers and needs of female workers, and therefore have a strong capacity to create safer, more diverse and equitable workplaces, resulting in financial and performance improvements, as well as the innovativeness of teams (Schomer & Hammond, 2020).

Women entering the railway sector face more difficulties than their male coworkers. These obstacles are classified as explicit and implicit barriers (Ballesteros Doncel & Maira Vidal, 2019). Explicit barriers are understood as those that are visible, material and concrete, such as the lack of differentiated spaces or work clothes adapted to the female body. Implicit barriers refer to beliefs, stereotypes and prejudices that affect the performance of women's work activities, who experience rejection when they are perceived as carrying out a job that does not correspond to their gender role (Ballesteros Doncel & Maira Vidal, 2019). This combination of discriminatory attitudes forces women workers to make great efforts to prove their worth and integrate into the team. In addition, they may face harassment from other employees because

they are perceived as mere objects of desire (Godoy, 2023). The result is a high drop-out rate from the sector (Fraszczyk & Piip, 2019). There are other factors that act as barriers to women entering and developing their careers in the railway sector. These include the difficulty of balancing work and family life, the low presence of women in STEM studies and the lack of a clear career path (Pirra et al., 2020; Ng & Acker, 2020).

It is crucial to understand why gender equality is so important in the railway sector. With an ageing workforce in need of generational change, it is imperative to harness the full potential that women can bring to the industry. Leone, Lacey and Barnes-Farrell (2024) detail in their research how the rail industry can benefit from implementing equitable and diverse work teams. Gender diversity improves the physical, mental and financial well-being of men and women. There is evidence that gender diversity in management positions can improve the performance and innovativeness of companies, as well as increase organisations' commitment to environmentally sustainable practices and social well-being (Leone et al., 2024).

Based on the above, it seems evident that gender inequality in the railway sector is not only a representation issue. This represents a structural problem that limits women's access, visibility and career development opportunities. Commitment to reducing the existing gender gap is necessary to create a sustainable, diverse and competitive industry.

WOMEN AS POTENTIAL WORKERS

The debate on the recruitment and career development of women in the transport sector is still largely unexplored. Therefore, studies and research focusing on this issue are scarce and even more unusual in the railway sector specifically, although there are some recent examples in Europe, Australia and Japan (CER, 2020; Kitada & Harada, 2019; Piip, 2020). Due to the scarce literature available, the texts found focusing on the railway sector and those focusing on the transport sector in general were reviewed to find out what the real reasons are for the low number of women entering the sector and what actions companies and organisations are taking to reduce this gap.

Some of the texts reviewed seek to identify the main barriers that hinder and slow down women's access to the railway or transport sector. It is an industry perceived as unattractive to women due to the lack of diversity among its workforce, the persistence of gender stereotypes associated with professions in these fields, the masculinisation of the sector or the lack of an appropriate environment and equipment for them (Godfrey & Bertini, 2019; Ng & Acker, 2020; Pirra et al., 2020). The lack of a defined career path, limited development opportunities and poorly targeted recruitment processes also limit women's interest in working in the sector (Godfrey & Bertini, 2019; Ng & Acker, 2020). The same is true for the difficulties they face in achieving a work-life balance and the persistence of harassment, bullying and discrimination (Godfrey & Bertini, 2019; Ng & Acker, 2020). In addition to the above factors, several studies establish a direct link between the low number of women entering the rail and transport workforce and the low participation of women in STEM studies (Ng & Acker, 2020; Pirra et al., 2020; García-Jiménez et al., 2020).

Transport-related sectors offer a wide variety of different occupations, but a large proportion of the jobs are related to STEM fields (Godfrey & Bertini, 2019). Today, these sectors need to hire personnel with skills related to the used of modern communication technologies, robotics and artificial intelligence (Piip, 2020), so STEM skills will also be needed in fields unrelated to these areas, making it imperative to develop initiatives that focus on women in these disciplines (Ivey, 2019). Over the last few years, a network of European associations, mentorships and European projects has been created to raise awareness of the potential of young female students in STEM careers, but very few of these initiatives focus on attracting female students to the transport sector in particular (Pirra et al., 2020) and, although the presence of women in STEM careers has increased, transport-related jobs remain male-dominated (Godfrey & Bertini, 2019). Rönnlund & Tollefsen argue that young female students need to be prepared for the difficult transition from education to work that they often experience in STEM fields, as they face great pressure from their work environment and find multiple inequalities they do not expect (2023).

Maternity is another barrier to entry and retention of women in the railway sector (Ng & Acker, 2020). Indeed, many women leave their professional careers after having a child (Fraszczyk & Piip, 2019). Implementing practices that support motherhood is a way to retain women in their roles after becoming mothers, while also attracting new talent to enter the sector (Baruah & Biskupski-Mujanovic, 2021). Some of these measures include offering flexible working hours, maternity and paternity leave and childcare support (Baruah & Biskupski-Mujanovic, 2021). In The Glass Ceiling panel organised by the History Council of Victoria, Claire Wright (2025) recounts the situation of women in the 1980s and 1990s, when they were forced to choose between career and family. If they decided to try to balance both they had to face numerous barriers, such as the lack of support in the workplace (Wright, 2025). This, combined with the socially assigned role of women as caregivers, led many to prioritise motherhood and domestic responsibilities over their professional careers (Wright, 2025). It may appear to be an issue of the past, but the idea that successful women must be able to balance family and work is still deeply rooted in our society today. Digital environments, such as social media, streaming platforms, video games, and forums, have a powerful capacity for globally spreading messages, often reinforcing stereotypes as the "Superwoman": an all-powerful woman who can build a successful professional career while also taking full responsibility for her home, raising her children, and maintaining an excellent physical appearance (Gilló Girard et al., 2024). This absence of role models narrows the professional aspirations of young women, reinforcing the idea that their value lies in serving others and perpetuating their relegation to domesticity (Gilló Girard et al., 2024).

Throughout their professional lives, women prioritise feeling fulfilled at work and tend to leave their jobs when they see no opportunities for career advancement (Fraszczyk & Piip, 2019). This is another reason why efforts must be made to ensure that women perceive the railway sector as a place where they can develop their professional careers. To achieve this, mentors are very useful in persuading other women to enter the railway sector, as they are an example that a successful career in this industry is possible (Fraszczyk & Piip, 2019). Women networking meetings have a similar effect, since they are safe spaces to share experiences, build connections and voice everyday inequalities (Leone et al., 2024). Likewise, it has been shown that membership in transport organisations for female professionals (Women in Rail, Women in Transport, Women in Mobility, etc.) has a positive impact on women in the sector, offering spaces to share concerns and find collective solutions (Fraszczyk & Piip, 2019).

Promotion about gender diversity in the rail and transport sector does not only benefit women. Transforming the sector to make it more attractive to potential female employees is crucial for increasing collective well-being, productivity, innovation and economic growth, as gender diversity creates benefits (Ng & Acker, 2020). Recognising the importance of bridging the gender gap, research explores how to improve women's interest in the sector and increase their recruitment. To attract and retain young people in the rail sector, regardless of their gender, it is recommended that clear promotion pathways be established, and that recruitment and induction processes be modernised (Piip, 2020). In addition, it is essential to provide opportunities for professional and educational development, access to mentors to serve as guides and role models, and to foster an attractive and sustainable working culture (Godfrey & Bertini, 2019; Ng & Acker, 2020; Piip, 2020). In addition, it is important to support women workers' participation in professional organisations and encourage networking (CER, 2020; Godfrey & Bertini, 2019). Effective communication is key to increasing women's interest in the sector. Research highlights the importance of campaigns that show a diverse and inclusive organisational image, committed to gender equality (CER, 2020; Godfrey & Bertini, 2019). Other measures taken by several European companies to promote women's employment and career development include ensuring reintegration after maternity, setting specific targets for the recruitment of female employees, improving health and hygiene conditions and reducing the pay gap (CER, 2020).

WOMEN AS USERS

During the literature review it was found that most of the existing contributions examine women as users from the perspective of public transport, mobility and transport in general. The documents specifically addressing the rail sector focus mainly on safety at stations, during the journey and on the way to the station, although there are also those that analyse travel priorities, perceptions of service quality and factors that favour or limit the inclusion of women. Some also analyse the different socio-demographic factors that influence the mobility of public transport users, such as age, place of residence and gender. The latter has been identified as the most important determinant of women's mobility choices and attitudes towards different ways of travelling (Ng & Acker, 2018).

Literature indicates that women's mobility is more challenging than men's (Pirra et al., 2021) as their activity patterns and travel chains are much more complex (Basbas et al., 2023). This often results in women preferring to use forms of transport that offer great flexibility in their travel, such as the private car (Ng & Acker, 2018), despite this, women are the main users of public transport. Heather Allen's study of the cities of Buenos Aires, Quito and Santiago de Chile estimated that, in all three capitals, journeys made by women account for more than 50% of public transport trips in each city (2018). In contrast, men tend to opt for private car use (Basbas et al., 2023), as they traditionally prioritise the use of the family car (Pirra et al., 2021).

A significant proportion of the literature reviewed focuses on identifying gender differences in transport in terms of mode of transport, travel time, purpose, chain and travel distance. To better define the complex mobility patterns of women, in 2009 the author Inés Sánchez de Madariaga introduced the term Mobility of Care (Porath & Galilea, 2025). This concept encompasses all journeys made daily to carry out care-related tasks (Sánchez-De Madariaga & Zucchini, 2020). These are unpaid activities, carried out mainly by women, which are usually compatible with paid employment, and which must be done with multiple trips to different parts of the city, at a specific time and using the available transport systems, under conditions of price, ergonomics and safety (Sánchez-De Madariaga & Zucchini, 2020). In the presence of children and elderly people in the care of women, these trips can become even more complex (Pirra et al., 2021), which is consistent with Wei-Shiuen Ng and Ashley Acker, who report that women in their forties make the most trips for caregiving purposes and that women make 77% more trips per day with children than men (2018). Sánchez de Madariaga estimated that, in Spain in 2007, 25% of public transport trips were made for caregiving reasons (Porath & Galilea, 2025).

These obligations require women to travel to different places at specific times, affecting their movement patterns (Scheiner & Holz-Rau, 2017). Several studies agree that women and men travel differently. These travel patterns are not universal and vary in some countries depending on their public transport system and social norms (Dominguez Gonzalez et al., 2023). Despite this, the data reviewed argue that gender-differentiated travel dynamics are very similar in most developed and developing countries.

Men tend to make long and direct trips (Allen et al., 2018), which correspond to commuting to and from work (Scheiner & Holz-Rau, 2017). For them, rail transport is often well suited to their travel needs (Allen et al., 2018). However, they prefer to use their private vehicle whenever possible, considering using public transport instead when a car is not a viable option (Basbas et al., 2023). Women use public transport more than men (Allen et al., 2018). They make more and shorter journeys during the day (García-Jiménez et al., 2020; Allen et al., 2018), which coincides with care trips in addition to work trips. Because of this, they organise complex travel chains to fulfil their daily obligations (Scheiner & Holz-Rau, 2017). In addition, women tend to travel outside peak hours (Ng & Acker, 2018). Even though male commuters make more trips for work and female commuters make more trips for care purposes and the differences between their commutes, both genders spend a similar amount of time on their journeys (Allen et al., 2018).

Referring to the term coined by Sánchez de Madariaga, Porath and Galilea (2025) define the concept of (im)mobility of care. It refers to the limited ability to move freely around the city, resulting from structural, social and gender factors that unequally affect women and other groups. Immobility is not synonymous with not moving, but doing so under disadvantageous conditions, with fragmented routes, limited time and less autonomy, mainly due to care responsibilities and a transport system that does not consider women´s specific needs (Porath & Galilea, 2025).

Undoubtedly, gender is a determining factor in women's mobility (Ng & Acker, 2018). However, not all women are the same and there are other socio-demographic variables that affect how women travel as well as their decision-making (Porath & Galilea, 2025; Pirra et al., 2021). One of these is the place of residence. The closer the proximity to urban areas, the higher the density of road and rail networks, which increases the supply of formal and informal transport services (Dominguez Gonzalez et al., 2023). For this reason, residents of suburban and rural areas are often unable to find efficient alternatives to the car given the low availability of public transport (Basbas et al., 2023; Pirra et al., 2021). Rural women generally feel safer in their place of residence and at railway stations compared to urban women. However, they are also more likely to take precautionary measures before traveling (Ceccato et al., 2024b). However, women are 1.8 times more likely to be victimised at the station in rural areas and therefore avoid them more often in the evening, preferring to travel in company (Ceccato et al., 2024b).

Olmo Sánchez and Maeso González (2016) assert that women have a greater sensitivity to change than men, which causes them to modify the way they travel over time. Young women (aged 18 and under) are more likely to be victimised, and the most common types of victimization experiences are of sexual nature, including stalking and sexual harassment (Ceccato et al., 2024b). Despite this, older women tend to be more fearful (Ceccato et al., 2024b). In the case of rail transport, young women without children are more likely to use it, although this tendency changes when travelling with children or pushchairs due to the structural and functional limitations of rail transport in terms of accessibility and flexibility (Allen et al., 2018). The sense of security when travelling on rail transport such as the metro decreases with age, while the opposite is observed for buses (Ait Bihi Ouali et al., 2020). Women in their youth or from the age of 50 onwards make greater use of public transport than in their 30s and 40s, when they use private transport more, coinciding with the time when they have more household responsibilities (Sánchez & González, 2016).

Several researchers agree that women belonging to minority groups are more likely to find the public transport available to them inadequate (Pan & Ryan, 2023). Ceccato (2024a) highlights that, among commuters, LGBTIQ+, disabled and economically disadvantaged women experience a greater fear of violence when travelling than other users. Ethnic minority women, especially those on low incomes, are particularly dependent on public transport, even if they perceive it as inefficient or unsafe, as they often have limited access to a private car and are even less likely to have a driving licence (Chowdhury et al., 2024), and women in general still have less access to a private car than men (McIlroy & McPeake, 2025).

Women with children and housewives experience greater limitations in their mobility capacity (Porath & Galilea, 2025). The presence of children, especially those aged 10 years or younger, makes mothers' commuting routines more complex, but does not have the same impact on fathers' (Scheiner & Holz-Rau, 2017). Living with a partner tends to simplify women's daily lives more than men's, reflecting a traditional division of roles in the household that, while reducing the complexity of routines, also perpetuates gender inequalities (Scheiner & Holz-Rau, 2017). As incomes increase, the mobility gap between men and women narrows and women adopt mobility patterns more similar to those of men, especially if they have the possibility of acquiring a private vehicle for themselves (Allen et al., 2018).

All of the above factors directly influence women's travel behaviour, but according to the studies reviewed, the perception of safety is the personal aspect that most affects mobility patterns and travel behaviour and remains one of the main barriers to mobility. These texts clearly reflect that there is a gender gap in the perception of safety and security. Laila Ait Bihi Ouali (2020) shows in her study that women tend to feel more insecure than men when using the metro and bus, a feeling that increases in night commuting (Carver & Veitch, 2020). Situations of violence during commuting are a reality for many women. In rail transport, trains and stations are often vulnerable spaces where the number of sexual harassment and assault cases has increased (ITF, 2018), but female users do not report them most of the time (Allen et al., 2018). Both genders show concern about safety when using public transportation, however, men show more concern about theft and arguments escalating quickly while women are primarily concerned about the possibility of sexual assault and harassment (Allen et al., 2018).

These forms of violence are highly traumatic and generate fear based on personal or other people's experiences (Allen et al., 2018), influencing the characteristics of the trip, as well as the choice of route and means of transport (Basbas et al., 2023). To increase their safety while traveling, women tend to choose transportation alternatives where they feel safer even if they involve a higher cost (Dominguez Gonzalez et al., 2023). Similarly, they take precautionary measures to protect themselves, such as avoiding certain stations at specific times of the day, traveling accompanied, not wearing certain types of clothing (Ceccato et al., 2024a), keeping in touch with family members and hiding behind their cell phones (Chowdhury et al., 2024).

Safety has a great influence on the satisfaction of female users (Pani et al., 2023). Research agrees that gendered travel needs should be a priority for the transport sector (Sil et al., 2024) but, even so, the design of public transport still fails to address the specific needs of women and vulnerable groups (Chowdhury et al., 2024) and an inequality is detected between the measures adopted and those perceived as most effective by female users (Useche et al., 2024). Actions such as the implementation of gender-segregated carriages have shown not to be as effective as expected and continue to present challenges to women's mobility (Arundhathi, 2024; Tillous, 2020). Some of the research analysed proposes measures to improve the situation of women such as changes in the transport and stations design to adapt them to their needs, reinforcement of surveillance services (Pirra et al., 2021), awareness campaigns and training staff to deal with violence (Mandhani et al., 2021). To encourage greater use of public transport by women, measures must be taken to ensure that it is safe, attractive, frequent, punctual, affordable, accessible and widespread (Dominguez Gonzalez et al., 2023; Mandhani et al., 2021). These aspects cannot be improved without the involvement of transportation companies, policy development agencies and educational institutions in the implementation of measures to ensure equal access to transportation (García-Jiménez et al., 2020).

6.3 Discussion and conclusions

Through the review and analysis of the literature, it has become clear that there is a profound gender inequality in the railway sector, as well as in the other industries related to the transport sector. This inequality happens transversally in the three dimensions studied: women as workers, as potential workers and as users.

Women workers in the sector face a deep occupational segregation, both horizontally and vertically. They are under-represented in technical positions, being relegated to tasks that have traditionally been considered as appropriate for them. The same happens in leadership positions, where they face limitations that hinder their opportunities for promotion in their professional careers and lead them to drop out of the industry. The lack of female role models, the deep-rooted gender stereotypes and the barriers to entry continue to perpetuate the masculinization of this work environment, making it an exclusive and non-diverse space where women feel they do not belong. The low number of women in leadership positions is the result of a system created and designed by and for men, in which measures to reduce the gender gap are more symbolic than effective. The low presence of women in decision-making generates a vicious circle, since, without women in positions of power, the necessary structural transformations that address the needs of female employees and clients are not carried out and, therefore, the existing explicit and implicit barriers continue to be reinforced.

The low interest of women in joining the railway sector is caused by several factors and cannot be seen as an isolated problem, as it is the result of a system that is not designed for them and that makes sporadic and disorganized efforts to try to promote their inclusion. The low presence of women in STEM studies, outdated and non-inclusive recruitment processes and organisational cultures that continue to allow situations of harassment and discrimination mean that not many women see the railway sector as a good option for developing their careers. This disinterest and early dropout are also reinforced by the lack of work-life balance policies, the absence of clear career paths and the lack of role models.

Women are the main users of public transport. However, it is still not designed to suit their needs. Women face more complex and unequal mobility patterns because of the role of caregivers that society has assigned to them. They are more sensitive to change, so their travel preferences and needs vary throughout their lives. Safety is the factor that most determines the travel of women users, who tend to be concerned about possible situations of harassment and sexual violence at all stages of the journey (on the way to the station, at the station and in the coach) and especially at night. The fact that women still fear for their safety shows that the measures implemented are ineffective and unsuccessful. Some of these measures include creating women-only spaces, modifying stations to reduce the feeling of unsafety, increasing station security systems (like security and surveillance personnel, video surveillance cameras, etc.) and training staff on how to act in the event of violence. However, it is striking that none of these actions focus on raising awareness among men who use these means of transport. Women 's safety cannot be their responsibility alone. It must be recognized as a shared social and institutional duty. Public administrations and companies must assume it as their responsibility and commitment. In addition, society must be made aware of this reality and re-educated to achieve truly safe environments. In this sense, measures should be designed and implemented after a real active listening to women's suggestions, needs and demands. Lawmakers and stakeholders should be truly aware of the relevance of promoting, strengthening and guaranteeing the involvement of women in the establishment of measures to improve the attractiveness of this sector in all areas.

From the three perspectives analysed, suggestions and initiatives for improvement are made. Some of these include creating links between women in the sector, preparing them for the difficult working environment they will encounter, and carrying out public communication campaigns to make the railway sector more attractive to women. Nonetheless, no initiatives have been found that aim to raise men's awareness to bring about significant changes in their behaviour and to facilitate the integration of female workers in the rail sector and make it safer for female users to travel. In addition, it is important to implement the DEI (Diversity, Equity and Inclusion) criteria, which extend beyond the gender issue, addressing the specific needs of other underrepresented and marginalised groups. It is essential to develop updated security plans and training programmes that address the needs of stakeholders and propose solutions to the structural problems facing the sector. Despite being the primary users of public transport, women are underrepresented in leadership positions and in decision-making within the rail industry. This suggests that the glass ceiling and the sticky floor are persistent, limiting their professional development and keeping them in the most basic positions. Subverting this reality is a key issue to achieve a real transformation of the sector.

As a result of the literature review carried out, we identified the following challenges:

- **Interconnected perspectives.** Women's roles as workers, potential employees, and users are closely linked and must be addressed together.
- **Barriers to leadership.** Occupational segregation, systemic barriers, and lack of role models limit women's access to leadership.
- **Mobility and safety challenges.** Current policies fail to address women's complex travel patterns and persistent safety concerns.
- **Path to transformation**. DEI principles, inclusive policies, and updated safety plans are key to breaking structural barriers.

Planned activities and expected outcomes of the research

This PhD aims to investigate the gender gap in the railway sector, focusing on improving women's experiences both as rail users and as members of the workforce. In addition to academic publications, the project will deliver an executive summary and practical outputs for industry stakeholders.

To address the main objective—examining the gender gap in rail companies and improving the experience of women as both rail users and workforce members—the research adopts a mixed-methods approach, combining quantitative and qualitative techniques. The methodology is structured into five phases covering the full research process. The sequence and interdependencies of the activities planned for this PhD are illustrated in Figure 5.

Specific actions that will be undertaken in the PhD research are:

Phase 1. Review. A systematic review will be conducted across four areas:

- Scientific publications (articles, books, chapters, papers).
- Academic work (PhD theses, Master's and Bachelor's dissertations).
- Research projects (national and European).
- Sectoral initiatives (studies, reports, equality plans, campaigns, awards, policies from associations, companies, and public/private bodies).

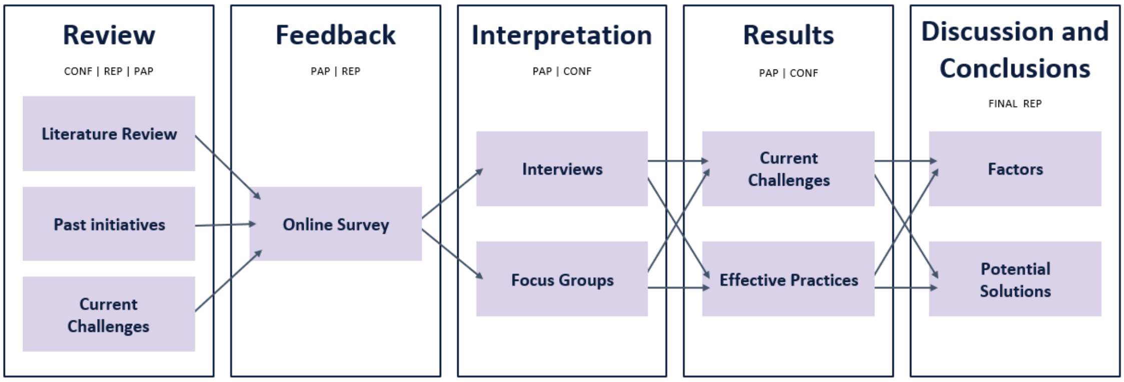

Figure 5-Order and relationships between the activities to be carried out in this PhD

Bibliometric and content analyses will be used to examine objects of study, methodologies, stakeholders, and conclusions. The review will cover the last 10 years, with a focus on women's representation in the rail sector and related industries, mobility habits, opinions, and assessments. This phase will also include data collection (with a gender-disaggregated focus) and stakeholder mapping.

Phase 2. Feedback. Online surveys will be designed and distributed across participating countries, targeting women in the sector—especially students and young professionals. The surveys, containing both open and closed questions, will adopt a gender perspective to explore women's roles as rail passengers and employees, highlighting specific needs and contributing to disaggregated data.

Phase 3. Interpretation. Survey findings will be validated through interviews and focus groups with companies, organizations, and women in diverse roles. The aim is to identify effective practices for recruiting and retaining women in the railway workforce and to design training solutions for HR departments. Input from gender equality experts in STEM, as well as collaboration with sectoral unions and associations, will help address stereotypes, the gender gap, and the glass ceiling.

Phase 4. Results. The analysis will focus on the challenges women face in rail—both as commuters and professionals—while identifying needs and best practices. This will lead to the creation of a handbook of good practices and the proposal of strategies for advancing gender equality in the sector.

Phase 5. Discussion and Conclusions. The final phase will synthesize the main findings, highlight the factors contributing to the gender gap, and propose actionable solutions. Following an action research approach, the study will not only analyze but also support the implementation of measures aimed at improving women's representation and experiences in the railway sector.

The research will generate knowledge about women as rail passengers, identify their specific needs, examine challenges faced by women in the workforce, and will propose effective practices to attract and retain female talent. A best practices manual, developed in collaboration with the UIC, will provide recommendations to help reduce the gender gap and glass ceiling in the industry. Thus, expected impacts include:

- Scientific publications (journal papers, conference presentations and proceedings…).
- Industry collaboration (work with UIC and Siemens Mobility has been already started).
- Supporting companies in promoting women's career progression and leadership opportunities, through a 'Handbook of good practices'.
- Policy recommendations to inspire female STEM students to pursue careers in the railway sector and other practical interventions to HR departments.

- Informing strategies to make rail transport more attractive for women and to highlight women's roles in rail.
- Final executive summary to disseminate.

The tasks to be conducted in this PhD, their timeframe and duration are visually represented in the Gantt diagram included in Figure 6.

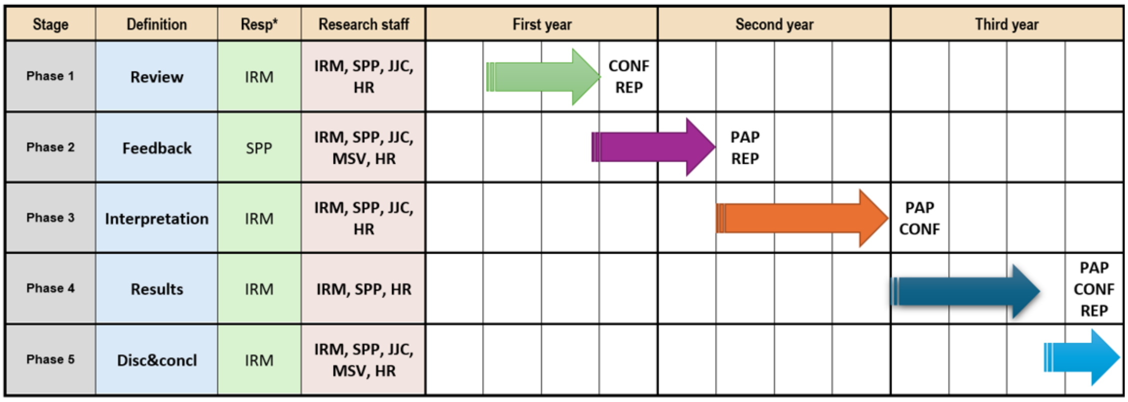

Figure 6-PhD 2 Gantt diagram.

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7 Education and Training in Railways

7.1 Introduction

Over the past two decades, the European rail sector has undergone profound transformations, reshaping the landscape of transportation and mobility. While these changes have been instrumental in driving progress and innovation, they have also given rise to two pressing challenges that demand urgent attention Firstly, demographic shifts, notably the impending retirement of a substantial portion of the workforce (*refer fig. 7&8*), pose a significant threat to the sector's sustainability. According to industry reports, a significant portion of the rail workforce is expected to retire due to demographic ageing, exacerbating the existing talent shortage within the industry (STAFFER, 2023; Robertson, 2022).

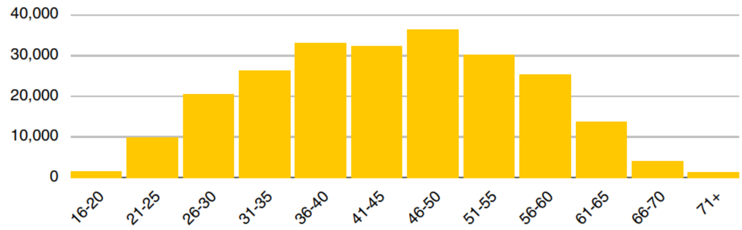

Figure 7-Age profile of current workforce

Source: (Annual Rail Workforce Survey 2023 NAVIGATING THE, n.d.)

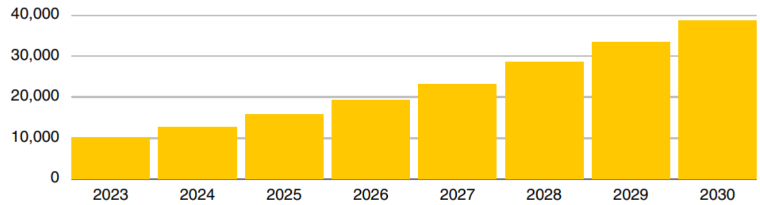

Figure 8-Rail industry cumulative retirees, 2023-2030

Source: (Annual Rail Workforce Survey 2023 NAVIGATING THE, n.d.)

Concurrently, the rapid advancement of digitalisation and high-tech technologies has created an unprecedented demand for skills and competencies that diverge from traditional expertise.

The rapid advancement of digitalisation and automation brings opportunities and challenges for the current rail workforce. The development of driverless prototypes and the adoption of Automated Train operation (ATO) models have the potential to make traditional positions like drivers and guards obsolete. The change extend to information points, ticketing offices, and station workers at ticket barriers, where technological improvements lessen the need for these professions. Online platforms and travel apps, for example, minimise the need for information points, and the change to paperless ticketing lower dependence to ticketing offices and people at barriers (Berti, A., 2019).

These challenges have highlighted the need for railway higher education programs that remain relevant and aligned with industry requirement.

7.2 Research methodology

The overall review methodology is outlined in *Fig. 9* below. The initial review is based on the previous EU projects that have made major contribution in the research of education and training in rail industry; namely, EURNEX (2004), TUNRAIL (2010), SKILLRAIL (2011), RIFLE (2013), SKILLFUL (2019), and ASTONRail (2023). The review also covers two systematic literature review about the curriculum evaluation, and they combined cover more than 156 review. Additional search was conducted to retrieve relevant peer-reviewed journal articles, conference papers, and industry reports published in recent years from databases such as Google Scholar, Scopus, Web of Science, and IEEE Xplore. This formed the basis (covering over 180 studies) of the review of existing rail curriculum evaluation practices and industry requirement.

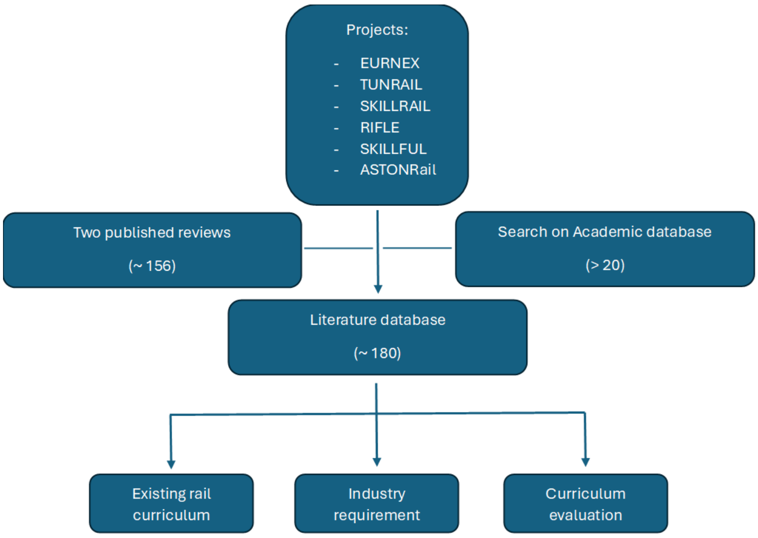

Figure 9-Review methodology

7.3 Existing rail curriculum in higher education

7.3.1 Structure and Content of Curricula

The overarching view of railway education in Europe is characterised by a broader and evolving nature of curricula, which strive to respond to the multidisciplinary and rapidly changing demands of the rail industry. The comprehensive analysis of existing railway programs reveals a wide range of technical, managerial, and cross-disciplinary elements that collectively form an integrated framework to equip students with the competencies necessary for effective professional practice.

Existing railway curricula encompass a wide range of technical, management, and cross-disciplinary topics. The RIFLE project modelled a railway engineering Master course (see *table 2*) with compulsory modules like fundamentals of railway engineering, rail control and signaling, rail infrastructure, railway operations, railway system design, railway operations safety, rail passenger and freight terminals, and railway vehicles. Optional modules included advanced railway technologies, maintenance of railway systems, railway traffic management, and rail freight yards.

Table 2-Railway engineering Master course structure according to RIFLE project

Source: (ASTONRail, 2020)

Compulsory Modules		***Optional Modules***	
1	*Fundamentals of Railway Engineering*	*1*	*Advanced Railway Technologies*
2	*Rail Control and Signalling*	*2*	*Maintenance of Railway Systems*
3	*Rail Infrastructure*	*3*	*Railway Traffic Management*
4	*Railway Operations*	*4*	*Rail Freight Yards*
5	*Railway System Design*		
6	*Railway Operations Safety*		
7	*Rail Passenger and Freight Terminals*		
8	*Railway Vehicles*		

Project such as ASTONRail looked at TUNRAIL (8 core competence areas and 35 keys skills), RIFLE and particularly SKILLRAIL (8 areas and 66 sub domains) that provided structured frameworks like competency matrices that effectively categorize the educational components, ensuring alignment with industry requirements (*see table 3*).

Table 3-SKILLRAIL matrix of competencies

Source: (ASTONRail, 2020)

General topic	Rail systems activities – Innovative materials and production methods – Safety Intelligent mobility – Environment – Other							
2nd level topic	Economics	Traction	Rail Vehicles	Civil Engineering	Operations	Systems Engineering	Control Systems	General Terms
3rd level topic	Whole life or life cycle cost	Diesel	Wheel	Track	Resource management	Interoperability	ERTMS	Human factors
	Business cases	Electric (including supply systems)	Wheel set	Stations	Timetable management	Risk analysis	ETCS	Simulation
	Demand forecasting	Traction drives	Wheel/rail interface	Bridges	Track capacity management	Failure mode analysis	Route-based signalling	Verification
	Revenue Forecasting	Magnetic levitation	Active steering	Tunnels	Passenger management	System modelling	Speed-based signalling	Testing
	Government regulation	Gas turbine	Suspension (passive)	Earthworks	Freight management		Computer-based interlocking	Remote monitoring
	Business strategy	Distributed power	Suspension (active)	Drainage	Security		Solid state interlocking	Reliability
		Braking	Body construction	Level crossings	Train regulation		Electric/mechanical interlocking	Availability
		Fuel Cells		Heating and ventilation			Automatic train control	Maintenance
				Lighting				Safety
								Component
								Passenger
								Freight
								Noise pollution
								Air pollution
								Sustainability
								Light rail and tram systems
								Electromagnetic compatibility

The curriculum also addresses innovative teaching approaches, such as railway operation laboratories, computer simulations, virtual labs, field visits, and global education programs. Key abilities include appreciation of other cultures, proficiency in diverse teams, cross-cultural communication, and dealing with ethical issues in a global context (ASTONRail, 2020).

Initiatives like RiFLE and ASTONRail emphasize the growing importance of multidisciplinary learning and student-centered, competence-based pedagogy. Curricula increasingly move beyond traditional lecture formats to include. These methods aim to bridge the gap between theoretical instruction and real-world application. The RiFLE project, for example, aimed to develop a multidisciplinary curriculum by analyzing and adapting existing courses across participating universities.

Marinov et al., (2013) study revealed that companies indicated a need for staff training to improve operations management skills, suggesting a demand for practical application of knowledge. While companies have varied preferences for the format and duration of employee education, options include evening courses, part-time, full-time, distance learning, and block learning. Many companies collaborate with higher education institutions by providing guest lectures, scholarships, and career services support.

The duration and level of specialization vary. A database categorizes programs by type (Bachelor, Master, PhD) and railway specialization based on credit percentage, also including program duration (ASTONRail, 2020). The MSc in Rail Freight and Logistics, for instance, employs a flexible model integrating subjects from different universities, designed to grant 90 ECTS credits (Marinov and Fraszczyk, 2014). Some programs also incorporate cultural and international elements, with student mobility encouraged for module completion (Ricci et al., 2011).

7.3.2 AI tools in education and training

Lestari, (2024) study highlighted that AI tools are transforming railway education and training by enhancing learning experiences and customizing instruction. These tools play various roles, including curriculum delivery, learner engagement, competency assessment, and personalized learning. AI facilitates personalized learning pathways by analysing student data to identify strengths and weaknesses.

Cengage also looks at five use cases on how AI can be used to support teaching and learning and indicates:
1] AI for Student Success and Personalized Learning

2] AI for Lesson Planning

3] AI for Administrative Tasks

4] AI for Classroom Engagement

5] AI for Assessment

Cengage is developing AI to create personal, equitable, and meaningful educational experiences, empowering students and educators in higher education. Their AI tools complement classroom learning by helping students apply what they have learned. A GenAI-powered Student Assistant tool is expected to include more features to enhance learning and provide analytics for targeted instruction, expanding to additional courses and platforms in the fall of 2025.

AI technologies like natural language processing are increasingly used for education feedback analysis, personalized teaching, and remote education (Lestari, 2024). AI can enhance conceptual understanding, offer personalized instruction, promote social interaction, and improve assessment methods (Lestari, 2024). Educators are encouraged to increase their AI literacy to effectively use AI tools (Lestari, 2024).

However, there are concerns about the risks associated with AI in education (*refer fig. 10*).

Many instructors feel they need support from their institutions to navigate these challenges and set clear standards and boundaries for AI use (Cengage, 2024).

Aston University circulated a briefing note explain the application and use of AI in learning, teaching, and assessment which instructed that programme teams determine effective approaches, subject to principles for assessment and an AI code of conduct. Students must understand whether AI use is permitted for each assessment, and this must be explicitly stated in the assessment brief. AI can be essential, optional, or prohibited based on learning outcomes and disciplinary norms. If use is permitted, students must acknowledge it fully.

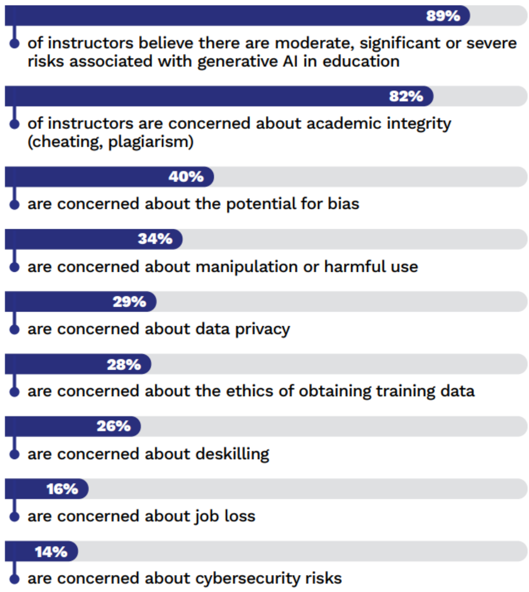

Figure 10-Risk and ethics concerning AI in education and training

Source: (Cengage, 2024)

Constructive uses of AI include summarizing text, generating images, providing feedback, and engaging with educational platforms. Aston encourages students to use technology constructively in their studies. Aston has principles for AI engagement, emphasizing leadership, good academic practice, and assessment literacy. The code of conduct calls for transparency, collegiality, constructiveness, creativity, and ethical considerations. AI tools should be disclosed, especially when generating content, and their use should be discussed with colleagues. Students should use AI as a starting point to assist thinking rather than replace it. It is crucial to reference all sources, including AI. Work submitted must be the student's own, and misuse of AI is a breach of regulations. Aston uses tools to detect AI use and encourages responsible application for enriching learning.

7.3.3 Best Practices in Curricula development

Developing railway curricula in higher education involves several best practices and methodological approaches.

The development of railway curricula in higher education has evolved from rigid, discipline-based structures to more dynamic, competence-driven, and future-oriented models. These advancements are informed by both educational theory and direct engagement with industry needs, ensuring programs are academically rigorous while preparing graduates for the complexities of the modern rail sector.

A notable approach is outlined in the work of Schlingensiepen (2014), who emphasizes a competence-driven methodology for curriculum development. This model focuses on identifying and structuring the specific skills and knowledge (competencies) that students must acquire to be effective in their professional roles. In contrast to traditional subject-based education, this methodology aligns closely with the Bologna Process, promoting modularity, transparency, and mobility across European higher education institutions.

Curriculum engineering under this model defines a structured hierarchy of modules, which represent distinct learning units delivering specific competencies. These modules may include a combination of lectures, laboratories, and projects, and are often interlinked through defined entry requirements or pre-requisites, allowing for personalized and flexible learning pathways—particularly vital for Master's level students with diverse educational backgrounds. To operationalize this, a competency tree is used to map industry requirements to educational offerings, with Boolean matrices enabling analysis of curriculum adequacy and identification of learning gaps.

Complementing this framework, the SKILLFUL project introduces best practices from a future skills and lifelong learning perspective. With the transport sector rapidly adopting technologies such as automation, digital connectivity, and intelligent infrastructure, curriculum design is increasingly centered around interdisciplinary thematic courses that address emerging services, tools, and professional roles. The project advocates for a Pan-European core syllabus for Transport Engineering at the master's level, complemented by transnational specialization modules tailored to regional contexts and sector-specific challenges.

Teaching methodologies also reflect this innovation-driven approach. Blended learning, virtual and augmented reality-based training, and simulated environments are gaining prominence, enhancing engagement and providing experiential learning opportunities beyond the traditional classroom. These tools not only increase accessibility and adaptability but also cater to the needs of professionals engaging in lifelong or part-time education.

Together, these practices reflect a shift toward flexible, personalized, and competency-aligned education, ensuring that railway curricula are not only academically sound but also responsive to the technological, operational, and societal changes reshaping the transport landscape.

7.4 Industry requirement

The effective alignment of railway higher education curricula with real-world industry needs is essential to ensure graduate employability and workforce readiness. The ASTONRail project provides critical insights into the competencies and expectations of the railway sector, offering a structured framework for curriculum development through the Rail Career Matrix (RCM).

The Rail Career Matrix is a pivotal tool that maps job roles to career levels across various functional areas in the rail industry (see fig. 11).

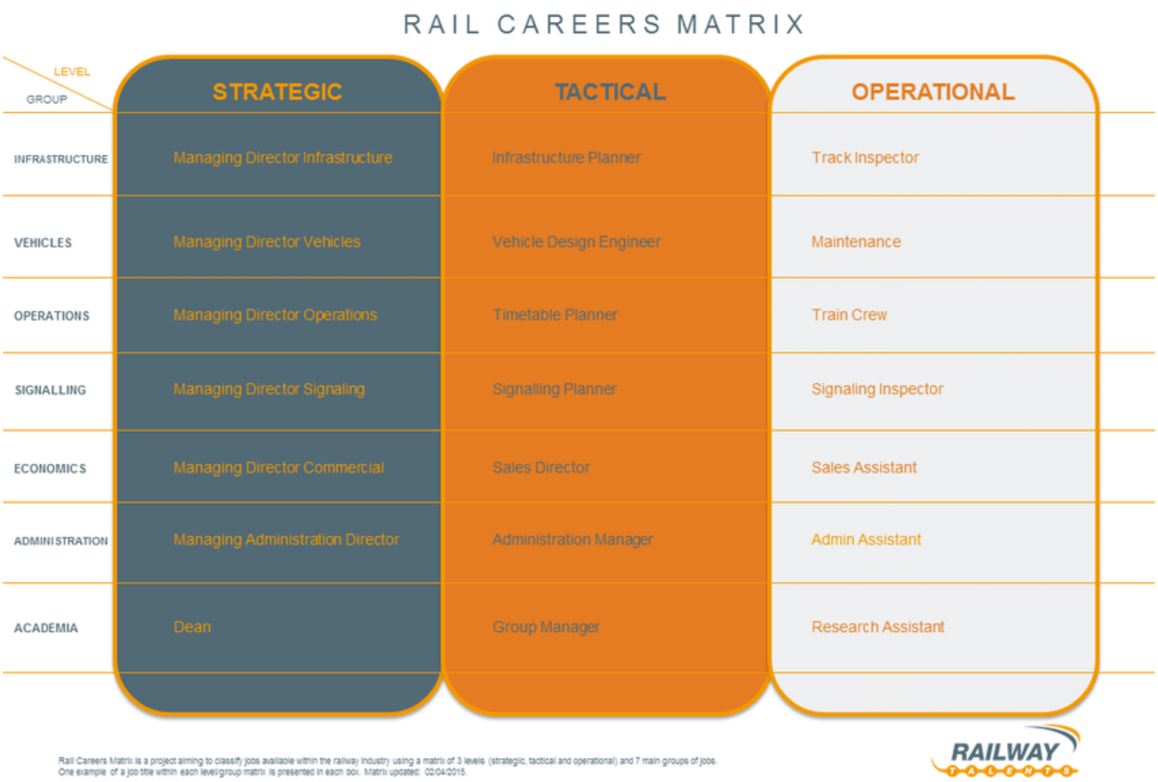

Figure 11-Rail career matrix

Source: (Railtalent, 2018)

This matrix serves as a bridge between academia and industry, providing clarity on the progression of roles and the associated competency requirements at each career level. It helps identify which knowledge areas and soft skills are essential for various functions, thereby informing curriculum designers of the learning outcomes necessary for industry alignment.

The ASTONRail findings show distinct expectations across career levels:

1] Operational Level: Emphasis is placed on technical proficiency, hands-on skills, and compliance with safety standards. Workers at this level are expected to operate systems, monitor performance, and carry out basic troubleshooting. Competencies include familiarity with signaling systems, maintenance routines, and passenger safety protocols.

2] Tactical Level: Here, the focus shifts to team leadership, problem-solving, and process optimization. Professionals are expected to apply engineering principles to manage resources, coordinate projects, and implement solutions. Competencies include data interpretation, team management, and effective communication with cross-functional stakeholders.

3] Strategic Level: At this level, professionals are expected to engage in strategic planning, policy development, and innovation leadership. Key competencies include systems thinking, digital transformation strategy, regulatory compliance, sustainability integration, and the ability to anticipate future mobility challenges.

Across all levels, industry stakeholders consistently highlighted the importance of digital competencies, interdisciplinary knowledge, project management, and soft skills such as communication, adaptability, and cross-cultural collaboration.

7.5 Curriculum Evaluation practices

7.5.1 Methods and Frameworks for Evaluating Higher Education Curricula

Curriculum development and evaluation are vital elements of the educational planning process, and different models have been developed to analyse curricula for continuous improvement.

Notably, Stufflebeam's CIPP Model (for Context, Input, Process, Product). One of the most cited models, the CIPP approach evaluates not just the outcomes (product evaluation), but also the planning (context evaluation), resources (input evaluation), and implementation (process evaluation) of curricula (Sharma and Raval, 2019). With that said, it has been criticised as offering a possible overemphasis on efficiency while potentially under emphasising student aims, and for being resource intensive requiring significant time and financial resources for extensive evaluation (CleverControl, 2024; Ratnaya et al., 2022).

Tyler's Objectives-Centered Model which focuses on how well educational objectives are achieved, emphasizing alignment with predefined learning outcomes. This is especially critical in technical education where specific competencies must be measured against intended outcomes (Nouraey et al., 2020).

Stake’s Responsive Evaluation Model that emphasizes stakeholder perspectives, allowing curriculum assessment to incorporate views from students, faculty, and industry partners. This makes it highly applicable in fields such as railway engineering that require continuous industry interaction (Sharma and Raval, 2019). Despite its strengths, it can be challenging to implement and may be expensive to maintain (Hurteau and Nadeau, 1985).

Recent models increasingly adopt a constructive and competency-based framework, which defines the curriculum around skillsets expected from graduates in professional environments. These models support backward design which means defining outcomes first, then aligning instructional methods and assessments (Nouraey et al., 2020; Green, 1975).

Another model, Scriven's Formative and Summative Evaluation, differentiates between evaluations conducted during program development and those at its conclusion (Clinton and Hattie, 2024). This model aids in selecting program components and setting up quality control systems but may lack sensitivity to the complexities of educational environments.

Additionally, the Kirkpatrick Model, which works on four main levels of evaluation concept namely, reaction, learning, behaviour, and result (Nouraey et al., 2020). Widely used for training evaluations, has limitations when applied in higher education due to the complex environment and diverse objectives of academic programs (Cahapay, 2021).

In technical and vocational education, including railway engineering, curriculum evaluation frameworks increasingly emphasize alignment with professional expectations and measurable learning achievements. A core strategy is the adoption of Outcome-Based Education (OBE), which assesses curricula based on their ability to achieve predefined graduate attributes and program outcomes, often shaped by accreditation standards and industry benchmarks (Nouraey et al., 2020). In parallel, industry-informed curriculum design plays a pivotal role; through the integration of competency models and the active participation of industry panels, academic programs are continuously refined to reflect current technological developments and evolving labor market requirements (Green, 1975).

A review of existing curriculum development and evaluation frameworks reveals that they are limited in flexibility and scalability to adequately address the needs of railway education. Most pedagogies are domain-specific and traditional in their approach, lacking integration with forthcoming technology like AI, robotics, automation, and advanced analytics. This leads to an enduring discrepancy between skills taught through formal education and those demanded by industry (ASTONRail, 2020). Also, although training programs such as the STAFFER project have led to important findings regarding the vocational and educational needs across Europe (STAFFER, 2024), they do not include a structured real-time evaluation and improvement mechanism for the syllabus.

AI holds transformative potential to bridge these divides. AI can thus revolutionise railway curricula design, evaluation, and improvement through data-driven analytics and predictive modelling.

In conclusion, Traditional curriculum evaluation methods have long relied on manual review, expert judgment, and static benchmarking. While these approaches provide valuable insights, they suffer from several limitations:

1] Time-consuming and resource-intensive – The manual nature of traditional evaluations makes frequent updates impractical, leading to outdated curricula that struggle to keep pace with industry advancements.

2] Subjectivity – Evaluations often depend on individual interpretations and expertise, introducing inconsistencies and biases in curriculum assessments.

3] Limited scalability – Traditional methods are not well-equipped to efficiently compare curricula across multiple institutions, making it difficult to establish industry-wide standards or address emerging skill gaps.

With the increasing demand for industry-aligned and adaptive learning models, AI-driven curriculum evaluation presents a transformative alternative. By leveraging AI, institutions can benefit from:

1] Automated large-scale analysis – AI reduces the workload for academic and industry experts by processing vast amounts of curriculum data efficiently.

2] Data-driven insights – AI minimizes subjectivity by relying on empirical evidence rather than individual opinions, leading to more objective evaluations.

3] Continuous adaptation – AI ensures that curricula remain aligned with emerging industry trends and technological advancements, making education more responsive to real-world needs.

4] Standardization and harmonization – AI promotes a consistent framework for evaluating and improving curricula across different institutions and industry sectors, ensuring better alignment with workforce requirements.

7.5.2 Key Evaluation Criteria and Indicators in Assessing Academic Programs

The evaluation of railway and transport-related academic programs relies on a set of key criteria and indicators that collectively measure the effectiveness, relevance, and impact of the curriculum. Central among these is the assessment of learning outcomes, which evaluates the extent to which students acquire both foundational knowledge and specialized technical competencies through direct assessments such as examinations, project work, and practical laboratory exercises (Green, 1975). Stakeholder satisfaction is another critical indicator, incorporating feedback from students, alumni, faculty, and industry partners to ensure the curriculum aligns with professional expectations and adequately prepares graduates for the workforce (Sharma and Raval, 2019). The relevance and currency of course content are also closely examined, particularly in dynamic fields like railway engineering, where ongoing technological advancements necessitate regular updates to instructional material (Nouraey et al., 2020). Additionally, graduate employability and career readiness serve as important metrics, with programs increasingly utilizing alumni surveys and employment tracking to evaluate how effectively graduates transition into relevant industry roles (Taş and Duman, 2021). These indicators, collectively, offer a comprehensive framework for judging the quality and impact of academic programs in the transport sector.

7.6 Conclusion

The rail industry stands at a pivotal juncture, facing a dual challenge that threatens its long-term sustainability and competitiveness. The impending retirement of a substantial portion of the workforce, coupled with the rapid advancement of digitalisation and automation technologies, has created a critical skills gap. Existing education and training practices within the rail sector are not fully aligned with these rapidly evolving industry needs, necessitating a transformative approach.

This review indicates that while substantial progress has been made through European projects and institutional initiatives to modernize railway education, existing curricula often lag behind the pace of technological change and industry evolution. Fragmented approaches, outdated content, and inconsistent evaluation models hinder the sector's capacity to produce a future-ready workforce. The study reveals an urgent need for developing an evaluation tool for railway program curricula that integrates AI-driven methodologies.

This research study aims to bridge this gap by developing innovative, next-generation methodologies for rail education and training. The overarching purpose is to cultivate a skilled and adaptable workforce equipped with the competencies required to navigate the complexities of an increasingly digitised and automated rail environment. Specifically, the study seeks to address key objectives such as bridging the gap between curricula and industry demands, integrating advanced technologies, establishing robust evaluation methods and promoting standardisation and collaboration across the European rail education landscape.

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7.8 Planned activities

TASK ID NO.	TASKS	Year 1																							
		April Month 7				May Month 8				June Month 9				July Month 10				August Month 11				September Month 12			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	Define evaluation criteria and metrics																								
2	Develop tool framework structure and components																								
3	Meeting with supervisor																								
4	Prepare Qualifying report (QR)																								
5	Proofreading and submission																								
6	Develop tool prototype																								
7	Viva																								

In line with the project proposal, the first major milestone is the development of the curriculum evaluation tool, targeted for completion by the end of Month 18. Accordingly, the primary focus over the coming months will be on designing, testing, and refining the tool to ensure it is both academically rigorous and aligned with current industry needs. Alongside this, I will also be progressing with key university milestones, including the submission of the first qualifying report by the end of July, followed by the mandatory progression viva scheduled for September.

On the dissemination front, one manuscript has already been accepted and successfully presented at the AI4RAILS 2025 The 6th International Workshop on “Artificial Intelligence for RAILwayS”. Looking ahead, an abstract has been accepted for the 2025 UK Horizons in STEM Higher Education Conference, where I will present this research on the 25th and 26th of June 2025. Additionally, I have been invited to speak at the Railway 200 event on the 17th of September 2025, where I will present this PhD project.

8 Rail-Enabled Urban Logistics

8.1 State-of-the-Art Review Results

The growing emphasis on integrating rail into urban logistics in EU cities stems from efforts to meet sustainability targets outlined in the Green Deal and Sustainable and Smart Mobility Strategy. Shifting freight from road to rail can significantly reduce emissions (Ramani et al., 2019; Wedemeier et al., 2022). Despite its potential, implementing rail-based urban logistics faces challenges, particularly in multimodal hub development, last-mile integration, and effective cross-sector collaboration. One of the primary advantages of rail-enabled urban logistics is its ability to alleviate traffic congestion and reduce emissions. Behiri et al. 2018 emphasize that urban freight transport using rail networks has been underexplored. Nevertheless, it presents significant opportunities for reducing urban congestion and improving air quality by shifting freight from road to rail. Similarly, Apichottanakul et al. demonstrate that integrating light rail transit with road transport can optimize freight movement, minimizing transportation costs and environmental impacts (Apichottanakul et al., 2021).

Research on this topic spans multiple domains, including feasibility analyses, optimization models, and implemented system case studies. Several studies employ cost-benefit analysis (CBA) and scenario-based approaches to explore the viability of urban rail freight solutions. For instance, González-Feliu and Dablanc L. analyzed freight tram systems in Paris, highlighting the environmental and economic trade-offs of rail-road logistics integration (Dablanc L. 2013; González-Feliu, J. 2016). Similarly, Regue and Bristow explored freight tram scenarios in Barcelona, comparing the performance of the waste collection and delivery use cases, with the latter showing higher financial feasibility due to lower startup costs and significant operational savings (Regue, R., & Bristow, A. 2013). Case studies in Berlin, Vajihi, M. & Ricci, S. (2021), Rome, Alessandrini, A., et al. (2012), and Zurich, Marinov, M. et al., (2017) further demonstrate the potential of multimodal hubs and last-mile delivery systems yet emphasize the reliance on existing infrastructure for cost-effective implementation.

In summary, urban rail freight presents a transformative opportunity for sustainable city logistics. Although these advances present promising solutions, challenges remain, particularly in ensuring seamless integration and managing disruptions in urban rail transit systems.

8.1.1 Transition to Sustainable Urban Logistics and Rail Integration

Integrating rail networks into urban development is key to sustainable logistics in Europe. The TEN- T, especially the Mediterranean Railway Corridor, promotes high-performance rail systems that reshape urban areas along Spain's Mediterranean coast, significantly impacting urban form and infrastructure (Boira & Berzi, 2023). Sustainable urban logistics is key in lowering environmental impacts and enhancing urban living. European cities such as Vitoria-Gasteiz, Tartu, and Sønderborg are adopting sustainable logistics strategies to cut CO_2 emissions and boost energy efficiency, improving both their appeal and competitiveness (Rut et al., 2024). The CIVITAS initiative, a European Commission co-funded program, supports sustainable urban mobility by implementing innovative urban freight logistics measures in numerous cities, highlighting the importance of stakeholder partnerships (Rooijen & Quak, 2014). Additionally, the integration of urban waterways, as demonstrated in Amsterdam, offers a promising alternative to traditional road-based logistics, resulting in substantial cost savings and emission reductions (Pourmohammad-Zia & Van Koningsveld, 2024).

The aim of the review is to present the results of the state-of-the-art review, focusing on logistics operations, environmental sustainability, and policy effectiveness. The contributions are twofold: (1) providing the foundations for developing a theoretical framework that policymakers can use to ensure resilience and adaptability to change, and (2) identifying the need for research to examine best practices in European cities and providing practical recommendations, especially for the implementation in the conditions of the Czech Republic.

8.1.2 Innovative Urban Distribution Models and Rail Freight

Emerging research underscores the role of new technologies and collaborative freight systems in tackling urban logistics challenges. Innovative concepts like freight-sharing with public transport (Li et al., 2022; Cochrane et al., 2017) and digital integration into rail-based systems (Li et al., 2022) are gaining traction. Solutions for last-mile delivery, such as autonomous robots and urban consolidation centers linked to rail, are being explored under strict emission regulations (Vajihi & Ricci, 2021; Alessandrini et al., 2012; Seeck et al., 2023). Rail freight is increasingly central in sustainable urban distribution, with cities piloting new hubs and terminals (Dablanc & Beziat, 2023). In Szczecin, Poland, Light Freight Railways (LFRs) have shown strong potential for emission reductions and clean transport (Pietrzak et al., 2021). Mobile depots offer emission and congestion advantages over traditional consolidation centers (Arvidsson & Pazirandeh, 2017), while green activity zones, based on LEZ frameworks, have been proposed for more intelligent vehicle charging (Tretvik et al., 2018). Despite promising European models, broader adoption of rail-based urban logistics will require overcoming technical, organizational, and policy barriers alongside further research and innovation.

8.1.3 Policy and Governance

Rail-enabled urban logistics research intersects closely with European Union policy goals, including the Green Deal, the TEN-T network, and the Sustainable and Smart Mobility Strategy. Policies promoting modal shifts toward environmentally friendly transport modes have provided a framework for these initiatives, but studies reveal gaps in local implementation and inconsistencies in funding or stakeholder coordination mechanisms (Fumasoli, T. & Weidmann, U. 2016; Tsamboulas, D. & Moraiti, P. 2014 Langhe, K. D. 2014). Governance challenges, such as the misalignment of objectives among public authorities, logistics operators, and private stakeholders, remain a recurring barrier (Fumasoli, T., & Weidmann, U. 2016 Tsamboulas, D. & Moraiti, P. 2014). Collaborative governance models, such as Freight Quality Partnerships, have seen limited but promising applications in fostering cooperation among stakeholders (Tsamboulas, D. & Moraiti, P. 2014).

Integration of rail into city logistics often requires significant policy support and collaboration between public and private entities. Paddeu D. et al. (2024) discuss stakeholder engagement as a critical element for successful rail logistics integration, with case studies from cities such as London demonstrating the need for alignment between public authorities and private stakeholders in achieving seamless freight flows. According to the European Commission (2022), Sustainable Urban Mobility Plans (SUMPs) are essential in guiding urban areas toward integrated and sustainable freight solutions. Low Emission Zones (LEZ) are widely used in Europe to reduce emissions from all vehicles. Diesel HGVs contribute disproportionately to NOx and PM2.5 emissions compared to their numbers (Saleh et al., 2022). However, specific LEZs for freight traffic are rarely mentioned (Savadogo I. et al., 2023).

For example, LEZs encourage updating freight fleets to Euro VI and renewable energy vehicles, creating a significant burden for Small and Medium Enterprises (SMEs) (Savadogo, I. et al., 2023). With advances in renewable energy vehicles and technological innovation, LEZs are seen in some regions as a strategy to transition to Zero Emission Zones (ZEZ) (Fransen et al., 2023). Typical examples are Milan and Turin, where greenhouse gas emissions can be reduced by almost 50% and particulate matter emissions by 20% using a zero-emission fleet (Croci, E. et al. 2020). A fleet of electric vehicles can reduce greenhouse gas emissions by 44-53% compared to diesel trucks (Giordano, A. et al. 2018).

8.1.4 Multimodal and Integrated Freight Solutions

Research highlights that multimodal hubs play a vital role in the success of rail-enabled logistics. These hubs serve as transition points where goods are shifted from rail to low-emission last-mile delivery vehicles, such as electric vans or cargo bikes (Vajihi, M., & Ricci, S. 2021; Alessandrini, A.et al., 2012; Langhe, K. D. 2014). Key examples include the multimodal urban distribution center (MUDC) in Rome (Alessandrini, A.et al., 2012) and micro-hub trials in Berlin (Vajihi, M., & Ricci, S. 2021). Several optimization models, such as Mixed Integer Linear Programming (MILP), have been proposed to enhance the efficiency of these hubs and facilitate seamless coordination between rail and last-mile transport (Li F. et al., 2022; Behiri, W. et al., 2016). Multimodal systems leverage the strengths of different transport modes, such as rail and road, to optimize freight logistics.

Alessandrini et al. (2012) demonstrate how multimodal urban distribution centers, combining rail and low-emission road transport, can reduce congestion and emissions in cities like Rome. González-Feliu (2019) emphasizes the importance of economic viability, proposing a socio-economic cost-benefit.

The Haropa Port's multimodal strategy prioritizes a modal shift towards mass transit options, particularly targeting a 20% shift for container freight and 40% for bulk freight via rail and river transport. This approach includes upgrading rail infrastructure, enhancing inland terminals, and improving river access (such as through the "cat flap" channel). Supporting measures include investments in sustainable energy and advanced IT systems. Additionally, integrating rail into intermodal networks can significantly improve freight efficiency while contributing to environmental sustainability (Postuła et al., 2022; Szaruga, 2024).

8.1.5 Case Studies of Rail-Based Urban Freight Initiatives

Multiple case studies illustrate the practical implementation and outcomes of rail-based urban logistics. In Zurich, the Cargo Tram has successfully reduced road traffic by transporting bulk waste and materials via tramways, with last-mile delivery integration (Marinov et al., 2017). Similarly, Barcelona's multimodal rail freight hub facilitates the convergence of various transport modes, reducing reliance on trucks for urban deliveries (Generalitat de Catalunya, 2022). Paris and London have conducted trials and commercial operations using rail freight, highlighting both the potential and implementation barriers (Browne et al., 2014).

Berlin's freight tram system is a model of successful integration, leading to reduced vehicle use and emissions (Comi et al., 2024; Vajihi & Ricci, 2021). Using metro systems for last-mile delivery in Madrid demonstrates potential cost savings over traditional road-based systems (Villa & Monzón, 2021; Regue & Bristow, 2013). Shared infrastructure models utilizing metro networks for freight and passenger transport are gaining interest (Amrani et al., 2024). Rome has introduced an innovative model where freight is delivered into the city via rail to a multi-modal urban distribution center (MUDC), then distributed via low-emission vehicles. This approach has been shown to offer environmental and social cost benefits over road-only alternatives (Alessandrini et al., 2012).

8.1.6 Sustainable Last-Mile Deliveries

Sustainable last-mile delivery is a critical component of urban logistics, aiming to reduce environmental impact while maintaining efficiency. The integration of sustainable practices in last-mile logistics is increasingly important due to the rise of e-commerce and urbanization, which have led to increased traffic and pollution in cities (Viu-Roig & Alvarez-Palau, 2020; Bertolini et al., 2024). The last mile involves delivering goods to residents in every city corner. The authors divided the last mile measures into hard and soft measures based on published studies.

Investments in freight infrastructure and technological innovations play a critical role in reducing vehicle mileage in urban logistics. However, due to their low cost and swift implementation, soft measures offer an equally valuable contribution when effectively aligned with broader strategies (Cossu, 2016; Letnik et al., 2020). At the same time, the diversity of last-mile delivery vehicles is expanding, helping cities adapt to urban restrictions and environmental goals. Lightweight, zero-emission cargo bikes and e-bikes can navigate dense urban environments and meet regulatory requirements (Škultéty et al., 2021). Cargo bikes are particularly efficient for loads up to 100 kg, providing optimal emission reductions (Vasiutina et al., 2023). For heavier freight, tricycles present a safer and more capable option, accommodating standard pallets and up to 200 kg (D'Hondt et al., 2022).

Moreover, cities are leveraging their unique topographies by introducing water-based freight systems to replace Light and Heavy Goods Vehicles (LGVs and HGVs), increasing flexibility and reducing road congestion (Galambos et al., 2024). In niche scenarios, drones are also being deployed, particularly for time-sensitive deliveries such as pharmaceuticals (Serrano-Hernandez et al., 2021). Wehbi et al. (2022) further advocate for optimized transfer points and porters, which could halve travel time and significantly reduce emissions. Importantly, high-cost logistics solutions are not always the most effective; cost-benefit analyses indicate that contextual relevance and scalability matter more than expenditure (Russo & Comi, 2020).

Collaborative models are gaining traction in last-mile logistics. Buerklen et al. (2023) emphasize the importance of cooperation, shared urban hubs, and digital technologies to improve service efficiency while minimizing environmental impact. Similarly, Boysen et al. (2021) highlight how innovative city frameworks address e-commerce-driven challenges by incorporating drones, autonomous delivery robots, and other innovations to mitigate pollution and traffic.

Micro-hubs are also emerging as a pivotal element of sustainable urban logistics. Acting as decentralized nodes, they reduce the travel distances for last-mile delivery and enable cleaner operations (Novotná et al., 2022). Complementing these are alternative delivery points, such as parcel lockers and mobile collection stations, which offer greater consumer flexibility and environmental benefits (Pourmohammadreza et al., 2025). Successful last-mile delivery solutions depend on the active engagement of diverse stakeholders. Aligning the goals of municipal authorities, logistics providers, and end-users ensures equitable and sustainable strategies (Boggio-Marzet et al., 2023).

In conclusion, the evolution of last-mile delivery in European cities is shaped by innovations such as micro-hubs, electrified fleets, and alternative delivery models. When coupled with strategic collaboration and supportive policy frameworks, these developments pave the way for more efficient and environmentally responsible urban freight systems. Table 4 provides an overview of the review's finding

Table 4-An overview of the literature on rail-enabled urban logistics.

Author (Year)	City/Country	Problem Addressed
Alessandrini et al. (2012)	Global	Lack of sustainable practices for urban freight distribution using rail systems.
Marinov et al. (2013)	Global	Inefficiencies in rail-based urban freight movement systems.
González-Feliu (2014)	General	Underutilization of rail for urban freight despite sustainability advantages.
Langhe (2014)	Europe	Lack of integration between urban freight and rail systems.
Pietrzak et al. (2021)	Global	Challenges in integrating rail transport into zero-emission urban delivery systems.
Boysen et al. (2021)	Global	Lack of comprehensive evaluation of last-mile delivery concepts from an operational research perspective.
European Commission (2022)	EU Cities	Challenges in integrating urban freight with rail networks for sustainable logistics.

Generalitat de Catalunya (2022)	Barcelona, Spain	There is a need for enhanced rail-based multi-modal freight hubs to reduce road congestion.
D'Hondt et al. (2022)	Belgium	Need for sustainable alternatives like electric tricycles for last-mile parcel delivery.
Dablanc & Beziat (2023)	Global	Limited innovative urban freight distribution models using rail.
Pietrzak K., Pietrzak O., et al. (2023)	Szczecin, Poland	The potential of Light Freight Railway (LFR) trains in achieving zero-emission urban deliveries.
Europe's Rail Joint Undertaking (2024)	EU Cities	Challenges in making rail transport more sustainable, comfortable, and quieter.
Haropa port (2024)	France	Lack of multimodal strategies integrating rail and waterway freight in urban areas.
Comi & Hriekova (2024)	European Cities	Limited adoption of railway-based solutions for urban freight logistics.

8.2 Implications for policy and research

Integrating rail into urban logistics offers a promising solution to challenges like environmental sustainability, urban congestion, and the increasing demands of e-commerce. Multimodal hub operations in cities such as Rome and Zurich illustrate rail's capacity to reduce CO_2 emissions, noise pollution, and road congestion when combined with last-mile solutions like electric vehicles and cargo bikes (Vajihi & Ricci, 2021; Marinov et al., 2017; Alessandrini et al., 2012; González-Feliu, 2012, 2016). These outcomes align with the European Green Deal and the Sustainable and Smart Mobility Strategy.

Despite its environmental benefits, the widespread adoption of rail-enabled logistics faces significant economic and operational barriers. High infrastructure costs and poor financial returns, especially in retail freight, limit scalability (Regue & Bristow, 2013). Policy frameworks such as the TEN-T and urban freight legislation provide structural support, yet inconsistent implementation and weak stakeholder cooperation slow progress (Fumasoli & Weidmann, 2016; Tsamboulas & Moraiti, 2014). Effective public-private partnerships and inclusive governance models show promise for enhancing collaboration among municipalities, rail operators, and logistics companies, but further development is needed to align interests and improve long-term viability (Fumasoli & Weidmann, 2016; Tsamboulas & Moraiti, 2014).

8.3 Assessment and analysis of the current situation

Rail-enabled urban logistics has garnered considerable attention as a potential solution to address urban congestion and reduce emissions. Despite significant advances in both theoretical and empirical research, several research gaps persist. On the one hand, several studies focus on the use of trams and light rail within the urban context for freight delivery as cargo trams (Marinov M. et al., 2017; Alessandrini A. et al., 2012 A. et al., 2024; Vajihi M. Ricci S., 2021). Other studies proposed using the metro as an alternative solution for urban freight movement during off-peak hours (Villa & Monzón, 2021; Regue & Bristow, 2013). For the conditions of the Czech Republic, the most promising model seems to be the use of multimodal centres transferring shipments going to city centres from rail to one of the variants of ecological last-mile delivery (cargo bikes, electric vans, crowd shipping, etc.). The reasons for using this solution are as follows. There is a historical positive experience with the transport of goods (specifically postal consignments) by rail, which was implemented by a national postal operator across the Czech Republic (east-west direction) between large cities. One of the densest and longest rail networks in Europe exists here, so no major investment is needed to build the necessary infrastructure (except for new rail sidings and the micro hubs). In the transport strategy of the Czech Republic, the construction of a new high-speed railway network has already been implemented, with the existing rail network being replaced by a new high-speed railway network. It will be primarily intended for freight transport and suburban passenger transport. The existing road network is congested and destroyed by heavy trucks transporting domestic and international shipments of goods, and there is frequent congestion.

8.4 Conclusion and next stop of action

The urban and regional logistics systems, for the most part, remain unprotected from the future carbon cost shocks because of their reliance on road transport, thus Heavy Goods vehicles (HGVs) and light commercial vehicles powered by diesel. Without action, operators will be stuck with shrinking profit margins due to heightened costs, or their services will be priced out for consumers. As a result, there is a need to develop proactive emissions-resilient functional logistics systems for the business to remain viable. Despite significant policy and research interest, there are currently limited published studies that fully combine rail freight transport with low/zero-emission last-mile delivery and its comprehensive economic evaluation. Although some elements of rail integration and multimodal last-mile logistics have been discussed in prior studies, our contribution lies in the unique and novel combination of backbone rail transport of shipments to an urban micro hub and direct transshipment by cargo bike delivery, electric van, or pedestrian delivery (crowdshipping, etc.) to customers or parcel lockers in the city center. Specifically, previous research has typically investigated either the economic dimension (operational costs, efficiency) or the environmental dimension (emissions reductions, sustainability impacts) in isolation, with a focus on larger cities considering trams and metros, which lack scalability in mid-sized cities. Our study integrates both into a unified modeling framework, explicitly demonstrating the dual benefit of rail-enabled logistics when carbon pricing is introduced through time step operational simulation and economic analysis using software applications such as Python, MATLAB, and QGIS, which facilitate seamless cooperation between regional, inter-city rail freight, and green last-mile logistics.

A key innovation is the unique shipment configuration, which connects freight movement at the regional levels using a rail network, through a micro hub, then to parcel lockers or recipients using green last-mile logistics such as e-cargo bikes, electric vans, and crowdshipping, providing a solution for mid-size cities. This strengthens the corporation between regional rail freight and last-mile logistics. The research provides evidence-based insights for policymakers, logistics operators, and urban planners, highlighting the role of rail-integrated, multimodal systems in shaping sustainable and resilient urban freight networks.

Research applies a mixed methods approach (Fuzzy Logic, Multi-Criteria Decision-Making, Deep Learning, Machine Learning, Global Information System, etc.), combining literature analysis, case studies, collaborative design, simulation modelling, and real-world piloting. Below are the intended outcomes:

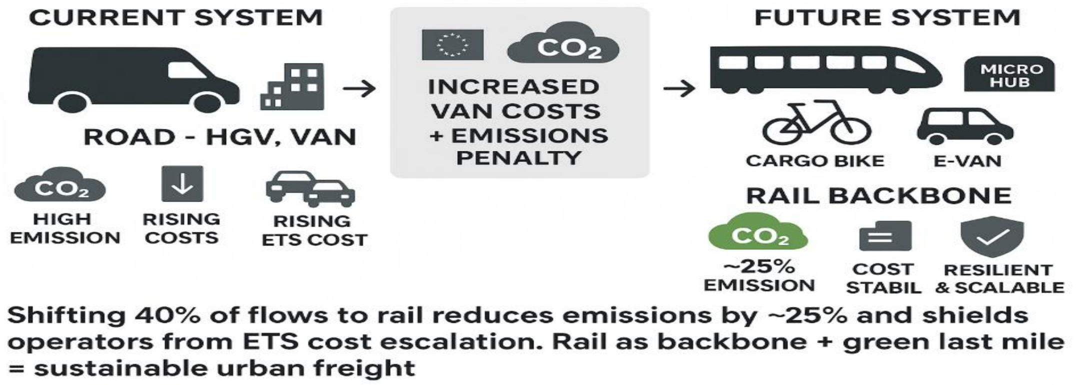
1) new technological concept.

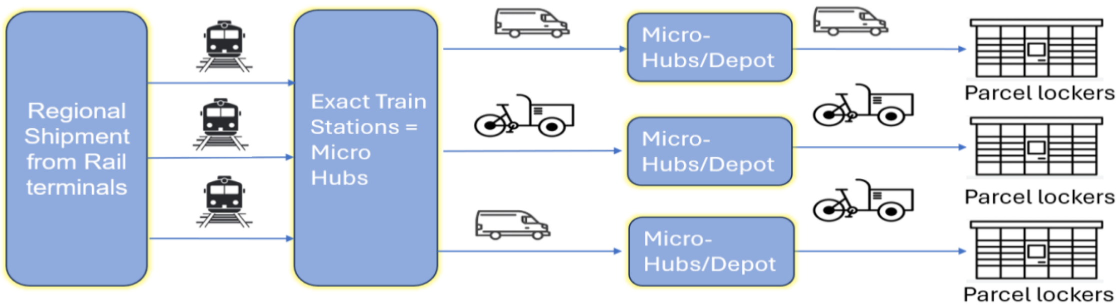
2) Handbook of good practices.

3) Set of recommendations for involved stakeholders.

The state-of-the-art review is followed by comprehensive data collection through industry collaboration. Locally, we are cooperating with the Czech post, CD Cargo, and various municipal authorities to be able to obtain reliable data for the preparation of conference and journal papers. To achieve the intended outcomes of the project, two journal papers are to be published. To implement the above-mentioned model, research activities will be carried out through data collection, interviews with logistics and rail industry stakeholders, and experimental designs with a case study. This will lead to journal publications with recommended policy frameworks and implications that support the above objective and model. There will also be industry cooperation to help implement the proposed policy framework with a case study in Pardubice City. It is then finalized with real-world piloting, where emission and economic analysis are going to be evaluated and validated for different scenarios as per SDGs and the EU emission trading system (ETS) policies.

Conceptual framework





Plan of Action

RAIL ENABLED URBAN LOGISTICS-(PhD4)

PROGRAMME FOR 2025/2026 YEAR

ACTIVITIES	FIRST YEAR				SECOND YEAR			
	1	2	3	4	1	2	3	4
COLLECTION OF DATA AND CASE STUDY				■	■			
					FIRST ARTICLE SUBMISSION			
ANALYSIS OF DATA					■	■	■	■

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9 Fast Night Train Operations

The ambition of the PhD project on fast night trains using HS rail networks in Europe encompasses pivotal future directions in rail transport. Firstly, it seeks to understand better the role and importance of fast and HS night train services in Europe and identify feasible and profitable routes with a focus on customer needs including an analysis of managerial, operational, technical, financial, and logistical viability. This will help to establish a novel organisational model for fast night train operations, redefining the structure and efficiency of their management. Secondly, the research aims to introduce a "fresh" approach to rolling stocks for fast and HS night trains, exploring innovative technologies and designs (both interior and exterior) to enhance both system performance and passenger experience. and thirdly, this research will produce an Intellectual Outcome introducing new services of fast and HS night trains on feasible and profitable routes in Europe, envisioning amenities and offerings that elevate the overall journey.

As a result, the PhD project will contribute significantly to developing a fast and HS night train network across Europe which involves creating an interconnected and efficient rail network that spans various regions, facilitating seamless travel. This project will work towards achieving an overarching goal, that is to promote sustainable travel throughout Europe, emphasising environmental considerations and eco-friendly practices of the use of fast night trains operating in a HS rail network. This PhD project strives to reshape the landscape of fast and HS night train operations, fostering efficiency, connectivity, and sustainability across the European rail network by addressing market-focused, demand-related, operational, managerial, technical, cost and logistical challenges.

First step seeks to better understand the role and importance of fast and HS night train services in Europe and identify feasible and profitable routes with a focus on customer needs. The second step introduce "fresh approach" of rolling stock vehicles used for fast and HS night trains which is innovative technology and design of interior and exterior. Third step determines methodology of conducting new services of fast and HS night trains on feasible and profitable routes in Europe which is anticipating advantages and offers which will raise the level of journey in total.

The goals are:

- creating a network of high-speed night trains across Europe, which includes the interconnected and efficient rail network that spans on different regions, facilitating purposeful travel.
- Promoting sustainable travel throughout Europe, with an emphasis on environmental issues and ecological practices of using high-speed night trains.
- Reshaping current organization of high-speed night trains to promote efficiency, connectivity and sustainability across the European rail network by addressing demand and market-oriented, organizational, management, technical, cost and logistical challenges.

9.1 Background

The long-distance travel in the European Union relies on airplanes, posing environmental challenges and hindering decarbonisation goals. To help tackle these challenges some railway companies have reintroduced night trains, which is a bold yet risky move due to outdated organisational structures and equipment. There is an imminent need for academic research being coupled with industry collaboration to propose a new organisational model for fast and reliable night trains, and to establish a sustainable business model for their operations. HS rail in Europe has proven its credential and presents a real opportunity to replace busy Air-routes in Europe. To be able to help balance CO_2 footprint, it is paramount to understand the importance of night train services in Europe and identify the potential market and most feasible routes for high-speed night trains based on customer preferences, demand, and potential revenue streams. In addition, it is critical to study the exiting rolling stock that can be used for HS night train services and reveal areas for technical, operational and logistical improvement that will enhance service quality, reliability and passenger experience.

From the time of Georges Nagelmackers, who introduced the first sleeping and restaurant wagons on the train in 1882 from Paris to Vienna, there was no change in the organisation of the night train service. In the last few years, we have found interesting but numerically limited scientific papers about night train organisation.

Kantelaar et al. (https://doi.org/10.1016/j.tbs.2022.08.002) investigate willingness to use night trains for long-distance travel. They have investigated the following points: (1) estimating willingness to use night trains over airplanes for long-distance travel, (2) The comfort level is the most important determinant for night train mode choice, and (3) perceived night train comfort is most influenced by the accommodation's privacy. Gunkel et al. (https://doi.org/10.1002/net.20380) investigate how to find good night train connections. They have investigated the following points: (1) the objective of travellers on a night train is to have a long sleeping period without interruptions due to train changes, and (2) for most passengers, it is also undesirable to reach the destination too early in the morning. These objectives sharply contrast standard information systems, which focus on minimising the total travel time. Li et al. (https://doi.org/10.1007/978-981-13-0302-9_56) analyse and predict the passenger flow of high-speed night trains. In the first step, they analysed traffic flows of daily trains and then analysed newly introduced night trains. After that step, they have predicted scenarios of development of high-speed train services. Döményand Dolinayová (https://doi.org/10.2478/ttt-2021-0002) investigate possibilities for introducing a new night train connection in middle Europe. This study aims to analyse current night train services in middle Europe and find opportunities for their further development. They concentrated on assessing the economic efficiency of introducing new connections. Curtale et al. (https://doi.org/10.1016/j.tmp.2023.101115) try to understand preferences for night trains and their potential to replace flights in Europe with the case study in Sweden. They have investigated: (1) people's willingness to switch from airplanes to night trains, (2) set of innovations will affect the probability of choosing night trains, and (3) night trains could increase the sustainability of long-distance travel in Europe.

According to the Green Deal of the European Union, there is a high concentration of talks about the decarbonisation of the transport sector. On the other hand, there is no concrete action in the field of the organisation of fast night trains. Only Austrian state railway company introduced some new design wagons at the end of 2023. Also, a very proactive privately owned company, RegioJet, keeps pace with night trains. Interestingly, Central and East European countries run night trains on a very old-fashioned organisational basis. The main disadvantage of current operation is the average speed of the trains. Also, we can determine that on the high-speed lines, currently in Europe, there is no offer for night trains. This issue needs to be tackled at organisational, technical, financial, and logistical levels.

An interesting fact is that in China, they started to experiment with fast night trains on routes longer than 10 hours. At this moment, the maximum speed of the fast night trains is 200 km/h, and trains usually run on Friday, Saturday, Sunday and Monday between important cities on the high-speed network.

9.2 Methodology

Methodology of PhD5 is according to the following steps:

- Literature Review: Review relevant scientific papers, focusing on high-speed night trains to understand historical context, challenges, and advancements.
- Analysis of High-Speed Night Trains:
  - Operational Perspective: Investigate current operational models, efficiency, and challenges in high-speed night train operations.

    - Infrastructure Management: Evaluate the impact of infrastructure on high-speed night trains and explore advancements.
    - User Perspective: Examine passenger preferences and comfort factors specific to high-speed night trains.
    - Decision-Making Stakeholders: Investigate societal, political, and NGO perspectives influencing decisions about high-speed night trains.
- Stakeholder Survey: Conduct a survey focused on stakeholders' perspectives regarding the feasibility and desirability of high-speed night trains.
- Rolling Stocks Challenges: Identify and evaluate technical, operational, and logistical challenges specific to rolling stocks for high-speed night trains.
- Timetable, Service, and Cost Challenges: Examine challenges related to timetable optimization, service provision, and cost management in the context of high-speed night trains.
- New Organization Paradigm for High-Speed Night Trains: Develop an organizational model tailored to high-speed night train operations, integrating insights from literature and stakeholder feedback.
- Environmental and Social Impact Assessment: Assess unique environmental and social impacts associated with high-speed night trains. Propose targeted mitigation strategies based on the assessment.
- Simulation Test Case for High-Speed Night Trains: Design a simulation model based on the proposed organizational model and evaluate its effectiveness in optimizing high-speed night train operations. Utilize realistic data and scenarios to simulate the impact of changes in organizational structure on efficiency, cost, and user experience.

When discussing rolling stock and its potential enhancements, it is essential first to investigate the needs of the customers/users. The fact is that railway operators providing night train services are constantly improving interiors and service in general to satisfy passenger needs and to justify the costs that this service generates. The PhD program has its own agenda and is organised in a manner that combines different fields of research through its courses. Each course will cover a different field of research.

For example, the course Applied statistics for traffic research, whose aim is to gain knowledge about the importance of theoretical foundations of applied statistics in traffic and transport technology, which are necessary for understanding and applying statistical research. Within the course, doctoral students will be introduced to advanced statistical techniques for application in scientific research work using specialised statistical software packages. After successfully completing the learning process, the doctoral student will be able to identify a theoretical distribution or statistical model that best suits the given problem, classify the observed data feature, compare the values of data features using the SAS statistical package that enables access, management and analysis, create reports with purposeful content and a professional appearance, interpret the results of statistical analysis in the function of active participation in the decision-making and management process, and independently select a statistical model that is applicable and adapted to a specific scientific research, and provide an argumentative explanation of the advantages and possible disadvantages of their choice.

The following is the course Sustainable mobility, whose aim is to connect the results of scientific research work in the field of sustainable mobility and the doctoral student's own knowledge into a new functional unit. The content encompasses the following topics: aspects of sustainable mobility, global environment, economic sustainability, transport system performance, electric vehicles, sustainable mobility practices, active modes of transport, sustainable mobility indicators, and sustainable mobility evaluation. After completing the course, the doctoral student will be able to evaluate proposed solutions in the field of sustainable mobility in accordance with a predefined set of indicators, integrate different aspects of sustainable mobility into a new functional unit in accordance with the given transport environment, design new practices for sustainable mobility, plan and reorganize the sustainable mobility system, plan new services in the field of sustainable mobility, and critically assess the applicability and transferability of a set of solutions in the field of sustainable mobility to a new environment.

Urban transport aims to prepare the doctoral candidate to conduct independent research in the field of sustainable travel modes, including understanding the behavioural models of participants in urban movements, selecting optimal urban rail systems, and evaluating measures and strategies for sustainable transport in cities. The content consists of topics such as derived indicators of the urban transport system, objective function analysis, analysis of sustainable urban development, induced transport demand and generalised travel cost; the concept of optimal public urban transport; monorail systems; a model of comparative analysis when choosing the track width of rail urban systems; analysis of road traffic safety management in cities. After successfully completing the course, the doctoral candidate will be able to identify, collect and revise indicators of the urban transport system, assess and evaluate dominant indicators of the urban transport system, adapt strategies and measures for a selected urban area, modify a new plan for sustainable transport in a specific urban environment based on examples of good practice, select an optimal model of rail urban systems, and write a seminar paper in the field of urban transport.

Within these courses, two research seminars are obligatory. Through research and a study of available literature, issues such as the introduction of new rolling stock or the enhancement of existing stock will be addressed. This will help determine whether improvements are needed for specific services and to what extent.

To conclude, the theme of improved rolling stock is covered by users' future experiences and the direction in which new rolling stock needs to be built. Regarding the topic services, this is a core part of the research on the operation of fast night trains across Europe.

9.3 Challenges

Considering growing awareness about carbon emissions, the scientific community started to investigate more about long distance travel (van Goeverden K., van Arem B., van Nes R., 2016), by analysing behavioural process which includes night trains as an alternative to air transport. Since we know very little about current night train users, what is their motivation for such choice of transport mode, article by (Tiziano Gerosa, Francesca Cellina, 2024) shows research about travel behaviour of a group of night train users within Switzerland and journey towards central Western Europe, such as Amsterdam, Berlin. Hamburg, Bremen and Wien and also central Eastern Europe such as Dresden, Leipzig, Prague, Budapest, Ljubljana and Zagreb. When speaking of travel choice there are individual factors such as socio-demographic characteristics, finding that individuals with higher education seems to be associated more with transportation modes that have lower environmental impact (Curtale R., Larsson J., Nässén J., 2023). Other factors that have influence on travellers' mode of travel are costs of the journey, punctuality, number of transfers between modes and travelling time in general (Gunn H., 2021.). It is important that travellers use their time productively and that they are satisfied with choice they made. Long waiting time between transfers, non-adequate transportation vehicle, delays, uncomfortable seats/beds are just some of the key performance indicators that has significant influence on personal choice regardless the time-consuming effect or environmental impact. The research made by (Fleischer, A., Tchetchik, A., Toledo, T., 2012.) shows that some passengers are more willing to choose overland travel modes such as train because it makes them feel much safer.

According to (Wouter Moors, 2023) and his Master thesis Night train service, the scope of research was "Which factors influence the preference and use of night train services among the Belgian population and what is the corresponding heterogeneity?” To retrieve answer, a stated choice experiment was conducted, and respondents were users of Belgian IC train services. The main research problem was to establish the willingness of general population to use night train, and which customer needs and expectations must be considered. The Belgian train operator, NMBS, had investigated the possibilities about offering night train services to connect Belgium with other European cities and 60% of the Belgians would consider choosing a night train to travel within Europe according to Belgian government (Enquête BEMOB, 2021).

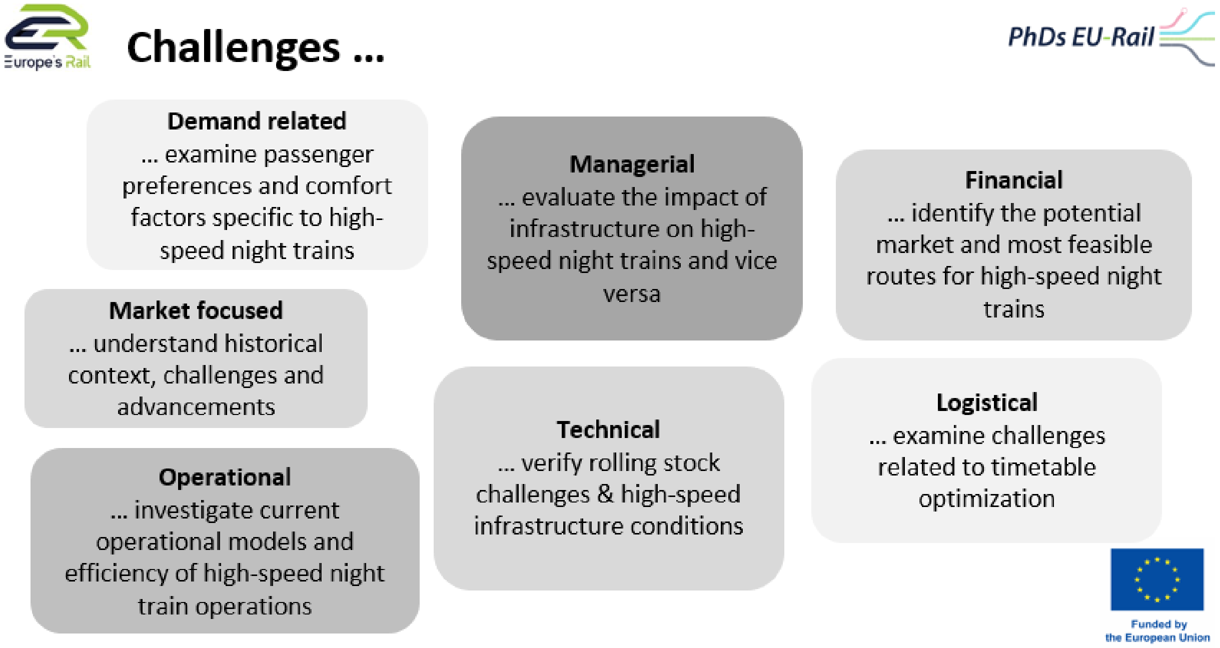
In order to encourage modal shift within general public i.e. encourage shift from flights to trains, in this case of night trains, it was necessary to investigate scenarios of carbon footprint reduction and present it to general public related to Swedish tourism within Europe. According to research made by (Johannes Morfeldt, Anneli Kamb, Riccardo Curtale, Jörgen Larsson, 2023.), a modal shift could be achieved by creating new night train policies with fewer transfers and prices which are similar to flight costs. By using greener transport modes instead of air travel, it would significantly reduce carbon footprint by 9% in the time period from 2025-2050.

When referring to Europe, conditions of railway infrastructure has various limitations due to heterogeneity of railway systems within different countries, cost for railway personnel are high, obvious lack of unified reservation and ticketing system and not enough passenger information (Lena Donat, M.T., Janeczko, L., Majewski, A., Lespierre, T., Fosse, J., Vidal, M.,Gilliam, L., 2021). The year 2021 was named the European Year of Rail by the European Commission and it was expected to boost train adoption in Europe, including a night train renaissance. With an action plan developed aim was to make cross-border train services more user friendly regarding ticket fares and help operators to upgrade their rolling stock (European Commission, 2021).

The majority of night trains within the EU operate wholly within the 1435-millimetre standard gauge network (European Parliement, 2017), but:

- “Hotel trains” operate on the 1668-millimetre gauge network in Spain and Portugal.
- “Hotel trains” operate on the 1600-millimetre gauge network of Ireland and Northern Ireland (in the United Kingdom).
- Night trains operate on the 1520-millimetre Russian broad gauge networks including Finland (notionally 1524 millimetre), the Baltic States, and Belarus, where some of them exchange bogies to enable them to operate on the standard gauge network.

One of the biggest challenges for the sustainability of night trains is their cost of operation. Once on the rails, operators are required to pay infrastructure fee and payment of Track Access Charges, then there are costs for staff, both on board and on the ground, considering that salaries of night shift workers are generally higher. Maintaining, repairing, refurbishing, upgrading, cleaning, and preparing cars and engines for travel are also costly operations. Another important issue is pricing of train tickets because some trains run under the Public Service Obligation scheme, which guarantees public transportation in areas or lines with low demand. This often means they need to be subsidized. Others run in the open access market, competing with other companies in what should be a level playing field. Most train companies use dynamic pricing, to adapt to the demand and increase their revenue. Lastly, taxation (especially VAT) varies between countries, complicating the pricing of international tickets. This all requires cooperation between State and railway operators but also cooperation among different operators within different countries and all is under European Commission regulations. The Fourth Railway Package of the EU (Scordamaglia D, Katsarova I, 2016) establishes that: “The liberalization of domestic rail passenger services covers both open access rights for any passenger services provided it does not compromise the economic equilibrium of existing public service contracts and common rules for the competitive tendering of public service contracts for passenger transport by rail.” Thus, open competition and public service obligation co-exist in a delicate balance in many EU member states, often considering night trains purely competitive than PSO-worth (Perennes P, 2017).



When referring to Europe, the conditions of railway infrastructure have various limitations due to heterogeneity of railway systems within different countries. This not only refers to gauge differentiation but most if railway tracks are electrified or not, and which type of electric currency country uses and the most challenge part the signalling systems. Indeed, this implies not only to the night trains but day trains as well. However, day trains have different kind of wagons and most of them are motor units whose electric currency can be adjusted to different systems, while we speak about night trains, train disposition is quite different because we are talking about sleeper wagons who require certain track gauge and specific electricity. Not only technical conditions and restrictions have to be explained, but there are also numerous logistical issues that follow providing international transport service, such as personnel escorting night train, drivers, ticketing and passenger information. For that reason, interoperability between different rail systems is an issue and deserves to have specific chapter within the research.

Given the limited scientific research and the current structure of night train services, there is a substantial potential for further exploration and development in the realm of fast night trains in Europe. (Curtale et al. 2023) investigate offers an opportunity to improve the efficiency and sustainability of long-distance travel, aligning with broader goals of reducing the transport sector's carbon footprint while enhancing the convenience and flexibility of travel across the continent.

To conclude, some aspects of daily trains are the same as in night trains, but also exist new elements in interoperability for night trains that will be tackled in our research.

9.4 Analysis of High-Speed Night Trains

At present, the operating mode of night trains on highspeed railways tends to share a single operation diagram for running and maintenance (Mohamed Alhossein, Qiyuan Peng, 2022). Their study investigates the application of existing models to investigate the difficulties and problems of ultra-long-distance night trains and proposes optimization strategies to adapt their maintenance operations under the modes of waiting.

Considering long tradition in Europe, the night trains have been popular in the past, however, nowadays long-distance night travel needs to be upgraded to accommodate passengers and their needs at the first place (Bulkova

Z., Dedik M., Gašparik J., 2022). According to research by (Martini, F., Pesci, G., 2022) in recent history there has been noticed that night travels has returned to transport scene despite years of neglects and insufficient investments. By restoration of international train connections, the long-distance concept was restored as well. This was primarily concept of "hotel on wheels" for businesspeople and tourists. The concept for people travelling for is not often practical due to accommodation and connection disadvantages, therefore improvement in harmonization of timetable and direct connection is a must because several studies showed that train connections are unprofitable, uneconomical and have no future. Despite negative prognosis, NightJet project implies service of direct night trains between Zurich and Rome, Berlin-Paris and Berlin-Brussels and Zurich and Barcelona gradually from December 2023 to December 2024 (Dromedar.zoznam.sk., 2019). For such service it was necessary to conduct research that analyse number of inhabitants, long-term passenger frequencies, transport distance between individual settlements and the attractiveness of the monitored area (Bulkova Z., Dedik M., Gašparik J., 2022). Research was conducted with calculation crated by (Dedík, M., 2020) on the route between Bratislava and Žilina with proposal to connect Slovak and Czech cities at night with advanced centres in Austria, Germany, and Switzerland and also between Budapest and Berlin via Bratislava and Prague with an extension to Hamburg. The potential routes of night trains represent only a certain framework proposal in which way night transport could be developed in the short- and medium-term time horizon. To have this concept operational, it is necessary to increase the quality and level of service, primarily the possibility to sleep on the train and arrive at destination rested in the morning. In comparison to research made within Sweden population and by (Curtale R., Larsson J., Nässén J., 2023) among 1.691 residents of Sweden, showed no difference. Travellers' preferences and needs, in this case Swedish travellers are first to understand and follow. Within the research it was crucial to understand and consider mode choice based on travel cost and travel time. Other depending factors are comfort level and number of transfers (Creemers L., Cools M., Tormans H., Lateur P. J., Janssens D. & Wets G., 2012). This was a case study for Scandinavian countries within the project "On track to climate neutral long-distance travel 2045 - technology, travel patterns, high altitude impact" with the purpose to achieve knowledge regarding further investments in railway infrastructure, comfort level gained by replacing old rolling stock and promote sustainable travel solution instead of air travel. Conclusion is that by introducing new comfortable trains, shorter travelling time and by extending collaboration on international routes, the demand of market would be satisfied, and rail transport would replace air travel. Research by (Hualiang T., Toughrai T., Yu T., Ozawa R., 2022) was made for Europe and America, however reference for France and Spain are considered valuable. By using linear regression model, study showed that highly correlated variables are transfer time, schedule, number of service and facilities are most important for French RER. Considering that Spain has the longest high speed rail service, for their case only two variables were significant, and those are number of bus lines and number of bicycle parking stations. Numbers were retrieved by regression model and are in correlation with three types of operation lines within Spain's high-speed rail system and reflection of inhabitant's needs. The more bus stations connected to high-speed rail stations means higher ridership of those stations.

9.5 Results

Expected results will be:

- Contribute to the development of a fast and HS night train network across Europe
- Create an interconnected and efficient rail network
- Promote sustainable travel throughout Europe
- Reshape the landscape of fast and HS night train operations
- Intellectual outcome introducing new services of fast and HS night trains on feasible and profitable routes in Europe, envisioning amenities and offerings that elevate the overall journey.

The EU plays only a limited role in relation to night trains which is setting the overall regulatory framework, including for rail infrastructure charges, and investing in infrastructure. The Member States could require infrastructure managers to reduce infrastructure charges or could subsidise night trains in recognition of their benefits, as occurs in (at least) Austria, Sweden, the United Kingdom and France. However, parliamentary debates in 1983 (in the United Kingdom) and 2016 (in Germany) rejected the idea that any long-distance services should be subsidised. The operators of night trains generally appear to manage them well. Cross-border operations, and changes of locomotives and crew, are long-established. The past practice of allocating blocks of tickets to each railway for sale through stations is declining. Best practice appears to be:

- to offer a range of accommodation and the opportunity to pay more for exclusive use of a compartment;
- to use yield management to maximise revenue from the capacity available; and
- to sell through a single (multilingual) website. However, some operators appear to offer only a small range of accommodation at fixed low fares, probably to meet an inflexible national PSO.

The Trans-European Transport Network (TEN-T) core network corridors may be of some help to night trains, where they provide additional capacity, but major new international links appear not to have attracted night train services, and high-speed lines appear to have contributed to their decline.

9.6 Conclusion

"A passenger night train is any train consisting partly or wholly of rolling stock dedicated to, or reconfigured for, overnight travel" (European Parliament, 2017).

An idealised overnight train would provide a non-stop journey of 8-10 hours between two stations, departing after 22:00 and arriving before 08:00. In practice, few night trains operate wholly within this period, and none that we have identified do so without stops on route, with the result that few offer an uninterrupted journey of more than six hours. Night trains and sleeping possibilities provide a unique combination of mobility and accommodation, enabling passengers to cover significant distances overnight while saving time and reducing the need for additional lodging. The train consists of various wagons designed to meet the diverse needs of passengers, ensuring comfort and convenience throughout their journey. Each wagon type serves a specific function, from dining via couchette to sleeping wagons, and at the end of the train, the possibility to add a wagon that transports cars (Abramović, B., Greguš, T., Greguš, B. & Krutilek, T., 2025).

In recent decades, however, the competitiveness of sleeping wagons has been challenged by the rise of low-cost airlines and the increasing use of private wagons. Despite this decline, renewed interest in sustainable mobility and climate-friendly transport solutions has brought night trains back into the spotlight as an environmentally responsible and user-oriented alternative.

From the perspective of transport policy, the revitalisation of night train services directly supports the objectives of the European Union's White Paper on Transport (2011), which calls for a significant modal shift from air and road transport to railway to reduce greenhouse gas emissions. Compared to aviation and private car use, trains offer a much lower carbon footprint per passenger-kilometre, particularly when powered by electricity from renewable sources (IEA, 2018). Night trains, therefore, represent not only a traditional form of travel but also a contemporary solution aligned with the principles of sustainable development, urban accessibility, and passenger comfort.

With the support of various legislative acts and the European Commission, railway transport holds significant importance in the transport world; however, additional changes at the State level will be required. Member States will have to interact and be involved in decision-making processes and request funding for these operations to succeed.

Future research on fast and high-speed night trains should explore their potential for adoption in Europe by evaluating their environmental benefits compared to air travel, particularly in reducing carbon emissions across long distances. Also, it will be necessary to assess (1) passenger demand, (2) pricing strategies, and (3) infrastructure compatibility within Europe's existing railway systems to determine feasibility and scalability. Additionally, research should investigate operational challenges, such as integrating fast and high-speed night trains with Europe's cross-border railway networks and improving passenger experiences to ensure competitiveness with other transport options. Additionally, the research will go in the direction of passenger needs when travelling in night trains, which will end with their satisfaction with fast night train services.

In a climate friendly Europe where we have intend to reduce air travel, night trains are necessary. Without these trains, effective cross-border travel between all parts of Europe -also the remote – is much more difficult.

One reason that people abandon international trains are the high costs for travelling. Local and even national trains are often subsidized and have special fares (like BahnCard), which makes fares reasonable. But international trains do not have these subsidies and discounts. The price difference sometimes is ridiculous.

One important conclusion is that the night train fleets are getting older and that it will be expensive to build new coaches, especially in a deregulated market where operators don't have guarantees to continue the traffic until the investment costs are paid. One possibility is that the European Union invests in a fleet of modern night coaches that operators can rent during the time they run the traffic.

An "idealised" night train might run non-stop from after 22:00 to before 08:00 and allow passengers to sleep for 8 hours or more, but this is rare.

European high-speed lines have been built to provide faster and more frequent day trains, which may take demand away from night trains. However, they have rarely been used to allow night trains to connect more remote points, as has occurred in China and India.

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10 Bridge-Train Dynamics Normative Framework

10.1 Introduction

The rules and guidelines that shape how train stability on bridges is approached in Europe go back to research from the late 20th century, especially the studies led by the ERRI/D214 committee (D214/RP9, 1999). This group played a key role in developing harmonised standards that eventually shaped the current Eurocode documents, like EN 1990-Annex A2 (2001) and EN 1991-2 (2003). These codes have provided a valuable benchmark for bridge design across the continent, establishing criteria that ensure safety, operational reliability, and passenger comfort. However, it is crucial to recognise that these criteria were developed during a period marked by significant limitations in computational tools and modelling capabilities. At that time, the dynamic train-bridge interaction (TBI) behaviour assessment largely depended on empirical methods, simplified analytical models, and isolated experimental results, particularly for vertical and lateral deck responses under dynamic railway loading.

Fast forward to the present, and the substantial evolution of computational mechanics, high-performance simulation platforms, and the availability of more refined experimental data have introduced a paradigm shift in how TBI problems are approached. Advanced numerical models now capture the complexity of the coupled dynamics between train, track, and bridge, including non-linear wheel-rail contact behaviour, track irregularities (Arvidsson et al., 2019, Cantero et al., 2016, Ling et al., 2018, Peixer et al., 2021), nonlinearities (Ticona Melo et al., 2020, Xu et al., 2018), and even multi-hazard scenarios like crosswind (He et al., 2018, Montenegro et al., 2020, Montenegro et al., 2020, Montenegro et al., 2020, Olmos & Astiz, 2018) or seismic actions (Chen et al., 2019, Jin et al., 2016, Montenegro et al., 2016, Zeng & Dimitrakopoulos, 2018). The TBI models support various applications, from analysing bridge dynamic response and assessing train running safety (Chen et al., 2018, Gong et al., 2020, Montenegro et al., 2022) to evaluating passenger comfort (Montenegro et al., 2022, Olmos & Astiz, 2018).

This progress in modelling capability has naturally sparked a growing debate within the engineering community. On one side, we have long-standing code-based limits, often conservative and rooted in earlier empirical findings, while on the other, new research based on advanced simulations suggests that some of these criteria might be overly restrictive. Many of these criteria are now being questioned within the scientific community due to their apparent conservativeness and the growing body of evidence from recent studies suggesting that they may not fully reflect the real behaviour of modern railway systems (Andersson, 2023, ERA Technical Note, 2022).

In 2022, the European Union Agency for Railways (ERA) published a Technical Note to address several open points that still exist within the current standards related to railway bridge dynamics (ERA Technical Note, 2022). These open issues reflect a growing awareness across the railway sector that some criteria used in designing and assessing railway bridges, particularly those outlined in EN 1990-Annex A2 (2001), need revision and refinement. In response, a Europe-wide call for research and innovation was launched through Europe's Rail Joint Undertaking, funding the InBridge4EU project (InBridge4EU, 2025). This project is dedicated explicitly to revisiting and updating the normative criteria governing railway bridge dynamics, seeking to bridge the gap between current design practice and the available advanced modelling capabilities.

While InBridge4EU focuses on addressing some of these outdated aspects, particularly those explicitly highlighted by the ERA Technical Note (2022), there remain other criteria within the European standards that are increasingly being questioned by both the research community and practising bridge engineers, but which fall outside the current scope of the InBridge4EU project. In this context, PhD6 aims to address this gap by critically reviewing and proposing improvements to these remaining criteria, focusing on aspects of railway bridge dynamics not currently covered by InBridge4EU. The research will specifically target the following criteria, which are considered outdated and in need of revision:

- Lateral vibration limits of bridges related to running safety (EN 1990-Annex – A2.4.4.2.4) (EN 1990-Annex A2, 2001)
- Deck deflection limits for passenger comfort (EN 1990-Annex – A2.4.4.3.2) (EN 1990-Annex A2, 2001)
- Vertical deformation limits of bridge decks for running safety (EN 1990-Annex – A2.4.4.2.3) (EN 1990-Annex A2, 2001)

This project will use modern computational power with advanced train-bridge interaction simulations and broaden to more bridge types to propose more realistic limits that reflect today's infrastructure and train performance. By doing so, the PhD6 seeks to support the evolution of European standards and to align future design practices with a more evidence-based and performance-oriented approach, ensuring safety and comfort while avoiding unnecessary conservatism that can lead to overly expensive or inefficient bridge designs.

10.2 Normative and Explicit Approaches for Traffic stability on bridges

Traffic stability on bridges can be evaluated with two methodologies: i) via the indirect bridge response indicators identified as a normative approach and ii) through the assessment of running safety criteria derived from the dynamic TBI analysis, identified as an explicit approach. The second method requires a complete TBI model to simulate train responses, such as car body accelerations for evaluating passenger comfort or wheel-rail contact forces for assessing running safety (see Figure 12). While this method provides a more accurate representation of vehicle behaviour and interaction with the structure, it does not align well with routine design applications due to its complexity and computational demands.

As a result, current design codes continue to rely on indirect criteria, which are simpler to apply and compatible with standard structural analysis methods applied by practicing bridge designers. These indicators, usually based on static or simplified dynamic analyses, provide a conservative but practical way to assess traffic safety on bridges. However, recent research efforts have focused on using TBI analysis to gain deeper insight into the vehicle–structure interaction and develop new performance indicators that could bridge the gap between accuracy and practical applicability. It is essential to clarify that adopting full TBI models in design codes remains limited to particular cases, such as in the most recent Chinese standards (TB 10002-2017, 2017). The general objective is not to replace traditional methods with complex simulations but to use TBI analysis as a reference to inform and enhance simplified design criteria.

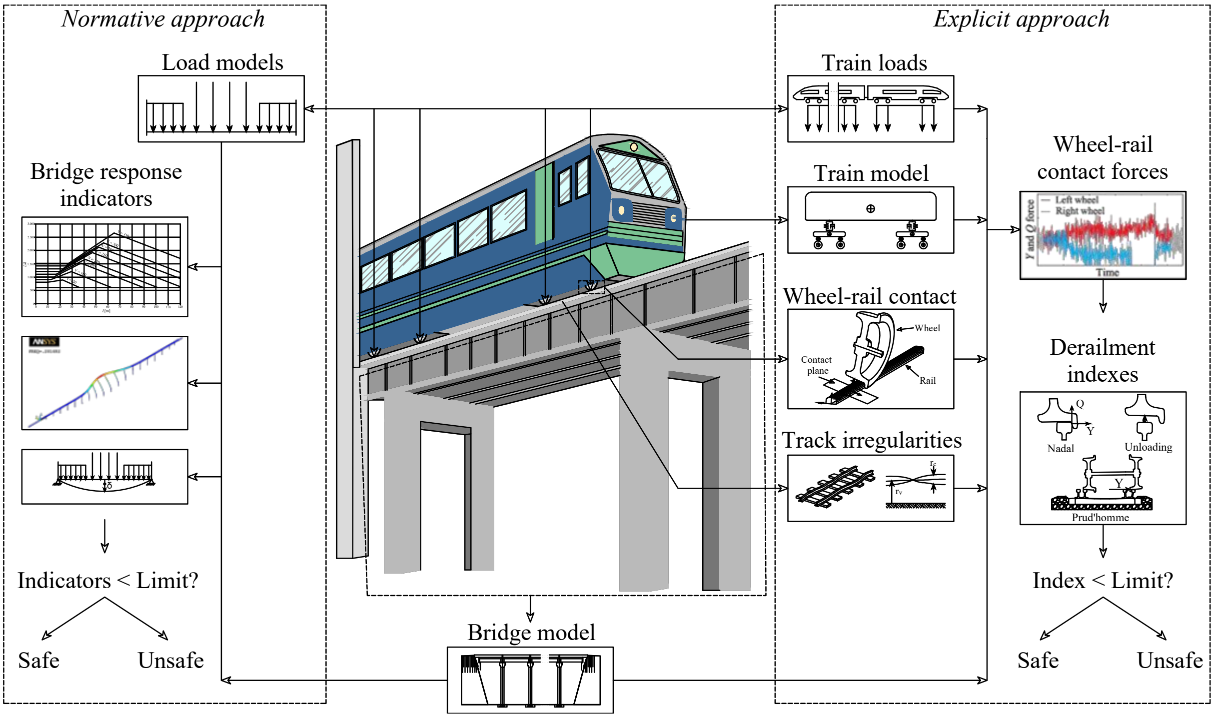

Figure 12 Normative and Explicit Approaches for Traffic stability on bridges.

The TBI analysis is necessary to calculate the contact forces in the wheel-rail interface to determine the safety of the train reliably and explicitly. In contrast to the indirect indicators assessed by the normative method, these criteria aim to directly control the risk of derailment by investigating the relationship between the contact forces, such as force unbalances and ratios between lateral and vertical contact forces, among others. The occurrence of the derailment is typically the result of wheels running off the rails that provide the vehicle with the necessary support, which may lead, in the final scenario, to wheels climbing off the rail or in rail rollover, causing the wheels to fall between the rails or outside of them (Wilson *et al.*, 2019).

The derailment mechanisms must be avoided and controlled by applying appropriate running safety criteria, which, depending on their cause, may be classified as wheel flange climbing, track panel shift, and wheel unloading. Even though these criteria are not used solely to determine bridge traffic safety, it is crucial to define them to understand the stability limits of the train exposed to external excitation. Table 5 summarises the main safety criteria and the derailment mechanisms that may occur during regular and exceptional operational scenarios. Each criterion targets a specific failure mechanism and supports safety evaluations beyond simplified structural displacement checks.

Table 5 Main criteria used in the direct assessment of train stability.

Criterion	**Main Risk Addressed**	**Key Parameter**	**Typical Limit**	**Remarks**
Nadal (ξ_N) [28]	Wheel flange climbing (derailment risk)	Lateral-to-vertical force ratio (Y/Q)	$\xi_N \leq 0.8$ (EU) [29]/ JP [30]/ (CN) [26]), $\xi_N \leq 1.0$ for heavy haul wagons (CN) [26]/ freight trains (US) [31]	Widely used derailment index. Applied to individual wheels
Prud'homme (ξ_P) [32]	Track panel shift due to	Total lateral force Y vs. static load Q_0	$\xi_P \leq 1$ (EU) [29], Depends on the type of rail traffic (CN)	Prevents excessive lateral force on the

	lateral wheelset forces			track. Relevant to infrastructure integrity
Unloading Factor (ξ_U)	Wheel lift-off/loss of contact with the rail	(Q_0 – Q) / Q_0 or bogie load ratio	$\xi_U \leq 0.9$ (EU) [33]/ (US) [31], 0.8 (JP) [30], 0.6 (CN) [26]	Ensures vertical stability. Also used for bogie analysis under crosswinds

10.3 State of the Art Concerning Train Running Safety and Comfort on Bridges

10.3.1 Initial Consideration

The present section starts with lateral bridge vibrations, revisiting classic studies, checking how European standards have evolved, and spotlighting recent research that questions those rules. Next, it looks at deck deflection limits for ride quality, comparing the indirect approach of EN 1990-Annex A2 (2001) with detailed comfort metrics and examples from around the world. Then, it turns to vertical deformation thresholds for safety, outlining Europe's span-wise limits alongside other countries' practices and bringing in insights from modern train–bridge interaction simulations. Throughout, it highlights gaps and opportunities for enhancing normative recommendations.

10.3.2 Lateral Vibration of Bridges for Running Safety

10.3.2.1 Background Studies

The dynamic effects of lateral forces on railway bridges have long raised concerns about train stability and passenger comfort. To tackle these issues, the European research group ERRI D181/RP6 (1996) was formed in the early 1990s to investigate how bridges respond laterally to passing trains. Between 1991 and 1995, the committee conducted a series of field measurements and numerical simulations that laid the foundation for key recommendations now integrated into European railway bridge design standards.

Their study focused on six steel bridges across Europe, featuring metallic trusses and arches with spans ranging from 30 to 120 meters. Due to their low mass and high flexibility, many bridges showed excessive lateral vibrations under traffic, sometimes leading to speed restrictions. To better understand this behaviour, the team measured lateral forces, assessed bridge responses, and analysed the effects of different train types and speeds. Based on comparisons with experimental data, they selected the VAMPIRE software (Scott, 1993) as the most reliable tool for detailed parametric studies.

The committee proposed a minimum first lateral natural frequency of 1.2 Hz to reduce the risk of vehicle-bridge resonance. This threshold reflects coaches' typical lateral motion frequencies (0.5–0.7 Hz) and locomotives (0.7–1.0 Hz), with an added 20% safety margin. Based on ERRI D181/DT329 (1995) studies and included in EN 1990-Annex A2 (2001), this recommendation and others were intended to safeguard ride comfort and vehicle stability more than the bridge's structural integrity.

During the first phase of their parametric study, the team modelled 11 different bridge configurations to assess how variables like span length, stiffness, and mass influence lateral dynamic response under varying train speeds and types. In the second phase, their analysis expanded to include three critical factors affecting resonance: multi-span viaduct behaviour, track quality, and the combined effects of stiffness, span, and natural frequency. The analysis revealed that specific bridge configurations were prone to lateral resonance, increasing the lateral displacements and accelerations in the bridge, thus supporting the need for a minimum frequency threshold. However, while the study suggested that resonance could impact the vehicle's lateral motion, this was inferred rather than conclusively proven by looking to the vehicle response itself. The analysis focused primarily on the bridge's dynamic behaviour, and further work is needed to explicitly explore how the vehicle responds to these effects.

10.3.2.2 Normative Recommendation

The European standard EN 1990-Annex A2 (2001) recommends that a bridge span's first natural frequency of lateral vibration should exceed 1.2 Hz. This requirement applies specifically to the deformation mode of the deck within each span, assuming that the supports are laterally fixed. In other words, assessing this frequency should not consider the flexibility of piers or abutments, as the criterion is intended to control the deck's local dynamic behaviour rather than the entire structure's global response

10.3.2.3 Recent Studies

Recent research has focused mainly on the impact of strong crosswinds and seismic events on the lateral behaviour of railway bridges, especially those with low lateral stiffness. Studies involving advanced Train-Bridge Interaction (TBI) models have shown that even bridges with very low first lateral frequencies (as low as 0.2–0.6 Hz) do not necessarily pose a safety threat to railway vehicles.

A series of works applied these models to real structures, such as the “Las Piedras” viaduct with a first lateral frequency of 0.29 Hz (Cuadrado Sanguino *et al.*, 2008, Dias *et al.*, 2008, Goicolea Ruigómez & Antolin Sanchez, 2012) and the Ulla viaduct with a frequency of 0.22 Hz (Goicolea *et al.*, 2014), showing that lateral deformation of the bridge contributed minimally to the dynamic response of the train. In both cases, track irregularities were identified as the primary source of lateral vehicle accelerations, and no resonance effects or increases in derailment risk were observed.

A more detailed study simulated multiple lateral flexibility configurations for “Las Piedras” (Montenegro *et al.*, 2022). The risk of derailment remained virtually unaffected across all scenarios, including cases with extremely low stiffness (down to 0.199 Hz). Likewise, for the Volga River bridge (first lateral frequency 0.595 Hz), simulations with Shinkansen coaches (with a lateral rolling frequency of 0.58 Hz) found no significant lateral resonance or dynamic amplification, supporting the use of simplified or even rigid bridge models for such assessments (Montenegro *et al.*, 2020). Additional research also confirmed that crosswind-related dynamics are primarily influenced by the wind acting directly on the train body rather than the bridge’s structural flexibility. Even when factors like deck height above ground, which intensifies wind loads, were considered, bridge behaviour had a negligible impact on running safety (Montenegro *et al.*, 2020). Finally, studies evaluating passenger comfort under various bridge stiffness and wind conditions, using vehicles like the Siemens Velaro AVE S-103, concluded that bridge flexibility had minimal effect. Comfort indexes remained within the “very comfortable” range at low speeds and in calm wind scenarios (Montenegro *et al.*, 2022).

The literature consistently indicates that flexible bridges do not compromise train running safety or passenger comfort, especially under typical crosswind and seismic scenarios. While structural vibrations should still be considered in detailed dynamic assessments, they do not pose a significant threat to the integrity of the bridge, and simplifications in bridge modelling are often justified when focusing solely on vehicle safety under lateral actions.

10.3.3 Deck Deflection Limits for Passenger Comfort

10.3.3.1 Background Studies

Passenger comfort in railway travel is primarily affected by the accelerations and vibration frequencies experienced within the car body. As highlighted by ERRI Committee D214/RP9 (1999), extensive research was conducted by Committees D160 (1993) and D190 (1993) to define acceleration thresholds associated with various comfort levels. These efforts led to the development of general bridge deflection guidelines to ensure a smooth and comfortable ride, which is present nowadays in EN 1990-Annex A2 (2001). In particular, Committee D190 (1993) adopted advanced modelling approaches that captured vehicle–structure interaction, incorporated simplified track behaviour, and considered the dynamic influence of both primary and secondary suspension systems.

10.3.3.2 Normative Recommendation

This section evaluates passenger comfort in rail transport using various international standards, focusing on vibration and acceleration levels affecting ride quality. EN 1990-Annex A2 (2001) sets vertical acceleration limits and offers indirect structural checks. EN 12299 (2009) assesses comfort through vibration-based indices using frequency-weighted data. The Japanese RTRI (2006) controls structural displacements and acceleration limits to ensure smooth rides. In China, GB/T 5599-2019 (1985) uses the Sperling index (W_z) to evaluate comfort based on frequency-domain analysis of vehicle vibrations.

10.3.3.2.1 EN 1990-Annex A2

Passenger comfort is ensured through controlled acceleration inside the car body, requiring a dynamic train structure interaction model capable of analysing the vehicle's behaviour. The EN 1990-Annex A2 (2001) defines the limits for vertical acceleration b_v within the car body according to the comfort level, as shown in table 6.

Table 6 Recommended levels of comfort [2].

Level of comfort	Limits
Very good	$b_v \le 1.0$ m/s²
Good	1.0 m/s² < $b_v \le 1.3$ m/s²
Acceptable	1.3 m/s² < $b_v \le 2.0$ m/s²

Once this modelling approach is not ordinarily available to design engineers, the EN 1990-Annex A2 (2001) recommends an indirect method to assess the passenger comfort, limiting the ratio between the deck span L and the deck formation due to the LM71 load model amplified by the dynamic factor. Besides, the limits are defined according to the structural typology and circulation speed. Figure 13 indicates the limits related to a very good comfort level and supported bridges with more than two spans. When assessing the other levels of comfort, the values of L must be divided by the respective upper limit value of b_v. Also, the limit values shown in Figure 13 must be multiplied by 0.7 in the case of single-span bridges or continuous and supported bridges with two spans, while for continuous bridges with more than two spans, the limit values must be multiplied by 0.9.

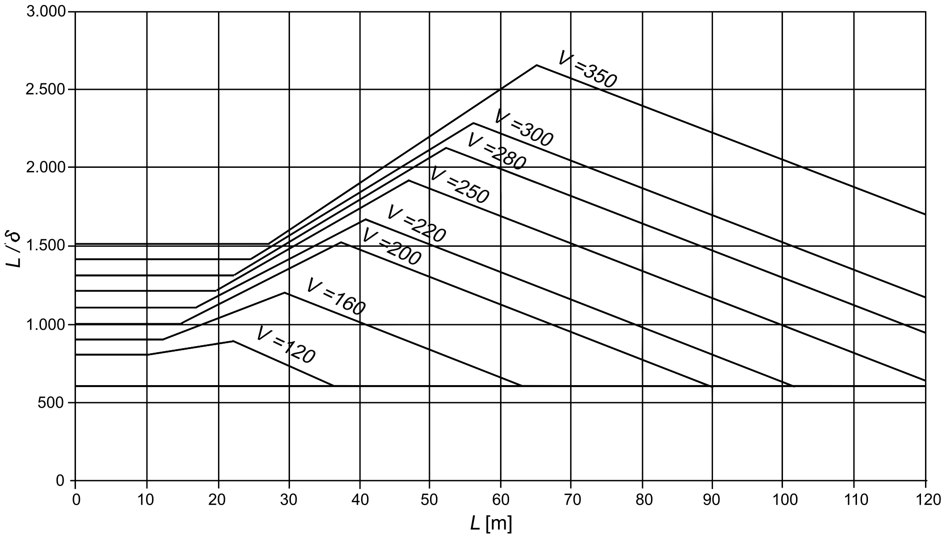

Figure 13 Limit values of L/δ related to a very good level of comfort and supported bridges with more than two spans.

10.3.3.2.2 EN 12299

EN 12299 (2009) provides a standardised method for evaluating passenger riding comfort in railway vehicles based on how the human body perceives vibrations from the train's movement. The standard classifies comfort into long-term (mean), short-term (instantaneous), and curving-related (quasi-static) sensations. Acceleration signals are filtered using frequency weighting functions (W_b, W_c, W_d) to assess comfort, and they are designed to reflect human sensitivity to vibration in different directions. The filtered data is divided into time intervals and processed to calculate comfort indexes like NMV (standard comfort) and C_{cy}/C_cz (continuous comfort in lateral and vertical directions). These values are compared to classification tables to determine comfort levels, ranging from "very comfortable" to "very uncomfortable.

Although EN 12299 (2009) offers more advanced and human-centred comfort criteria than EN 1990-Annex A2 (2001), it does not explicitly address railway bridges. For instance, mean comfort indexes like NMV are calculated over time intervals of five minutes, which makes them incompatible with the brief duration of a train crossing a bridge. As such, the standard is primarily designed to assess generalised comfort conditions over extended stretches of track rather than the short, dynamic events associated with bridge crossings.

10.3.3.2.3 RTRI

In Japan, the railway bridge stability is governed by the Design Standard for Railway Structures – Displacement Limits (RTRI, 2006). This standard sets limits on structural displacements to control the vibrations experienced by passengers during regular operation. The main goal is to ensure that bridge deflections do not cause excessive vehicle vibrations, which could affect passenger comfort or increase track maintenance needs.

When dynamic analysis uses a TBI model, vehicle body acceleration is the key comfort indicator. The acceptable limit for this acceleration should be adapted to the specific conditions of each railway line. For example, a maximum vertical acceleration of 2 m/s^2 has been introduced for low-frequency vibrations (below 1.5 Hz), reflecting comfort standards for express trains.

In cases where structural displacement is used as a verification criterion, regardless of the complexity of the dynamic analysis, the standard also requires checks on girder deflection, track irregularities, and angular rotation. RTRI (2006) provides corresponding limit values for these factors to ensure passenger comfort across different structural components

10.3.3.2.4 GB/T 5599-2019

In China, riding comfort for railway passengers is commonly evaluated using the Sperling index (W_z), as outlined in national standard GB/T 5599-2019 (1985). The index quantifies comfort based on vehicle vibration, using weighted acceleration data to reflect human sensitivity to different vibration frequencies, particularly in the 3–7 Hz range, where the body is most responsive.

According to Deng *et al.* (2021), there are several methods to calculate the W_z index, including the use of frequency-domain weighting functions (*F(f)* and *B(f)*) and the integration of filtered acceleration data described in Jiang *et al.* (2019). The standard accounts for both vertical and lateral directions using separate weighting formulas. Since vehicle vibrations are stochastic rather than harmonic, the index is calculated by integrating across a frequency spectrum rather than using a single frequency. The final W_z value represents the overall ride comfort and is compared to defined thresholds to assess whether the ride is comfortable.

10.3.3.3 Recent Studies

Recent research has concentrated mainly on EN 12299 (2009) and GB/T 5599-2019 (1985), which, while essential standards for evaluating passenger comfort in railway vehicles, are limited and were not explicitly developed for train–bridge interaction scenarios. EN 12299 (2009), for instance, is based on how the human body reacts to vibrations, which is useful, but it does not capture the specific dynamics that happen when a train crosses a bridge. Very few studies have looked at passenger comfort in this context, and the ones that do tend to be limited in scope. Guo *et al.* (2007) numerically assessed comfort on the Tsing Ma Bridge in Hong Kong, finding acceptable levels at lower speeds (100 km/h), while He *et al.* (2018) evaluated a rigid–flexible train–track–bridge interaction (TTBI) model on the Xijiang viaduct in China at a single speed (200 km/h). Olmos and Astiz (2018) modified the EN 12299 methodology for a high-pier viaduct in Spain, but their approach remained limited to one bridge typology and a single comfort index. Using advanced simulations, Montenegro *et al.* (2022) explored TTBI systems under crosswind conditions. It demonstrated that wind loads are the dominant factor influencing passenger discomfort, more so than bridge lateral flexibility or track quality.

In parallel, broader studies on railway comfort have not explicitly focused on bridges. Kumar *et al.* (2017) modelled an Indian train using biodynamic representations of the human body. They found that flexible car body modes had little impact on the Sperling index below 80 km/h. Dumitriu and Leu (2018) examined the relationship between the Sperling and EN 12299 (2009) Mean Comfort indices, noting a non-linear discomfort increase with speed due to vertical vibration filtering. Jiang *et al.* (2019) compared both indices using acceleration data from Australian trains, ultimately proposing a compound Sperling index to better align with EN 12299 (2009). Deng *et al.* (2021) showed that different algorithms for computing the Sperling index can lead to markedly different comfort evaluations. Additionally, Dumitriu and Stănică (2021) compared the Sperling and EN 12299 (2009) methods, concluding that both are effective yet respond differently under varying conditions, suggesting that their combined use offers a more holistic comfort assessment.

Despite these contributions, current standards remain geared toward a narrow range of bridge types and overlook the complexity of modern bridge dynamics. Therefore, there is a clear need for a more comprehensive framework that explicitly considers bridge-specific dynamic effects to enhance safety and passenger experience across today's railway infrastructure.

10.3.4 Vertical Deformation of Decks for Running Safety

This section highlights the international standards that regulate vertical deformation in railway bridge decks to maintain safety and stability. EN 1990-Annex A2 (2001) sets limits for deformation to prevent track instability and ensure the integrity of the rail system. In Japan, RTRI (2006) establishes displacement limits for both standard and seismic conditions, prioritising safety and the ability to restore the track. TB 10621-2014 (2014) and CMR 120 (2004) in China focus on deflection limits based on factors like bridge type, traffic speed, and dynamic effects, especially for high-speed rail. These standards ensure the safe operation of railway bridges under various conditions.

10.3.4.1 EN 1990 Annex A2

The restriction of the vertical deformation of the deck in each span is established to guarantee acceptable vertical track radii and usually robust structures. Therefore, according EN 1990-Annex A2 (2001) and as shown in Figure 14 Vertical deformation of the deck, δ_v., the maximum vertical deformation of the deck due to the characteristic values of the vertical loading model LM71 and, where applicable, SW/0 and SW/2 may not exceed L/600, where L is the span length.

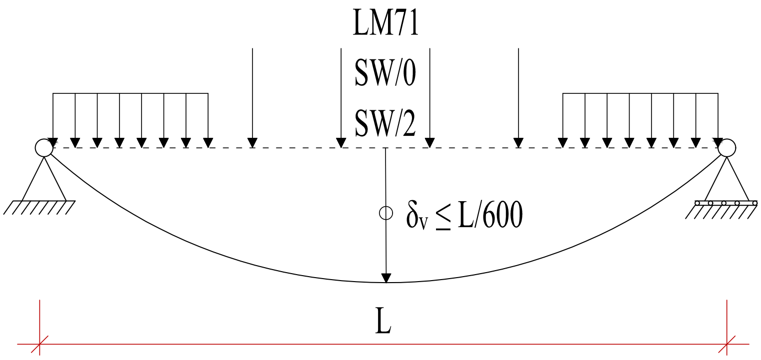

Figure 14 Vertical deformation of the deck, δv.

10.3.4.2 RTRI

In Japan, the stability of railway vehicles on bridges is regulated by RTRI (2006), which outlines requirements for both safety and restorability under normal and seismic conditions. Safety verification ensures smooth train operation throughout the bridge's design life. It minimises derailment risk during earthquakes, particularly under Level 1 seismic motion (defined by RTRI (1999), with peak acceleration up to 2.5 m/s^2 on firm ground). Restorability criteria focus on maintaining the track in a usable condition without major repairs, even after seismic events.

The safety verification may be carried out using indexes based on the contact forces between wheel and rail, the differential displacement of track surfaces, or based on structural displacements. A complex TBI model capable of simulating the entire system's behaviour is required to perform the first and second options. At the same time, the latter can be done by calculating the structural displacement design using static analysis due to training load and spectral analysis due to seismic loads. However, displacement-based indexes are commonly used to simplify verification and avoid complex TBI modelling. These include girder deflection δ due to train passage, alignment irregularities δ_r at girder ends or transitions, and angular rotations θ_r caused by deck-pier or abutment movement in both vertical and lateral directions.

For normal conditions, maximum allowable values for these displacements are defined based on train type, speed, and span length. For instance, Shinkansen bridges allow θ_r values as low as 1.0×10^{-3} at 300–360 km/h. Under seismic conditions, additional limits are applied to δ_r and θ_r to ensure safety, with stricter values imposed as speeds increase

10.3.4.3 TB 10621-2014 and CMR 120

In China, standards such as TB 10621-2014 (2014) and CMR 120 (2004) define verification methods using finite element models that account for dead and live loads. These standards introduce specific load models (ZK, ZC, ZKH, ZH) tailored to various traffic types, including high-speed, intercity, mixed-use, and heavy haul railways. The vertical deflection limits depend on the bridge type, span length, and traffic speed. For example, high-speed railway bridges have stricter deflection limits derived from dynamic simulations considering factors like train acceleration, wheel unloading, derailment risk, and bridge vibration amplitude.

CMR 120 (2004) provides vertical deflection limits for double-track supported bridges with three or more spans, but correction factors are applied for single-track or continuous-span configurations. Moreover, residual deformations due to track construction must also be verified, limited to 20 mm for ballasted concrete bridges, 10 mm for ballastless spans under 50 m, or a minimum between 20 mm and L/5000 for spans larger than 50 m.

10.3.5 Identified Gaps and Concluding Remarks

The lateral vibration limit of 1.2 Hz was initially based on studies of six simply supported bridges. These studies showed that resonance could occur in the bridge itself, observed through lateral displacements and accelerations. However, that does not necessarily mean the same resonance happens in the train. It is especially relevant for modern high-pier viaducts with continuous spans, which often have low-frequency, long-wavelength lateral modes, sometimes even below 0.3 Hz. These bridges were not part of the original analysis, and for resonance to occur in such cases, the whole train would have to move laterally in unison, which is highly unlikely. There are several bridges in service today in Spain with these exact characteristics, and they have been operating without any known issues.

The passenger comfort check in EN 1990-Annex A2 (2001) is another area that could be improved. It relies on an indirect link between bridge deflection and car body acceleration, initially designed for bridges with simply supported beams with three or more spans. While EN 12299 (2009) does offer a more detailed comfort assessment method, it was created for general journey comfort, not specifically for what happens when a train crosses a bridge. So, despite being more detailed, it still leaves a gap. To truly reflect the current understanding of train dynamics, we need to update these standards through TBI analyses that account for different bridge types and operating conditions.

Regarding vertical deformation, EN 1990-Annex A2 (2001) limits deck deflection to L/600 to protect track stability. However, unlike other international standards, these European limits do not adapt based on bridge type, train speed, or vehicle characteristics. Instead, they apply the same rules across the board. These criteria were created decades ago and do not reflect the capabilities we now have with advanced simulation tools, especially TBI models. Today, it is possible to analyse safety more realistically by looking directly at wheel-rail contact forces, using established criteria like Nadal, Prud'homme, or unloading factors.

10.4 Description of the Plan Activities

10.4.1 Initial Considerations

The Ph.D. thesis working plan comprises seven activities (A1 to A7) subdivided into tasks (e.g., T3.1). The first activity, A1, consists of courses targeting the training required to complete the Ph.D. thesis. Activity A2 conducts a comprehensive review of international standards and foundational research on train running stability criteria, focusing on EN 1990-Annex A2 (2001) and recent developments related to each criterion. Activity A3 defines a representative bridge dataset to be used in the analysis. This dataset will be the foundation for evaluating various train stability criteria on bridges through dynamic simulations conducted in the following activities using in-house TBI tools (Montenegro & Calçada, 2023, Montenegro *et al.*, 2015). Activities A4, A5, and A6 involve the development of alternative normative recommendations for lateral bridge vibrations concerning running safety (A4), vertical deck deflection limits related to passenger comfort (A5), and vertical deformation limits of bridge decks concerning running safety (A6). Finally, the research will culminate in the writing of this thesis in active A7. The activities and tasks are described in detail below.

10.4.2 A2 – State of the Art

Activity A2 develops a comprehensive state-of-the-art review on train running stability, covering current normative approaches adopted in Europe and other countries. It also critically analyses the key studies that shaped the criteria defined in EN 1990-Annex A2 (2001) and explores recent research on each criterion. This document summarises the progress made so far.

10.4.3 A3 - Bridge Database for Analysis

The initial database comes from the EU-Rail project, coordinated by UPORTO (InBridge4EU), which has provided a dataset of 450 bridges from five countries. To further support the research objectives, the team plans to collaborate with railway infrastructure managers such as *Infraestruturas de Portugal* (IP, Portugal), *Administrador de Infraestructuras Ferroviarias* (ADIF, Spain), *Deutsche Bahn* (DB, Germany), *Société Nationale des Chemins de Fer Français* (SNCF, France), and *Trafikverket* (Sweden) to gain access to additional bridge databases (Task 3.1). From the original dataset, bridges exhibiting the most significant characteristics for each evaluation criterion will be selected. These selected cases will then undergo parametric adjustments, modifying properties such as mass, stiffness, and span length to develop representative models of critical scenarios for dynamic analysis (Task 3.2).

10.4.4 A4 - Lateral Vibration of Bridges for Running Safety

This activity involves performing TBI simulations with a focus on the lateral dynamics of the train–bridge system. Detailed models of trains and bridges will be developed in Task 4.1 based on the defined dataset. A comprehensive series of dynamic analyses will be conducted in Task 4.2 using a wider variety of bridge types than those considered in previous studies by the ERRI D181 committee (D181/RP6, 1996). The objective is to assess whether resonance effects arising from the similarity between the lateral natural frequencies of the bridge and the vehicle's car body also occur in other bridge configurations. The study also aims to determine whether the resonance observed in the bridge, seen through increased lateral displacements and accelerations, causes a similar resonance in the train. The findings will help clarify whether the current criteria should apply to all bridge types or only to specific cases. Tasks 4.3 and 4.4 then synthesise these findings into an alternative normative recommendation.

10.4.5 A5 - Deck Deflection Limits for Passenger Comfort

This activity will extend the numerical models developed in Task 4.1 (and any new models required in Task 5.2) to investigate how deck deflections from simplified static analyses correlate with accelerations from dynamic simulations across various bridge types (Tasks 5.2 and 5.3). Based on these results, alternative approaches and recommendations for assessing passenger comfort on different bridge configurations will be developed (Task 5.4).

10.4.6 A6 - Vertical Deformation of Decks for Running Safety

Following the framework of the preceding activities, Task 6.1 will extend the numerical models developed earlier, introducing any additional models deemed necessary. In Task 6.2, extensive TBI simulations will be conducted using TBI analyses to refine the permissible deck deformation limits. Task 6.3 will then assess derailment-related factors, such as Nadal's criterion and wheel unloading, by analysing wheel-rail contact forces to understand their impact on train running safety. Finally, these results will be synthesised in Task 6.4 into an alternative normative recommendation.

10.4.7 Timeline

Figure 15 illustrates the ongoing progress of the PhD research, which focuses on normative approaches for the dynamic stability of trains over bridges. The work blends theoretical development with advanced numerical modelling within the broader scope of European research initiatives like EU-Rail. Key milestones include contributions to collaborative reports, leadership in normative research, and paper publications. Partnerships with academic institutions and industry players are essential, as they help guide the technical direction and feed into future publications.

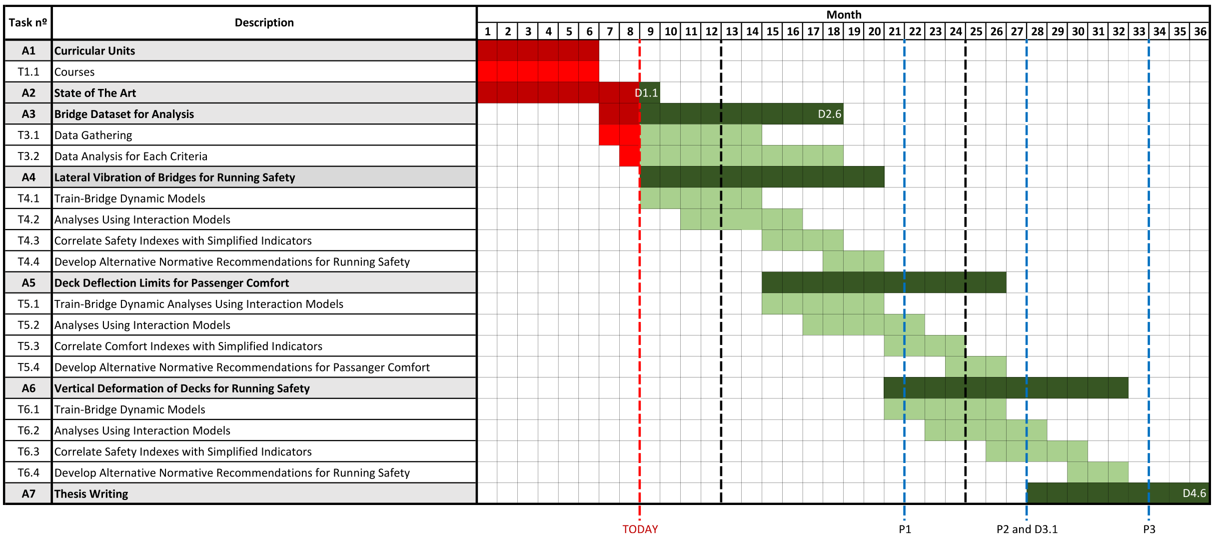

Figure 15 PhD Research Timeline.

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11 Human Factors in Digital Command and Control Systems

11.1 Introduction

Safe communication is a central element of railway operations and forms the backbone of reliable and secure train traffic management. Especially in situations where standard procedures are disrupted—such as signal failures, construction works, or technical malfunctions—a structured and error-free exchange between the involved operational units is of essential importance. In such cases, the so-called "Command" (order) serves as a formalized act of communication that enables deviations from regular operations to be handled safely.

With the ongoing digitalization of the railway sector, not only are the technical frameworks changing, but so too is the nature of communication itself. Systems such as the European Train Control System (ETCS)—particularly in higher levels that operate without conventional light signals—introduce new requirements for communication between dispatchers and train drivers. At the same time, digitalization opens up new possibilities for transmitting written commands no longer via paper but through secure digital channels. The so-called digital driving command reflects this development and is already being tested in practice as part of pilot projects, such as on the high-speed line between Wendlingen and Ulm. (Bjorn Norwig et al. “Der Digitale Befehl,(2023))

11.2 The written command

In German railway operations, the use of operational commands is precisely defined in the DB guideline 408.0411. This regulation specifies the types of commands that exist, the operational conditions under which they are applied, and the roles involved in the communication process.

The framework refers to an official command form, which must be filled out by both the dispatcher and the train driver when required by operational circumstances. The form itself is described in DB guideline 408.0342 and consists of (Jens Rasch and et all. Zuge fahren):

- 14 standardized commands, printed on the front of the form.
- Associated codes and justifications, listed on the reverse side of the form.

Table 7: The 14 command in german written command [3]

Command no.:	Description
Command 1	Passing a signal at danger or a failed main signal
Command 2	Cancellation of a previously issued command
Command 3	Shunting movement onto an open line
Command 4	Shunting movement beyond the regular end point
Command 5	Pushing or pulling back on the line
Command 6	Entry into a wrong track or blocked track
Command 7	Approval to pass a level crossing not fully secured
Command 8	driving on sight or observation while driving
Command 9	Passing a point not fully secured
Command 10	Protective measures during extreme weather conditions
Command 11	Announcement or consent for operating on special sections
Command 12	Measures for meetings or overtakings on single-track lines

Command 13	Instructions for behavior in specific operational situations
Command 14	Other operational measures not covered by previous commands

The guideline also provides detailed instructions on how to fill out the form to ensure consistent and error-free documentation.

Since every order is part of a verbal communication process between dispatcher and train driver, the entire exchange is also strictly regulated. The communication process follows the DB guidelines 408.0341 ("Issuing Orders") and 408.0351 ("Receiving Orders") and adheres to strict procedural steps to prevent misunderstandings:

The dispatcher dictates the order — the sequence and wording are strictly prescribed.

The train driver repeats the order verbatim to confirm accurate understanding.

The dispatcher then confirms the repeated order, which officially validates it and allows its execution.

This structured communication process, known as Closed-Loop Communication, eliminates ambiguities and minimizes the risk of errors resulting from unclear or incorrect formulations. (Jens Rasch and et all. Zuge fahren)

11.3 Adaptation to european standards

To ensure harmonization with European regulations, new versions of the written order forms have been developed in accordance with EU Implementing Regulation 2019/773 – TSI OPE (Technical Specification for Interoperability – Operation and Traffic Management). This alignment represents a key step towards a unified railway operation in Europe, as it seeks to standardize communication and safety procedures across different national railway infrastructures. (BahnPraxis B Ausgabe November/Dezember 2025)

Integration of European and National Orders

The newly introduced system integrates both European and national orders to enable smooth interoperability between various railway systems. This integration is particularly crucial for cross-border railway operations, where previously divergent national order structures often led to inconsistencies and communication challenges. Through the harmonization of order usage, both train drivers and dispatchers can now operate more efficiently when crossing national borders.(BahnPraxis B Ausgabe November/Dezember 2025)

Harmonization of Communication Principles

The revised order forms introduce a standardized communication protocol, ensuring clarity and consistency in railway operations. Key changes include:

The mandatory use of the International Phonetic Alphabet to avoid pronunciation-related misunderstandings.

The digit-by-digit pronunciation of numbers, which minimizes the risk of misinterpretation in safety-critical communication.

These changes contribute to enhanced reliability and safety, particularly in international railway contexts, where clear and precise communication is essential. (BahnPraxis B Ausgabe November/Dezember 2025)

Changes in Order Numbers and Structure

As part of this adaptation, editorial changes have also been made to the numbering of orders and the categorization of reasons for issuing them. This restructuring improves overall consistency and readability, allowing orders to be referenced and applied more easily in different operational scenarios.

The new order form maintains the traditional structure:

- All 14 orders are still located on the front page,
- while the numbered reasons for issuing them remain on the reverse side.

In addition, the layout has been improved for better clarity, and the list of reasons has been updated to reflect current operational requirements and European railway standards.

These updates ensure that the German order system is now better aligned with European railway practices, enabling a more standardized and efficient approach to safety communication and operational procedures across national borders. (BahnPraxis B Ausgabe November/Dezember 2025)

Comparison with the European Order Form

Since the project is EU-funded, it is essential to also consider the written orders as defined in the TSI OPE. In contrast to the German written orders governed by DB Guideline 408, the European order form includes only seven types of orders, with Order 6 currently reserved as a placeholder. (TSI OPE, 2019)(TSI OPE,2022)

A key difference also lies in the format of order transmission:

- In the German system, all orders are included on a single, standardized form. (Jens Rasch and et all. Zuge fahren)
- In the European approach, each order has a separate, dedicated form. (TSI OPE,2022)

Advantages of the European format:

- Improved clarity: Neither the dispatcher nor the train driver has to search within a multipurpose form to find the relevant order.
- Direct application: Each form is tailored to a specific order and only requires the necessary information to be completed. (TSI OPE, 2019)(TSI OPE,2022)

There are ongoing considerations to adopt the European order format in Germany within the next three to four years. However, there are currently no official sources or binding announcements confirming this transition. (TSI OPE, 2019)

11.4 The digital command

Contrary to the analog command in written form on paper the transmission of the digital command is done online and digitally. The dispatcher creates the command, uploads it to a cloud, and the train drivers can then access it. For this to allow secure communication there need to be other measures in place that ensure safe proceedings. Since January of 2025 the digital command is in operational testing (number 03-02-01-W-101) in the digital railway node of Stuttgart and the high-speed track Wendlingen–Ulm, where ETCS-Level 2 without main signals is already in operation. The usage of the digital command is quite similar to the written command. The procedure is as follows. (Marc Scheller. “Betriebserprobung - Digitaler Befehl”,2024)

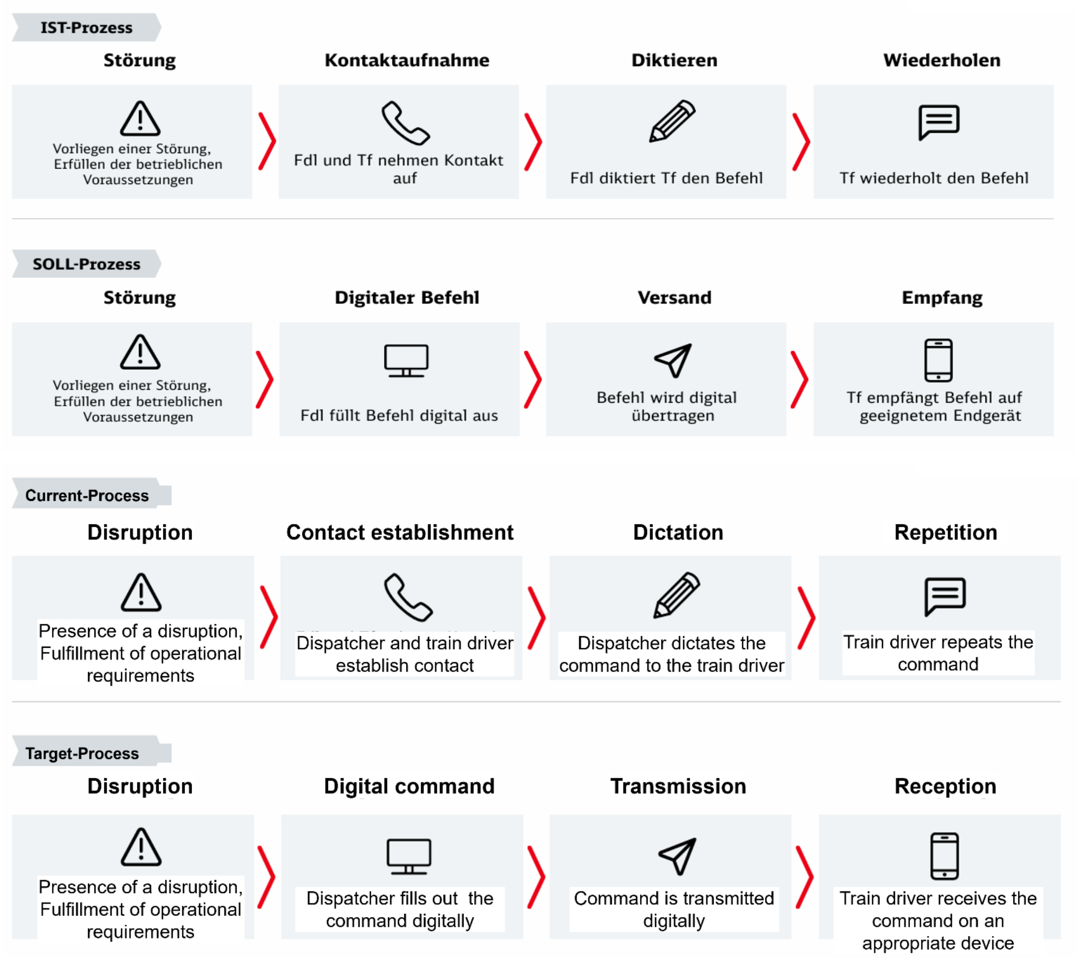

Figure 16: Comparison of written and digital command [2]

1. First an operational reason to create and transmit a command needs to occur.
2. The dispatcher gets information regarding this reason and realizes that they need to transmit a command to the driver.
3. The dispatcher creates one or multiple commands which are concatenated to one command message through a web interface. This command message is then automatically uploaded to the cloud. As soon as the command is uploaded the driver gets a notification and a text message via GSM-R which includes an access code.
4. This message and the notification via GSM-R is the sign for the driver that a command was written and needs to be read and acknowledged.
5. As soon as the train is stopped the driver can now access the command using the access code through the app on a suitable device. Access is granted as soon as the position of the train is confirmed by the dispatcher. This confirmation occurs after the driver enters their position in the app and the dispatcher confirms that it is as expected. This is analogous to the written command and is done to eliminate the risks of mix-ups and misinterpretations. If the position is as expected and that is confirmed by the dispatcher, access to the command message is granted to the driver. If the position differs from what was expected there needs to be further communication through GSM-R.
6. The driver now needs to read through all the commands and confirm each one. The train can now continue driving if the commands allow it.

7. The commands need to be opened on the device used to access them until all their contents are no longer relevant. If the driver for example needs to switch their drivers cabin they need to take the device with them so that the commands are still visible to them. After fulfilling all the commands the driver can mark the command message as done. The command message is then automatically placed in an archive so that it can still be accessed and checked later.
8. In some cases the dispatcher wants to retract a command because the reason is no longer existent. In this case the whole command message needs to be retracted. The dispatcher creates a new command message in which command 14.35 is marked and contains the original code of the first command message.

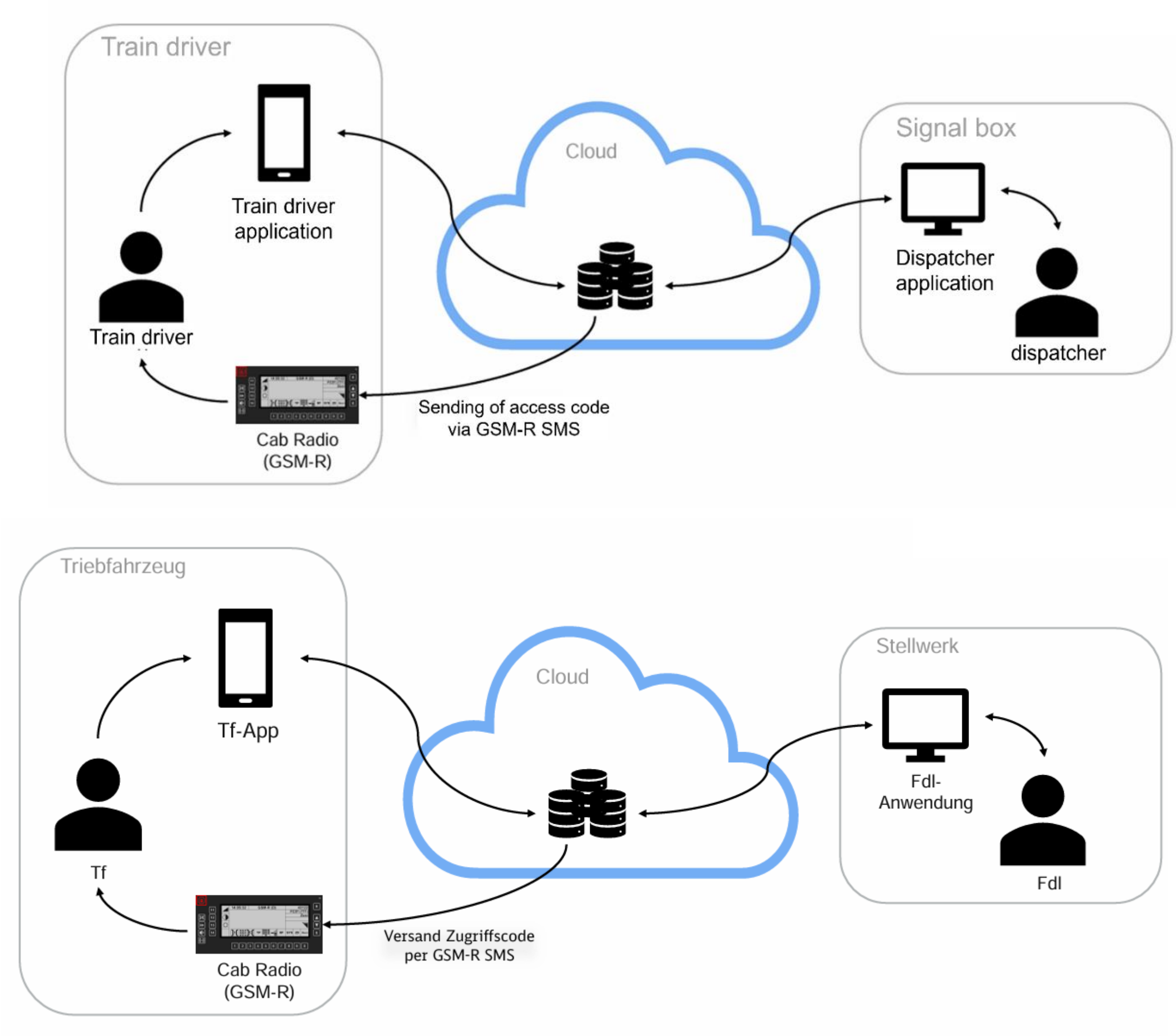

Figure 17: Sequence digital command

An exemplary rundown for the transmission of a digital command could be as follows Dispatcher Schmitt is informed by the local police that a barrier at a railway crossing is damaged because it was rammed by a car.

Soon the RB 4812 will drive through the railway crossing and needs to be informed. The dispatcher creates a command message in their web interface in which command 8 is marked valid with the instruction to stop before the crossing and then proceed with caution. This command message is now placed in the cloud and the driver Holly receives a text message with the access code and a notification on their GSM-R device. Because he is stopped at a platform anyway he can instantly use his tablet to access the command message. He enters his location in the app, which is then confirmed by the dispatcher. He can now read and acknowledge the command message. He can continue driving with minimal delays. For now he keeps the command visible on his tablet until he has passed the crossing. After that he marks it as done and it is placed in the archive. (Marc Scheller. “Betriebserprobung - Digitaler Befehl”,2024)

Time savings

Many transmissions of information are made secure against misunderstandings by repetition. This creates security but also takes a lot of time since there is prescribed wording that may not be shortened. With the written command it was also possible for the dispatcher to create commands ahead of calling the driver. However, for the transmission the entire command needed to be read out aloud by the dispatcher, written down by the driver, and then read aloud again. After that in some cases there need to be made corrections and an exchange of names before the driver could continue operating the train. The digital command shortens these steps. The dispatcher creates a command message, it is uploaded to the cloud, and they wait for the driver to enter their position into the app. If this position is as expected the work for the dispatcher is done. The time for reading and acknowledging the commands is also much quicker with the digital command. With this method both parties save time and ideally the doesn’t need to be any communication using GSM-R. (Bjorn Norwig et al. “Der Digitale Befehl,2023)

Easement of work

The simplifications that the digital command brings is not only noticeable through time savings. First the transmission is made much easier and entirely asynchronous except for the confirmation of the location, which is almost synchronous in the best case. Secondly only the needed commands are visible for the driver which further simplifies the information intake. This way the dispatchers have more time for other time intensive tasks that have not been digitalized yet. In the time is usually takes to write and transmit a written command the dispatcher can now easily create multiple digital commands and only needs minimal interactionwith the driver. (Bjorn Norwig et al. “Der Digitale Befehl,2023)

Sustainability

A little but not negligible argument for the digital command is the environmental impact of railway operations, which could be improved by saving on paper usage. Meanwhile the need for server infrastructure rises as well. This raises the amount of resources required for building and cooling said infrastructure. Whether this adds to the sustainability needs to be a topic of further discussion.(Bjorn Norwig et al. “Der Digitale Befehl,2023)

Technical difficulties

A possible negative is that connection problems could occur which would make accessing the commands difficult or even impossible. Also a technical defect on the tablet or other device the driver uses can’t be ruled out. This possible flaw is annulled however, since the written command using the very robust GSM-R system is still used as a backup. (Bjorn Norwig et al. “Der Digitale Befehl,2023)

Differences from the status quo

The main obvious difference is how the command is presented. Instead of being created through a radio dialogue it is transmitted digitally and accessible faster. Furthermore, the digital creation and transmission usually eliminates the need for two radio calls between dispatcher and driver. On the one hand the digital command saves time for the dispatcher since the command doesn’t need to be written and read aloud, on the other hand it also saves time for the driver who now just has to read and acknowledge the command message. The implementation of the digital command saves a lot of time without sacrificing security aspects. It also simplifies the work for drivers and dispatchers. The digital command futureproofs this aspect of railway operations.(Bjorn Norwig et al. “Der Digitale Befehl,2023)

Operational testing since January 2025

In addition to the planned operation in the digital railway node of Stuttgart the digital command is already in operation on the high-speed track Wendlingen–Ulm.

This line was massively expanded and improved until the end of 2022. In the first year of operations after that there were 6 million passengers using trains on it. The line is also equipped with ETCS-Level 2, which was also in operations testing here. With this operations testing the stability is tested and any flaws should be detected. DB expects the transmission of commands to be accelerated, thereby reducing downtimes, while safety will not suffer as a result. Also the proceedings in the signalling centres and the documentation and controlling are a focal point. The operations testing is planned until the end of 2026. (Bjorn Norwig et al. "Der Digitale Befehl,2023))

11.5 Research plan and project phases

The present research project is being conducted in close cooperation with Deutsche Bahn (DB) and consists of three core phases, with a potential fourth implementation phase in our laboratory. The aim is to systematically evaluate the digital order system from a Human Factors and practical implementation perspective, and to derive suggestions for further development and optimization.

Phase 1: Interviews with Train Drivers and Dispatchers

(Planned until August 2025)

The first phase involves conducting qualitative interviews with train drivers and dispatchers to collect their experiences and assessments of the new system after several months of use. The following research questions will guide the interviews:

- What advantages and disadvantages do users perceive in the digital order system?
- What challenges have arisen during practical implementation?
- What improvements or adjustments would they suggest?

The timing of the interviews—approximately 7–8 months after system introduction—ensures that participants have sufficient experience to provide a meaningful comparison with the previous process.

Phase 2: Cab Ride Observations and Operations Center Visit

The second phase will involve direct observations of railway operations:

- A cab ride will be conducted with selected train drivers, while on-site observation of dispatchers will be carried out at the operations control center.
- This observational phase is intended to deepen the interpretation of the interview findings and provide contextual understanding of the workflows.
- A second round of interviews will be conducted during the visit, to capture how perceptions have evolved after longer exposure to the system.

Phase 3: Evaluation of the New Order Forms

(Conditional – in case of system update in December 2025)

If the new order forms are introduced as planned in December 2025, a third data collection phase is intended to assess user acceptance and training outcomes. Questions will include:

- How do participants evaluate the new form compared to the previous one?
- How long did the re-training take? Were there any difficulties?
- Have problems or improvement ideas already emerged?
- Is the new form considered clearly superior, or are elements of the old form still preferred?

Phase 4: Development and Testing of a New Digital Order Prototype

(Early 2026 and early 2027 – in the research lab)

Drawing on the insights from the field study, a new digital order prototype will be developed for the research lab:

- Train drivers and dispatchers who have worked with the system in real-life conditions will be invited to the lab to test the prototype.
- Their feedback will help assess the realism and usability of the lab system and will support an iterative improvement process.

11.6 Challenges

Human Factors & Usability

The transition from verbal and written commands to digital systems presents significant challenges for both train drivers and dispatchers. To ensure a safe and smooth transition, it is essential that the user interface be intuitive, that information be clearly presented, and that the cognitive workload remains manageable under operational stress.

Communication & Interaction

The introduction of new digital command formats changes the dynamics of communication between operational staff. Key research questions include:

- How do train drivers and dispatchers adapt to digital orders?
- Do new forms of misunderstanding or delay emerge?
- How does the reduction in verbal communication affect situational awareness?

Metrics and ethical considerations

To systematically evaluate the digital command system, several key performance indicators will be measured: the number of errors or near-misses, confirmation latency, acknowledgement accuracy, and subjective workload (using NASA-TLX). Usability will be assessed through established questionnaires such as SUS, while message

94 readability will be analyzed to ensure clarity in safety-critical contexts. All studies will strictly comply with data protection regulations and informed consent requirements, thereby ensuring both scientific integrity and ethical responsibility.

Safety & Risk Considerations

Given that operational commands are typically used in disrupted or degraded situations, safety remains the top priority. Research must address:

- How can digital commands be designed to prevent misinterpretations?
- What fallback procedures are available in case of technical failure?
- How can it be ensured that human operators remain in control in safety-critical scenarios?

Addressing these challenges through empirical research, field testing, and iterative system refinement is vital to achieve both operational reliability and high safety standards in the digital railway context.

11.7 Conclusion

Safe communication is a cornerstone of efficient and secure railway operations—whether carried out through traditional written orders or modern digital systems. As new technologies are introduced, it becomes increasingly important to ensure that humans and machines interact effectively and intuitively. Human factors play a central role in this transformation: Only when train drivers and dispatchers fully understand and confidently apply the new procedures can safety and efficiency be maintained. This research project aims to optimize communication workflows, minimize risks, and support the practical implementation of digital command systems within a framework that is both user-centered and safety-oriented.

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12 Economic Impact (KPI) of Rail Research Programs

12.1 Introduction

12.1.1 Background

The transformation of European rail research from Shift2Rail (S2R) to the Europe's Rail Joint Undertaking (ERJU) reflects an intensifying policy effort to position rail as the backbone of sustainable mobility. S2R (2014–2021) launched as a public-private partnership under Regulation No. 642/2014, targeting cost reduction, capacity gains, and improved punctuality (Shift2Rail, 2015). Its innovations were tested through System Platform Demonstrators and assessed using a combination of spreadsheet-based KPI tools and a MATLAB based mode choice model (Academics4Rail, 2024). Though conceptually robust, these models were limited in transparency, granularity, and policy sensitivity.

Building on this legacy, ERJU was formally launched in 2021 to deliver "a high capacity, flexible, multi- modal, sustainable and reliable integrated European railway network" (ERJU, 2022b; Academics4Rail, 2024). Organised into seven Flagship Projects (FPs), its technical outputs (over 500 KPIs) are now monitored for conversion into societal indicators aligned with EU goals such as modal shift and decarbonisation (Academics4Rail, 2024). As of early 2024, ERJU demonstrators, such as Digital Automated Coupling (DAC) for freight and Automatic Train Operation (ATO) for metro and regional rail, are progressing toward Technology Readiness Levels (TRL) 6–7, with broader deployment targeted from 2025 onward. In parallel, the societal impact frameworks developed under the Academics4Rail WP3 project since 2023 are entering pilot application stages to complement the technical assessments (Academics4Rail, 2024).

This PhD project constitutes a targeted extension of the Academics4Rail WP3 assessment framework, explicitly addressing its principal empirical shortcoming: the lack of quantified estimates of the societal impacts emerging from EU-Rail technical research. Anchored within a Social Cost-Benefit Analysis (SCBA) framework (European Commission, 2021), the research operationalises the translation of technical innovation into measurable economic, environmental, and modal outcomes. It builds upon WP3's structured, multi-layered KPI system by converting intermediate performance indicators into variables compatible with mode choice modelling and, subsequently, into macro-level societal metrics such as carbon emissions, user welfare, and system resilience (Academics4Rail, 2024).

Beyond this alignment, the PhD contributes novel empirical depth by deriving new parameter estimates that enhance the behavioural realism and systemic robustness of the assessment model. On the demand side, this includes the monetisation of performance reliability and its impact on rail attractiveness; on the supply side, it encompasses modelling the interactions between cost structures, climatic disruptions, and operational resilience. These insights are generated through econometric analyses of large-scale datasets from Great Britain and France (e.g. Smith et al., 2023; Wardman & Batley, 2021; Bruscoli, 2016), thereby contextualising EU-Rail innovations within real-world demand and infrastructure performance dynamics.

In methodological terms, the PhD serves as the applied quantification component of WP3, advancing its theoretical architecture through empirical calibration and evaluative functionality. It enables a more comprehensive impact appraisal of ERJU research outputs by integrating technical merit with policy and societal relevance. Beyond ERJU, the modular and scalable structure of the proposed framework is intended to support broader applications in future societal impact assessments within the rail sector and across wider transport research programmes

12.1.2 Problem Statement

Despite significant investment in rail research through Shift2Rail and its successor EU-Rail, key methodological challenges continue to constrain the ability to credibly assess societal benefits. The current evaluation landscape remains fragmented, with diverse Key Performance Indicators (KPIs) employed across Flagship Projects lacking harmonised definitions and consistent baselines (Academics4Rail, 2024). This heterogeneity undermines the aggregation of technical outputs, such as improvements in punctuality or lifecycle costs, into higher-level outcomes such as modal shift or carbon reduction. Previous attempts within Shift2Rail, including the IMPACT-1 and IMPACT-2 frameworks, often depended on static assumptions that did not adequately reflect behavioural dynamics or policy feedback mechanisms (IMPACT-2, 2020).

Furthermore, the attribution of societal outcomes to technical innovation remains methodologically complex, particularly where technical KPIs, such as maintenance cost reductions or delay minutes, must be linked to macro-level objectives including decarbonisation and system resilience. While recent frameworks, including that of Academics4Rail, provide a structured foundation, the causal relationship between specific technical innovations and broader societal objectives has yet to be systematically established. This issue is compounded by the limited empirical grounding of demand-side parameters .

Additionally, data scarcity, especially in the form of harmonised cost and performance records across countries, continues to hinder robust model calibration (Academics4Rail, 2024). Addressing these limitations requires the integration of stakeholder expertise and access to high-quality data. Both are critical to enhancing the credibility and policy relevance of the impact assessment framework. This PhD seeks to respond to these gaps by advancing a generalisable, empirically grounded methodology within a Social Cost-Benefit Analysis (SCBA) framework.

12.1.3 Research Objectives

This PhD aims to develop a modular and generalisable framework for quantifying the societal and economic impacts of EU-Rail technical innovations, aligned with the overarching methodology proposed in Work Package 3 (WP3) of Academics4Rail. The primary objective is is to integrate technical KPIs such as improvements in life-cycle cost (LCC), reliability, and capacity into an impact assessment model that links innovation performance to modal shift and broader societal outcomes via mode choice modelling. The framework will be implemented across four rail markets (high-speed, regional, metro, and freight), and will be tested using methods such as TRIMODE and elasticity-based approaches.

Complementary objectives include streamlining the KPI-to-impact conversion process and generating new and updated evidence on key input parameters. Specifically, the research will quantify the economic and societal effects of ERJU innovations and strengthen the underpinning of the model by addressing two evidence gaps: (a) the cost and disruption implications of climate-induced shocks and their interaction with traffic density and delay incidents; and (b) the valuation of demand-side benefits from enhanced rail performance. These empirical tasks will be supported by multi-country datasets and ongoing collaboration with infrastructure managers and EU-Rail stakeholders. The final emphasis between these areas will evolve during the course of the PhD, recognising that not all aspects may be fully addressed within the available timeframe.

12.1.4 Relevance and Policy Alignment

This PhD supports EU priorities on modal shift, decarbonisation, transport resilience, and efficient public investment. By operationalising KPI frameworks from Shift2Rail IMPACT studies and Ernst & Young's societal cards (EY, 2023; EC, 2019), the project contributes to quantifying innovation-led impacts through a Social CBA lens. It aligns with TEN-T and Green Deal targets via models that link technical KPIs to societal outcomes such as greenhouse gas (GHG) savings, congestion relief, and safety improvements. The research provides policy-relevant evidence for ERJU, CINEA, and Member States, bridging the methodological framework from A4R WP3 with empirical appraisal needs, and filling a critical quantification gap identified across EU-Rail innovation assessments (Academics4Rail, 2024 ; IMPACT-2, 2022).

12.2 State of the Art

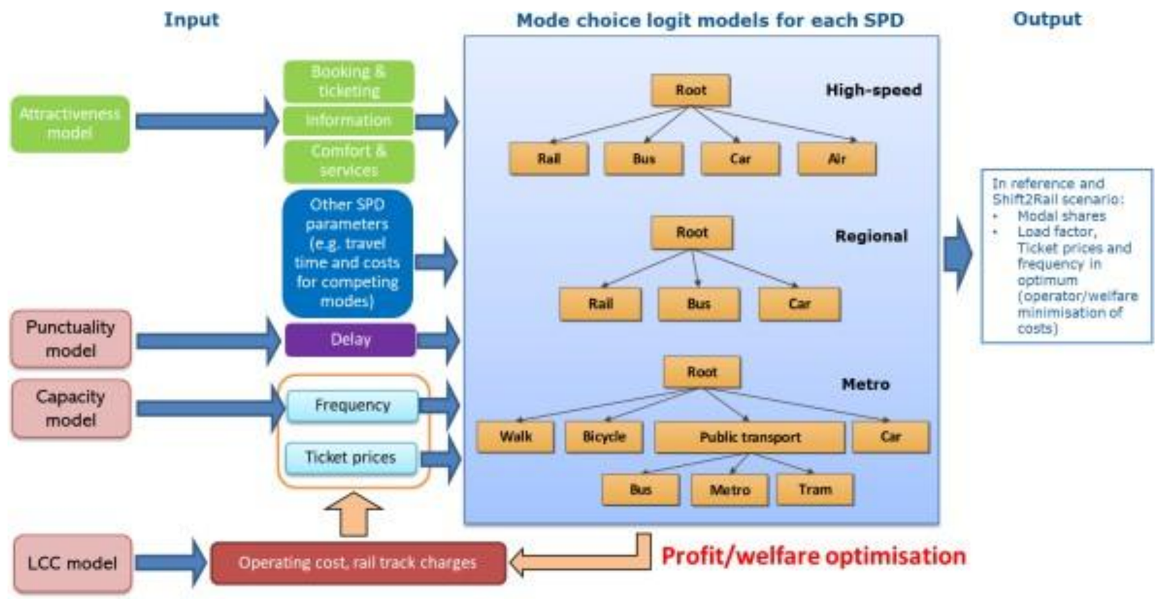

Figure 18-Connection between mode choice model, KPI model, and customer experience model (IMPACT-2, 2020)

12.2.1 Overview of Shift2Rail Frameworks

The Shift2Rail (S2R) Joint Undertaking was launched as the first European rail-focused public-private partnership to drive innovation, enhance performance, and support modal shift across passenger and freight rail segments. To evaluate the contribution of rail innovation to EU transport and societal objectives, the Shift2Rail (S2R) programme established a structured, model-based assessment methodology (Shift2Rail, 2015). This framework matured through two core initiatives: **IMPACT-1** and **IMPACT-2**, and was later supplemented by the more extensive socio-economic cost-benefit analysis developed in **EY (2023)** IMPACT-1 initiated the process by introducing **System Platform Demonstrators (SPDs)** as harmonised testbeds for assessing innovation impact across four market segments: high-speed, regional, metro, and freight. It also defined a multi-layered **Key Performance Indicator (KPI)** framework targeting core dimensions such as life-cycle cost (LCC), capacity, punctuality, and energy consumption (IMPACT-1, 2021; Academics4Rail, 2024). These indicators were designed to evaluate the system-wide effects of technical interventions under standardised operating conditions.

IMPACT-2 extended this structure by incorporating **socio-economic dimensions** and modelling user responses via a **nested logit mode choice model** developed in MATLAB (IMPACT-2, 2021A; IMPACT- 2, 2020). Calibrated on corridor-specific data, the model estimated changes in demand and corresponding welfare outcomes for passenger and freight rail under baseline and innovation scenarios, distinguishing by time-of-day and user segment (e.g. business vs. leisure). The resulting outputs (rail mode share, consumer surplus, and producer surplus) were derived from technical KPI inputs such as frequency and reliability improvements (Academics4Rail, 2024). The **EY (2023)** report scaled up these results to the European level over a 30-year period, incorporating implementation delays, regional correction factors, and capital cost estimates (EY, 2023). It also introduced a consistent discounting methodology and scenario modeling, including delayed uptake, constant ticket pricing assumptions, and interaction with electric and autonomous vehicles. It produced both **financial and societal benefit-cost ratios (BCRs)** for each SPD, making explicit the divergence between private returns and public value. Although EY's modelling built directly on the IMPACT-2 architecture, its scope was significantly broader in both time horizon and valuation logic.

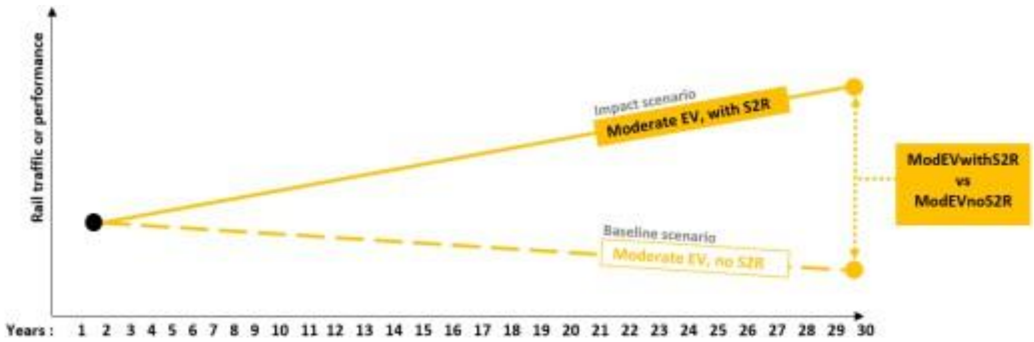

Figure 19-Illustrative example of the baseline and impact scenarios (E&Y, 2023c)

12.2.2 Key Findings from S2R Impact Studies

Across the frameworks, the most robust finding is that deployment of S2R innovations could generate substantial modal shift and social value. **IMPACT-1** identified indicative **cost savings**, particularly through reductions in LCC and improved punctuality (IMPACT-1, 2021). These effects were structured through SPDs to estimate technical benefits in real-world settings, though no formal demand modeling was included.

IMPACT-2 integrated these cost and service improvements into behavioural demand models. Results showed that that high-speed rail's share of intercity transport could rise from 24% to 35% under the innovation scenario (IMPACT-2, 2021B). Regional and metro SPDs showed capacity and punctuality improvements contributing to increased usage and reduced congestion.Freight analysis (based on an adaptation of the Swedish *Samgods* model) projected modal shift from road to rail, enabled by operational efficiency gains such as traffic automation and logistics platforms (IMPACT-2, 2020; 2021B). Welfare gains were calculated using social cost-benefit analysis. Consumer surplus, accident reduction, CO_2 savings, and noise mitigation were monetised using EU Handbook values (IMPACT-2, 2022). Although results varied across segments, all SPDs showed positive societal returns under baseline assumptions.

EY (2023) significantly broadened the scope, applying a 30-year appraisal period and calculating **financial and societal BCRs**. For instance, metro systems achieved a societal BCR of 15.62 and a financial BCR of 1.82, while high-speed rail yielded 13.02 and 3.90, respectively (EY, 2023). The analysis included implementation lags and nominal ticket price rigidity during early adoption years (EY, 2023). The EY report also introduced sensitivity scenarios for autonomous and electric vehicles, congestion levels, and demand elasticity. Results were generally robust, although implementation speed and regional variation significantly affected benefits.

Table 8-S2R's Financial and Societal CBA Outcomes by Rail Segment

Rail Segment	IRR	BCR (Financial Only)	BCR+ (Including Societal Benefits)	Baseline Modal Share	Post-S2R Modal Share	Key Financial Drivers
High-Speed Rail	**14%**	**3.90**	**13.0**	**24%**	**35%**	**Increased passenger demand, high operational efficiency**

Freight Rail	**10.7%**	**2.18**	**3.14**	**21%**	**32-47%**	**Large modal shift from road, reduced freight costs**
Urban/Metro Rail	**7%**	**1.82**	**15.6**	**30%**	**31%**	**Cost efficiency, high-frequency service benefits**
Regional Rail	**6%**	**1.23**	**4.61**	**18%**	**29-40%**	**Lower ticket revenue growth, requires cost savings**

12.2.3 Methodological Limitations and Assumptions

Despite their contributions, the S2R impact frameworks exhibit several important methodological limitations.

a) Behavioural Simplification

The nested logit models in IMPACT-2 assume **fixed demand**, **static Value of Time (VoT)**, and **symmetrical reversibility** in modal choice (IMPACT-2, 2020). Although these choices enhance analytical tractability, they restrict realism, particularly in contexts involving behavioural inertia or feedback from congestion and pricing. As Academics4Rail (2024) notes, such simplifications weaken model robustness in dynamic, policy-responsive environments.

b) Policy Inertia and Static Costs

All models assume constant external factors such as track access charges, congestion, and energy prices. While EY (2023) includes some sensitivity analysis, key variables like carbon taxation or fuel price trends are not dynamically modelled. This constrains realism under long-term investment appraisal.

c) Scaling Constraints

While IMPACT-2 results remained corridor-specific with no formal mechanism for EU-wide generalisation (IMPACT-2, 2021B; Academics4Rail, 2024), EY (2023) addressed this gap by introducing a structured scaling methodology. This included the use of asset-based multipliers, regional correction coefficients, and demand-side extrapolation factors to project SPD-level outcomes onto the European transport network (EY, 2023). However, the method still relied on stylised assumptions and single-corridor proxies, which may limit representativeness for more complex national systems.

d) Missing Wider Economic Benefits

IMPACT-2 only models **wider economic benefits (WEBs)** (such as agglomeration effects) in the metro SPD (IMPACT-2, 2022). EY acknowledges their relevance but excludes them from final estimates. In contrast, for UK projects like HS2 and Crossrail, after inclusion of WEBs to their CBA, total benefits were increased by 25–50% respectively, suggesting potential underestimation in S2R appraisals.

12.2.4 Summary of Gaps

Despite offering a structured foundation for assessing technical innovations, the Shift2Rail (S2R) framework exhibits persistent limitations that constrain its evaluative power. A core challenge lies in data availability. The baseline information required for both KPI and mode choice models is often incomplete, outdated, or fragmented (Academics4Rail, 2024; EY, 2023). Infrastructure cost estimates are partial (EY, 2023), freight projections rely on a single-country model not adapted for EU-wide application (IMPACT- 2, 2021b), and congestion and elasticity parameters are held constant (IMPACT-2, 2021b; Academics4Rail, 2024), undermining robust calibration and the credibility of impact estimates.

The generalisability of results is similarly constrained. Corridor-specific System Platform Demonstrators (SPDs) form the empirical basis, yet contextual heterogeneity, such as national pricing structures and infrastructure constraints, remains insufficiently addressed. Extrapolation of freight cases is particularly difficult given operational diversity in marshalling practices and network design (IMPACT-2, 2020; 2021b).

Further, the framework exhibits an over-reliance on high-level assumptions, including static Value of Time (VoT), fixed elasticity, and simplified operator behaviour, which reduces behavioural realism (IMPACT-2, 2022; Academics4Rail, 2024).

Finally, there is no integrated mechanism linking technical KPIs across market segments. Each SPD operates independently, with no modelling of ripple effects or system-wide optimisation between passenger and freight domains (Academics4Rail, 2024). Addressing these gaps requires a modular, empiricallygrounded methodology capable of integrating system-level interactions, an objective this PhD aims to advance.

12.3 Research Design and Methodological Approach

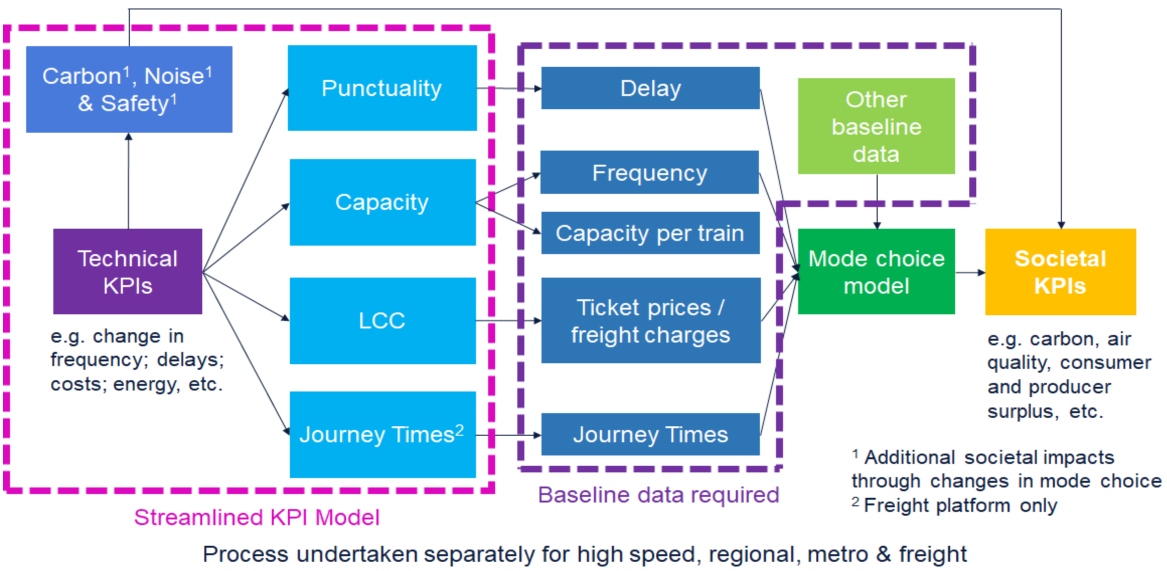

Figure 20-Schematic of Proposed ERJU Overarching Assessment Framework (Academics4Rail, 2024

12.3.1 High-Level Framework Overview

The proposed ERJU assessment framework operationalises a modular, multi-stage methodology for translating technical rail innovations into societal impacts. As outlined in Academics4Rail (2024), its architecture links project-level KPIs to modal shift outcomes and high-level societal benefits, thereby addressing core methodological gaps identified in prior S2R evaluations.

The first stage of the assessment framework is the KPI model that adopts a streamlined structure, designed to focus exclusively on the system components directly affected by each innovation. By limiting its scope in this way, the model minimises data requirements and avoids imposing assumptions on unaffected areas. Technical KPIs, such as percentage changes in reliability or capacity, are systematically converted into high-level impact indicators including life-cycle cost (LCC), punctuality, and safety, ensuring consistency between innovation-level outputs and system-level appraisal (Academics4Rail, 2024). This translation is performed through structured equations, such as calculating ΔLCC from defined cost elements like rolling stock maintenance, thereby maintaining methodological rigour without requiring fully disaggregated system data.

The second stage converts these impacts into mode choice model inputs. Where models like TRIMODE lack direct reliability modules, attributes such as punctuality are re-expressed in terms of generalised cost. The resulting outputs are shifts in mode share across four key platforms: high-speed, regional, metro, and freight (Academics4Rail, 2024).

The final stage computes societal KPIs (such as greenhouse gas emissions, safety, noise, and congestion) based on mode share variation and the relative unit cost per passenger or tonne-km in case of freight. Platform-specific disaggregation is essential, as flagship projects (e.g., FP5 for freight) vary in scope. Where direct KPI translation is not feasible, qualitative indicators are applied (e.g., +, ++).

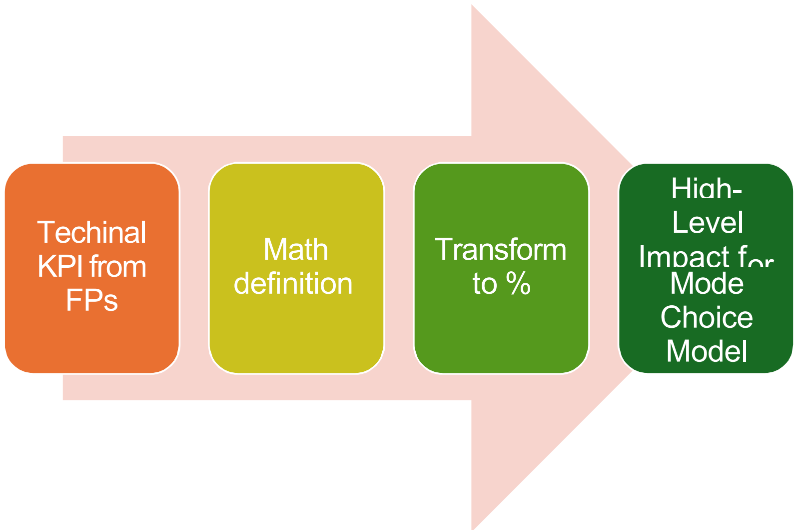

Figure 21-Process from Projects Technical KPIs to High-Level Impacts for Mode Choice Model (Academics4Rail, 2024)

12.3.2 Streamlined KPI Model

To reduce data burden while retaining evaluative depth, the ERJU framework proposes a streamlined KPI model that isolates only those rail system elements directly affected by innovation (Academics4Rail, 2024). This approach represents a departure from earlier S2R models which required exhaustive system-wide data, including for unaffected components. Instead, technical KPIs are mapped through a multi-tier attribution structure, from component-level metrics (e.g. rolling stock maintenance costs) to high-level impacts such as Life Cycle Cost (LCC), capacity, or punctuality (Academics4Rail, 2024).

For example, a 10% reduction in fleet maintenance cost can be translated to LCC impact using two ratios:

(i) maintenance as a share of operating cost, and (ii) operating cost as a share of LCC (Academics4Rail, 2024). This logic generalises across indicators such as journey time or carbon emissions (Academics4Rail, 2024).

KPI attribution is market-specific and requires assumption-based extrapolation when data is incomplete. Only ~50% of project-level KPIs are unambiguous; the rest necessitate stakeholder clarification or agreement (Academics4Rail, 2024). The framework explicitly accommodates such interpretive processes.

Thus, this model enhances feasibility and methodological transparency. By narrowing data scope, layering impact translation, and formally embedding stakeholder input, it aligns technical innovation with strategic performance metrics in a scalable and policy-relevant way.

12.3.3 Mode Choice Modeling and Calibration

Translating technical KPIs into societal outcomes requires a robust mode choice modeling architecture. Three primary approaches (case study models, network-based simulations, and elasticity-based estimations) are under review for implementation within this research (PhD8) and the Academics4Rail (A4R) WP3 framework. Each is evaluated for data needs, scalability, platform fit, and integration potential with the KPI logic underpinning Social Cost-Benefit Analysis (SCBA).

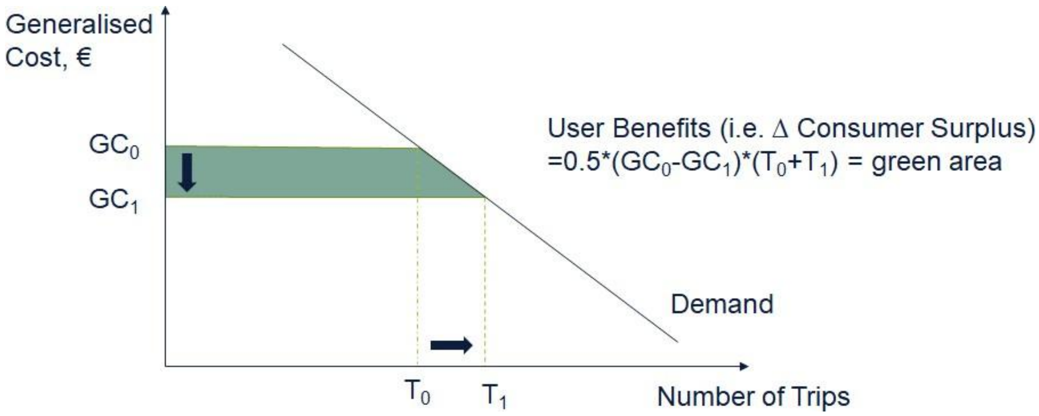

Figure 22-Elasticity-Based Approach for Estimating Benefits (Academics4Rail, 2024)

Case study models, as applied in the IMPACT-1 and IMPACT-2 studies, employ a corridor-specific and possibly a nested logit structure (Academics4Rail, 2024). These models incorporate fare and frequency optimisation mechanisms, simulating user responses to service changes and quantifying modal shift through estimated gains in both producer and consumer surplus. Their value lies in detailed scenario testing for high-speed and regional passenger rail, though their limited generalizability and high calibration requirements hinder EU-wide application (IMPACT-2, 2020).

Network models, such as TRIMODE or Samgods, represent spatial multimodal flows across passenger and freight systems (Academics4Rail, 2024). While TRIMODE is still under validation, Samgods offers disaggregated freight simulation, ideal for ERJU's logistics platforms. These models facilitate macro-level assessment but require assumptions to translate innovation-driven KPI changes into behavioural responses in transport demand and mode choice.

Elasticity-based approaches offer parsimonious yet theory-consistent estimates of mode shift using cost and time elasticities. Suitable where disaggregated data is sparse, these models support large-scale scenario analysis but lack dynamic interaction modeling (Academics4Rail, 2024).

PhD8 will tailor both model selection and calibration logic to the specific characteristics and data conditions of each rail platform (Academics4Rail, 2024). Case study models are proposed for high-speed and regional passenger segments, where detailed, corridor-level insights are required. For freight platforms, elasticity- based models offer a pragmatic solution under data constraints, enabling high-level estimation of cost responsiveness. Alternatively, where sufficient data exist and spatial disaggregation is critical, multimodal network models such as Samgods or TRIMODE will be applied to capture system-wide logistics interactions. Final model choice will be governed by the analytical resolution required and the availability of baseline data for each use case (Academics4Rail, 2024). Empirical parameter estimation will incorporate stated preference methods and econometric analysis, leveraging datasets such as SNCF Réseau's longitudinal cost and performance records. Particular emphasis will be placed on integrating climate variability, post-pandemic demand shifts, and extreme weather events into supply-side cost structures. Validation strategies will include stakeholder consultation and scenario-based sensitivity testing, ensuring transparent and policy-relevant linkage from technical KPIs to societal outcomes.

12.4 KPI Frameworks – Cross-Domain Insights

12.4.1 Broadening the Perspective

The preceding analysis of Shift2Rail (S2R) and Europe's Rail Joint Undertaking (ERJU) highlighted significant methodological gaps in linking technical innovations to societal impacts, particularly concerning behavioural realism, attribution, and scalability. To address these challenges, this section draws on cross- domain experience to identify evaluation techniques that can strengthen the KPI-to-impact translation logic underpinning ERJU and the PhD8 framework.

A structured corpus of documents, identified by Sapienza University of Rome and spanning sectors such as rail, energy, urban systems, and smart infrastructure, served as the foundation for the cross-domain review conducted for this deliverable. This corpus was subsequently refined based on three criteria: (i) explicit use of KPIs in impact evaluation, (ii) focus on modelling societal, economic, or environmental outcomes, and (iii) relevance to public-private partnership or Joint Undertaking-style governance structures.

This section reflects a range of evaluation approaches, highlighting key structuring methods, simulation techniques, scoring frameworks, and uncertainty management strategies that can inform the development of a modular, empirically grounded societal impact model for ERJU and PhD8. Rather than presenting full model details, this section selectively synthesises transferable techniques from the reviewed studies, addressing the structural gaps identified in Section 2.4 and informing the forward-looking methodological strategy outlined in Section 5.

12.4.2 Framework Structures for KPI-Based Evaluation

Cross-domain evaluation studies reveal three principal structures for translating technical Key Performance Indicators (KPIs) into societal impacts: results-based and logic chain models, simulation-based and forecasting frameworks, and scoring and multi-criteria decision models. Each structure provides a distinct approach for modelling causality, capturing dynamic responses, and assigning evaluative weight to KPIs.

Results-Based and Logic Chain Models establish linear or modular pathways linking inputs to outputs, outcomes, and societal impacts. These models are effective for ensuring attribution and traceability across evaluation stages. A prominent example is the Community Indicator System proposed by Macdonald et al. (2012), which structures KPI evaluation as a sequence from "Resources → Activities → Outputs → Outcomes → Impacts," enabling causal transparency. As detailed in Macdonald et al. (2012), such frameworks can introduce granularity by segmenting impact pathways into stages such as 'Immediate' and 'Ultimate' outcomes, or phased levels of policy engagement, supporting dynamic KPI layering across time and scale

Simulation-Based and Forecasting Models address the limitations of static chains by enabling KPI behaviour to evolve dynamically under alternative conditions, capturing feedback loops, behavioural elasticity, and policy responsiveness. Hainz (2019) illustrates this by linking noise-reduction KPIs to passenger modal choice through a nested logit model, simulating demand shifts under different noise scenarios. Similarly, Juan et al. (2023) employ simulation to monetise user experience KPIs from public Wi-Fi deployment around rail stations, incorporating time savings, willingness-to-pay (WTP), and triple- bottom-line aggregation (economic, social, environmental). These monetised indicators are directly translatable for SCBA applications.

Scoring and Multi-Criteria Decision Models (MCDA) prioritise KPIs using formal weighting schemes, accommodating qualitative judgments and stakeholder diversity. The SuBETool (Alwaer & Clements- Croome, 2010) exemplifies this approach by combining performance levels with stakeholder-assigned priority weights ("Sustainability Score = Level × Priority"). Extensions of this logic are seen in Djordjević et al. (2021), who apply Data Envelopment Analysis (DEA) to benchmark national rail system performance and use Pearson correlation to reduce indicator redundancy, and in De Sanctis et al. (2021), whose MIKADO framework formalises KPI dependency modelling with custom logic rules and spillover pathways (e.g., mobility affecting air quality).

Cluster	Category	KPI	Measurement Unit/Criteria	Scoring (Based on: [121,123])
2. RESEARCH AND EDUCATION	2.1 Research	Funding research on energy sustainability [123]	Energy sustainability research funding/total research funding	≤1%: 0 >1–8%: 0.25 >8–20%: 0.5 >20–40%: 0.75 >40%: 1
	2.2 Education	- Energy sustainability educational program for staff and students [121,128] - Increased environmental/sustainability education [22,107,129] - Involving the stakeholders [107,130]	Educational program/institution Yes/No	Yes: 1 No: 0
		- A program for local community about the importance of energy efficiency and clean energy [121] - Increased environmental/sustainability education [22,107,129]	Local community program/institution Yes/No	Yes: 1 No: 0
		Promote a public pledge toward 100% renewable energy beyond the university [121]	Public pledge/institution Yes/No	Yes: 1 No: 0

Figure 23-Selected list of Environmental and Energy KPIs (Juan et al., 2023)

Category	Indicator
Air Quality	Air pollution
	GHG emissions
Environmental Quality	EMF exposure
	Noise exposure
Energy	Consumption of renewable energy
	Electricity consumption
	Residential thermal energy consumption
	Public building energy consumption
	Adequate affordable energy supply

Figure 24-KPIs for research and education in the field of SESs (Kifor et al., 2023)

To support these modelling structures, structured KPI typologies and indicator chains are indispensable. Across diverse domains, indicator-based evaluation frameworks commonly adopt a pillar-based classification structure that clusters KPIs into high-level thematic domains. This typology serves two functions: first, it offers a conceptual scaffold to distinguish the multidimensional nature of sustainability or system performance; second, it facilitates operational alignment between technical outputs and broader societal objectives (2024) employs a similar logic). Causal indicator chains then map technical improvements → system effects → behavioural change → societal impacts (Academics4Rail, 2024), reinforcing transparent linkage from innovation to societal outcomes. Complementary models such as SuBETool incorporate priority weighting into performance scoring, while Macdonald et al. (2012) develop policy-action chains that trace how indicator knowledge influences decisions and impact delivery.

12.4.3 Addressing Attribution, Assumptions, and Uncertainty

A persistent challenge in societal impact modeling is the difficulty of attributing outcomes directly to specific interventions. As Hainz (2019) highlights, causal chains often rely on inferred relationships that lack empirical validation, while Macdonald et al. (2012) observes that societal indicators typically reflect cumulative effects arising from multiple policies, systemic dynamics, and behavioural factors. This complexity complicates efforts to establish clear, defensible attribution for research-driven innovations.

To strengthen attribution logic, cross-domain frameworks emphasise the need for greater transparency by systematically documenting input assumptions and adapting models to reflect different scenarios. For example, Bianco et al. (2021) enhance auditability by explicitly mapping assumptions across KPI clusters, while Juan et al. (2023) propose scenario-based techniques that adjust model outputs in response to variations in policy uptake and behavioural elasticity. These practices complement stakeholder-driven validation approaches, discussed further below, by improving the traceability and resilience of causal chains under uncertainty.

Stakeholder involvement is particularly advocated by Alsaid and Ambilichu (2022), who propose dialogic evaluation frameworks wherein attribution is collaboratively constructed with stakeholders rather than imposed through rigid, top-down modeling. Similarly, Hainz (2019) recommends stakeholder review of critical assumption sets, especially where social dimensions introduce additional uncertainty.

Together, these practices strengthen the credibility of evaluation frameworks, enhance the explanatory coherence of KPI chains, and mitigate bias, thereby increasing the policy relevance, stakeholder confidence, and empirical robustness of societal impact assessments.

12.4.4 Cross-Domain Lessons and Transferable Techniques

The cross-domain review identifies several modelling strategies that provide valuable insights for strengthening KPI-based impact evaluation. Collectively, these transferable techniques enhance causality, behavioural realism, adaptability, and strategic policy relevance within societal impact models.

Lesson 1: Multi-Layer KPI Chains

Panfilov et al. (2021) demonstrate how a hierarchical KPI system, structured across strategic, tactical, and operational levels, enables traceability and alignment with overarching goals. This structure allows granulartechnical indicators (e.g., dwell time, energy use) to be explicitly linked to broader objectives such as sustainability and modal shift.

Lesson 2: Feedback Loops in Scenario-Based SCBA

Costa et al. (2017) describe a real-time monitoring system in which technical KPIs (e.g., component failure rates) dynamically inform infrastructure decision-making. This feedback mechanism supports responsiveness to emergent risks and changing conditions. PhD8 could draw on this principle by modelling delay variability under peak load conditions or simulating infrastructure performance during extreme weather.

Lesson 3: Transparency Metrics as Societal Proxies

Blumenfeld et al. (2023) illustrate how institutional characteristics (such as governance transparency, safety disclosure, and public trust) can be operationalised into KPIs and benchmarked across systems. Though often omitted from technical evaluations, these indicators may serve as proxies for regulatory quality, user confidence, or institutional legitimacy.

Lesson 4: Flexible Weighting

Kifor et al. (2023) propose a model that permits adaptation of indicator weights and thresholds to reflect institutional or regional diversity. This flexibility allows for comparative evaluation while avoiding the imposition of a uniform logic across contexts.

Lesson 5: Composite Indicators

Panfilov et al. (2021) advocate the aggregation of individual indicators into composite indices (e.g., combining reliability, maintenance efficiency, and energy consumption). These aggregated KPIs facilitate benchmarking and simplify complex evaluations for high-level decision-makers.

Lesson 6: Strategic alignment

Costa et al. (2017) and Kifor et al. (2023) emphasise the importance of aligning evaluation frameworks with broader EU policy targets, such as the European Green Deal, Energy Efficiency Directives, and Sustainable Development Goals (SDGs). PhD8 could apply this principle by ensuring that KPI chains are explicitly linked to strategic benchmarks (such as modal shift targets, CO_2 reductions, or improved accessibility).

Table 9-Cross-Domain Lessons and Their potential Application to the PhD8 Impact Framework

Lesson	Source	Application in PhD8
Multi-layer KPI chains	Panfilov et al. (2021)	Translate technical KPIs to societal outcomes
Feedback loops	Costa et al. (2017)	Dynamic SCBA and mode choice sensitivity
Transparency proxies	Blumenfeld et al. (2023)	Governance indicators in societal KPIs
Lesson	**Source**	**Application in PhD8**
Flexible weighting	Kifor et al. (2023)	Adapt models to national or platform contexts
Composite indicators	Panfilov et al. (2021)	Enable multi-KPI benchmarking
Strategic alignment	Costa et al. (2017); Kifor et al. (2023)	Ensure outputs support EU policy targets

12.5 Anticipated Contributions to Literature and Practice

Building on the modular evaluation structure proposed under Academics4Rail WP3, this PhD research aims to adopt and extend the multi-layered KPI-to-impact framework by developing key components necessary for empirical validation and policy-ready deployment. The research focuses on three areas: (i) enhancing the translation mechanisms linking technical outputs to societal outcomes, (ii) strengthening behavioural realism in mode choice and elasticity modelling, and (iii) integrating weather-related performance risks into rail cost analysis. These focal areas respond to gaps identified in the initial WP3 framework and incorporate methodological innovations from the cross-domain review presented in Section 4. Lessons such as improved structuring of multi-layer KPI chains, the introduction of dynamic feedback loops, the design of flexible weighting strategies, and tighter strategic policy alignment are key elements that this research aims to embed in the final framework, ensuring that it is empirically robust, adaptable across different institutional and operational contexts, and aligned with EU societal objectives. It is recognised, however, that not all aspects may be fully addressed within the available timeframe of the PhD, and the final framework will prioritise feasibility alongside methodological advancement. The following sections outline the anticipated contributions of this research across methodological, empirical, and policy domains.

12.5.1 Methodological Contributions

PhD8 introduces a structured, multi-tier framework for evaluating the societal impact of rail technical innovation, grounded in the Social Cost-Benefit Analysis (SCBA) logic developed under Academics4Rail WP3. At its foundation is a **Modular Evaluation Architecture** that supports cross-platform scalability by linking subsystem-level KPIs (such as delay reductions, lifecycle cost savings, and punctuality improvements) to macro-level outcomes including modal shift, emissions reduction, and consumer surplus. This architecture flexibly accommodates case study, network, and elasticity-based modeling approaches, addressing the rigid and siloed structures seen in earlier frameworks (Academics4Rail, 2024).

At the core lies a **KPI Translation Mechanism**, which systematically converts technical outputs into SCBA-compatible indicators using logic models and indicator chains (Macdonald et al., 2012; Hara et al., 2016). This structured mapping provides the foundation for linking engineering achievements to economic and societal metrics in a consistent and replicable manner.

The model is further distinguished by an **Integrated Methodological Logic** that combines mode choice estimation, econometric cost-disruption modeling, and weather-sensitive performance analysis. This approach enhances behavioural realism and empirical depth relative to previous models such as IMPACT- 2 and EY (2023).

Crucially, PhD8 incorporates **Uncertainty and Attribution Strategies** that enable transparent traceability across causal layers. Techniques such as scenario sensitivity, indicator chaining, and adaptive weighting (Bianco et al., 2021; Djordjević et al., 2021) support robust inference under varying assumptions, offering a policy-relevant model with high explanatory value across EU-Rail innovation domains.

12.5.2 Demand- and Supply-Side Parameterisation

On the demand side, this PhD will generate new empirical insights into how rail system users perceive and respond to performance improvements, with a specific focus on punctuality and reliability, factors strongly linked to perceived quality but often insufficiently captured in aggregate demand models. Building on foundational work by Wardman and Batley (2021), this research will apply a mix of econometric analysis and stated preference data to derive updated behavioural parameters that quantify the value passengers place on system performance improvements across multiple European contexts. Importantly, the research will differentiate values by market segment and region, using data from both the UK and France and extending where feasible to additional EU member states, thus supporting external validity and policy transferability.

On the supply side, the research addresses a growing gap in the literature concerning the cost impacts of climate variability and extreme weather on rail infrastructure. By linking operational performance data with high-resolution weather indicators, the project will produce robust estimates of marginal and total maintenance costs associated with increased climate volatility. Building on the econometric tradition in rail cost modeling (Smith et al., 2023; Smith & Ojeda Cabral, 2022), this research integrates cost-performance- weather linkages in a way that is currently absent from EU-Rail assessment strategies.

Together, these demand and supply analyses address a critical limitation in the existing literature: the lack of robust parameterisation for how technical innovations (whose benefits are often indirectly expressed through KPIs) translate into real-world modal shifts and cost savings. By producing cross-validated evidence on both behavioural elasticities and marginal cost functions under weather stress, the PhD enhances the precision and policy relevance of future CBA exercises across rail systems.

12.5.3 Policy Alignment and Data Strategy

PhD8 advances the evaluability of rail research by combining robust data resources with alignment to EU policy standards. Central to this contribution is the framework's coherence with **EU Cost-Benefit Analysis (CBA) and TEN-T Evaluation Guidelines**, which demand monetisable, policy-relevant indicators such as time savings, carbon abatement, and safety gains. By embedding a structured translation of technical KPIs into SCBA-compatible variables, the PhD bridges a key methodological gap identified in earlier S2R evaluations (Academics4Rail, 2024).

This policy-ready structure enables both **ex-ante and ex-post evaluations** of EU-Rail innovations, supporting strategic reviews of Flagship Projects under the European Green Deal. Its modular logic allows for implementation at national, corridor, or platform scales, tailored to institutional contexts and data availability.

Critically, PhD8 is underpinned by **strong empirical foundations**. The **SNCF Réseau multi-year dataset** (comprising over 1,000 track sections annually across more than a decade) offers rich, disaggregated information on cost, performance, and weather impacts. This allows for statistically valid modeling of climate-related infrastructure costs and network performance under stress conditions. Supplementary datasets from the UK and other EU regions further strengthen the empirical scope.

Recognising persistent data constraints across some systems, PhD8 also incorporates **adaptive strategies**, including fuzzy logic, proxy indicators, and qualitative scoring (Bianco et al., 2021; Milbredt et al., 2017). Together, these design choices ensure the model remains both **empirically grounded and practically deployable**, balancing analytical depth with institutional usability.

12.6 Conclusion and Next Steps

This research deliverable has outlined a coherent strategy to advance the societal impact assessment of Europe's Rail technical research, addressing long-standing methodological and empirical gaps identified in prior frameworks such as IMPACT-1, IMPACT-2, and the EY (2023) SCBA study. Building on the structured logic of Academics4Rail WP3, this PhD provides a modular, policy-aligned model that links subsystem-level innovations to macro-level outcomes via a streamlined KPI model and flexible mode choice architecture (Academics4Rail, 2024).

The core motivation is grounded in the challenge of quantifying how rail technical research contributes to EU priorities on modal shift, climate resilience, and efficient infrastructure investment. The first PhD objective, producing new quantitative estimates of the impact of EU-Rail innovations on societal outcomes, is now underway. The resulting framework integrates technical KPIs into a scalable SCBA logic via behavioural modelling of mode shift and contextual performance baselines. This aligns with strategic EU targets (EC, 2021) and advances the assessment functionality of the A4R framework.

Looking ahead, the second PhD objective, developing new parameter evidence on demand-side valuations and weather-related supply-side costs, will be operationalised through applied econometric analysis using datasets from France and the UK (Smith et al., 2023; Wardman & Batley, 2021). These insights will inform the calibration of model parameters, enhance attribution chains, and increase behavioural realism in mode choice forecasts.

In conclusion, this PhD acts as the empirical extension of A4R WP3, delivering evaluative depth to its conceptual model. Its structured quantification of rail innovation impacts not only enhances the credibility of the EU-Rail assessment architecture but also offers policy-relevant insights to guide investment, prioritisation, and regulatory design across European transport systems.

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13 Inclusion and Accessibility for Individuals with Intellectual Disabilities

13.1 Introduction and contextualization

Disability raises fundamental matters, both for individuals and for society (Stiker, 2009). It is not limited to a medical reality, but must be understood primarily as a social phenomenon (Bodin, 2018). The experience of disability transcends the mere physical or mental condition, it is often imposed upon the individual's identity, to the extent that it encompasses and defines the person through their difference. This identity reduction reinforces a supposedly reassuring norm by classifying and symbolically distancing « the other », the one who disrupts the established order. However, the current use of the expression « persons in a situation of disability » rather than « disabled persons » reflects a significant evolution: disability is no longer seen as a personal attribute but as a contextual construction, influenced by the material, social, and psychological environment (Genet, 2012).

Thus, disability appears above all as the product of a situation, which places inclusion and the adaptation of society at the epicenter of contemporary reflections. Mobility is one of the key levers of inclusion. Accessibility of the rail system for people in situation of disabilities remains a major challenge for our society. While significant progress has been made in responding the needs of people with reduced mobility or sensory impairments, people in situation of intellectual disabilities are still too often on the margins of accessibility policies. Their experience of the rail system is characterized by a complexity of environments, a lack of specific adaptations, and limited autonomy in planning and carrying out their journeys.

Faced with this situation, it becomes crucial to rethink the modalities of accessibility by asking how to design an inclusive rail system for people in situation of intellectual disabilities, in order to improve mobility and guarantee real accessibility and autonomy for users? Despite the growing recognition of the rights of people in situation of disabilities to independent mobility, rail transport systems are still struggling to meet the specific needs of individuals in situation of intellectual disabilities. While accessibility measures do exist, they are still mainly focused on motor or sensory impairments, and do not take sufficient account of the cognitive, social and emotional dimensions of the user experience. Addressing these dimensions is essential to guarantee genuine equality of access. It's not only a matter of proposing ergonomic adaptations, but also of designing cognitively accessible environments, rethinking human support throughout the entire mobility process, and reflecting on the training of frontline staff, while also enabling the active participation of the persons concerned in the co-construction of solutions. From this perspective, individuals living in situation of intellectual disabilities should not only be seen as vulnerable users, but as citizens in their own right, with specific rights, skills and needs. It should also be pointed out that this population represents a significant proportion of society, and therefore a non-negligible potential user and customer base for transport services. According to the World Health Organization (WHO), around 15% of the global population lives with some form of disability, of whom 2 to 4% experience significant functional difficulties. This prevalence rate is higher than previous estimates, which, in the 1970s, were approximately 10%. This increase can be explained by the ageing of the population, the rapid progression of chronic illnesses, and improvements in disability assessment methodologies.[2] The use of the term « disability » to refer to individuals presenting impairments is relatively recent. It emerged in Western countries at the end of the 19th century (Cooter & Pickstone, 2000) (Winance, 2008).

Regarding intellectual disability, it should be emphasized that it is neither an illness nor a pathological condition. As such, individuals concerned do not « suffer » from this condition and should not be perceived as « afflicted by it », « they present » or « live with » an intellectual disability, an essential distinction to avoid stigmatization. The diagnosis of intellectual disability is based on three fundamental criteria, all of which must be met simultaneously. First, it involves the presence of significant limitations in intellectual functions, reflected in difficulties in

[2] *World report on disability* (2011). WHO Library Cataloguing-in-Publication Data.

understanding abstract concepts or anticipating the consequences of an action. Secondly, it implies limitations in adaptive behavior, influencing conceptual, social and practical skills. These limitations can affect, for example, the management of financial concepts, the establishment of interpersonal relationships, or the fulfillment of tasks such as meal preparation, home maintenance or the use of public transport. Finally, to be diagnosed in situation of an intellectual disability, the condition must manifest itself before the age of 18. Although each person in situation of intellectual disability is unique, certain common characteristics are frequently observed. These include difficulties with spatio-temporal location, short-term memory, language development and concentration. In addition, these individuals may encounter obstacles in problem-solving, generalizing newly acquired strategies and establishing logical links between different elements.[3]

Taking these specificities into account is essential to ensure an inclusive approach that responds appropriately to the needs of the individuals concerned, particularly through adaptations within the railway system (Alauzet et al., 2010). Beyond the simple right to take the train, accessibility is a key lever to guarantee the effective exercise of the right to mobility and promoting real inclusion. It's not just a question of being able to travel, but to do so on an equal footing with other passengers, without disability constituting an obstacle. The ability to move freely is not limited to physical presence in public space. It also involves the full and complete recognition of each individual as an active member of society. It is crucial to distinguish the possibility of « participating » in collective life from the notion of « real belonging ». Moreover, participation must not be reduced to symbolic presence, but must be accompanied by an effective recognition of each person's place and role (Ebersold, 2024).

In this regard, mobility and accessibility constitute fundamental levers for the inclusion of persons in situation of disabilities (Sze & Christensen, 2017). Individuals in situation of intellectual disability travel less than the rest of the population. This disparity is partly explained by difficulties in leaving their homes, resulting in particular from a lack of confidence in their ability to travel, as well as fears related to the attitudes of others, whether staff in contact with users or other passengers in the context of mobility via transport (Mackett, 2017). This phenomenon can be explained by the fact that society implements mechanisms to classify individuals into different categories, and to attribute to each individual characteristics considered to be « ordinary and natural ». These social frameworks influence our interactions and determine the types of people we expect to meet. The term « stigma » reflects this social process, as it refers to an attribute that causes profound discredit. However, this is not simply an individual trait, but a relationship between an attribute and a stereotype. An individual who might ordinarily be fully integrated into social interactions finds themselves excluded because of a particular characteristic. This characteristic, perceived as deviating from social expectations, attracts attention and alters the way he is perceived. It deprives them of the rights and social status they might otherwise claim based on their other attributes. The stigma thus becomes a difference judged as problematic. Social benevolence aims precisely to attenuate these reactions, so as to overcome apriori. Implicitly, society tends to consider that a person with a stigma is not « fully human ». Based on this perception, we implement, often unconsciously, various forms of discrimination that considerably reduce opportunities for inclusion. The stigmatized individual generally shares our conception of his own identity, but his experience differs according to the visibility of his stigma. If it is immediately perceptible or already known to their environment, he is considered discredited. Conversely, if the « difference » is not yet perceived or known to others, they are considered discreditable, i.e. liable to be stigmatized if discovered. To include and understand difference, it's not the different that needs to be looked at, but the ordinary (Goffman, 1975). Thus, it is not only individual factors that influence mobility, but also environmental and social factors that contribute to the creation of disabling situations and limit social participation (Alauzet, 2017).

13.1.1 Legal Framework within the Railway System as a Lever for Accessibility

[3] The Quebec Society of International Law (SQDI). (2018). *What is intellectual disability?*

Significant progress has been made in rail accessibility, notably through the adoption of international norms and regulations. Indeed, many countries have implemented regulatory frameworks aimed at ensuring the accessibility of infrastructure and improving mobility. Compliance with European and international standards constitutes a key lever in promoting more inclusive mobility. International Convention on the Rights of Persons with Disabilities (ICRPD), adopted by the United Nations, is a major reference in this field. Its aim is to promote, protect and ensure equal rights, while enabling the full and effective participation of people with disabilities in political, economic, social and cultural life. The Convention requires States to remove obstacles to accessibility in all its forms. Notably, Article 9 insists on the need to guarantee unhindered access to physical infrastructures, transport, information and communication, in both urban and rural areas. Article 19 recognizes the right of every individual to live in society with the same freedom of choice as other citizens, and obliges states to take concrete measures to ensure this inclusion.[4]

Other European instruments reinforce this legal framework. The Amsterdam Treaty of 1997 introduced an explicit non-discrimination clause based on disability in Article 13. This measure marks a significant step forward in the promotion of equal rights, and forms the basis for the emergence of a European disability policy.[5] The Charter of Fundamental Rights of the European Union, adopted in 2000, affirms the fundamental principles of dignity and inclusion. Article 1 states that human dignity is inviolable and must be respected and protected. Article 21 prohibits all discrimination based on disability, while Article 26 recognizes the right of people with disabilities to measures guaranteeing their independence, social and professional integration, and full participation in collective life.[6] Altogether, this legal framework highlights the importance of a comprehensive approach to accessibility, which cannot be limited to physical accommodations alone. Accessibility also involves cognitive and social dimensions, in order to ensure the effective inclusion and equitable participation of persons in situation of disabilities in all aspects of social life.

13.1.2 Contemporary challenges of accessibility in railway system

Accessibility of the rail system is a major issue in our contemporary societies, especially considering the accelerating urbanization. Several research studies and institutional reports have analyzed the progress made, while identifying persistent obstacles and prospects for improvement. In particular, we can refer to the report Les personnes en situation de handicap mental, psychique ou cognitif et l'usage des transports (People with mental, psychic or cognitive disabilities and the use of transport) published as part of the POTAS project[7], which demonstrates that, faced with the uncertainties associated with travelling, people in situation of disabilities are faced with a restricted choice of transport modes and are more reliant on the help of others. With the aim of better understanding these dynamics, the project is taking the approach of taking an overview of the different forms of mental disability and documenting the travel practices and specific obstacles encountered by individuals in situation of disabilities when using public transport (Alauzet et al., 2010).

In the same perspective, comparative studies such as *Rail Travel and Disability: An International Perspective on Accessibility*[8] provide an international overview of rail accessibility conditions. This report identifies the best practices and innovations deployed in different countries to improve the experience of users in situation of disabilities. It highlights the need for universal design in the conception of infrastructures (stations, trains,

[4] *Convention on the Rights of Persons with Disabilities.* (2007)
[5] The Amsterdam Treaty: Article 13 (1997)
[6] Charter of Fundamental Rights of the European Union. (2000)
[7] Alauzet, A., CONTE, F., SANCHEZ, J., & VELCHE, D. (2010). *Les personnes en situation de handicap mental, psychique ou cognitif et l'usage des transports : Rapport final Projet POTAS - Tome 2*
[8] The Rail Safety Standards Board (RSSB) & The Australasian Centre for Rail Innovation (ACRI). (2018). *Rail Travel and Disability: An International Perspective on Accessibility*

platforms), as well as the need to take into account the specific needs of passengers in situation of disability, which go beyond the usual criteria of perceived quality (such as value for money, punctuality or availability of seats). These needs include step-free access, accurate and accessible information, adapted sanitary facilities, quiet journeys and simplified booking. The report also highlights examples of best practice in passenger assistance, digital technologies (mobile applications, chatbots, guidance systems) and intermodal coordination from countries such as Spain, the UK, Australia, Sweden and the USA. The elements identified in the report illustrate the importance of a global approach to accessibility, integrating technical standards, an inclusive approach and the genuine involvement of the people concerned in the design of the proposed solutions.

Studies concerning disability and accessibility have focused relatively rarely on people in situation of intellectual disabilities, but they have provided a number of solutions and recommendations regarding the tools to be developed. The aim of the RAMPE project[9] is to develop and experiment an interactive assistance and information system for visually impaired people, to facilitate their autonomy and mobility on public transport. This system is intended for implementation at public transport stops (bus, tram) or multimodal transport hubs and primarily focuses on infrastructure adaptation. Initiatives such as the installation of ramps, elevators, and tactile indicators have gradually improved accessibility, alongside technological and digital innovations. The use of digital solution such as mobile applications designed to assist travelers in situation of disabilities further contributes to user autonomy. Until now, the issue of accessibility for persons in situation of disabilities has mainly been addressed from the perspective of infrastructure, design, or train ergonomics (Baudoin et al., 2005). However, what about the autonomy and inclusive support of individuals in situation of intellectual disabilities? We must therefore question the current organization of the railway system particularly the requirement for advance booking, and the lack of staff training on the ground which continues to limit autonomy and reinforce dependence on assistance services.

13.1.3 Inclusion: Beyond Integration, a Collective Challenge

Inclusion is not merely about integrating individuals into a pre-existing system. it requires a profound transformation of the environment to ensure it is adapted to everyone's needs and enables effective participation. The objective is not to adapt individuals to an existing structure, but to redesign the system itself in order to reduce social inequalities and foster personal autonomy. Serge Paugam emphasizes, inclusion is a social phenomenon rather than an individual one (Paugam, 1996). Consequently, it must be understood as a collective concern that involving a multiplicity actors and institutions. However, this notion is not exempt from limitations. Charles Gardou warns against the risk of categorizing people in situation of disabilities, which tends to lock their identity into a collective belonging, at the risk of obscuring their singularity and specific skills (Gardou, 2014).

It therefore becomes essential to reconcile inclusion and individualization of pathways, in order to avoid a standardization of the responses provided but also a possible instrumentalization of the concept, which could be applied too rigidly and uniformly, without taking into account individual and contextual specificities (Bouquet, 2015). From this perspective, « the walking interview » approach offers a relevant methodology for including individuals in situation of intellectual disabilities in research. This method consists of accompanying users along their journey, without direct intervention, to gather real-time insights into their perceptions and experiences. By identifying the obstacles encountered throughout the journey, this method offers a finer, more authentic understanding of the travel experience (Thibaud, 2001, 2003, 2022). Inclusion and social recognition are two essential and interconnected concepts for understanding the challenges of social mobility and autonomy, particularly for individuals in situation of disabilities. While inclusion implies a profound transformation of environments to meet the specific needs of each individual, social recognition is a key lever in this process.

[9] G. Baudoin, Y. Benabou, O. Venard ESIEE, A. Paumier, & Gérard Uzan. (2003). *Référentiel d'assistance aux personnes Aveugles pour leur Mobilité dans les transports publics et les Pôles d'Echange Phase 1 (RAMPE)*

13.1.4 From inclusion to recognition: considering vulnerability as a lever for action

Social recognition is a foundational condition of life in society. Mutual recognition is essential for individual self-construction, as each person can only establish a satisfactory relationship with himself or herself when recognized by others. It is by integrating the normative gaze of others that individuals learn to understand themselves. Societal transformation occurs through collective struggles led by social groups seeking institutional and cultural recognition of their identities, values, and rights. These mobilizations are the driving force behind social change, as they aim to broaden the forms of recognition available within society. Recognition, when institutionalized in a democratic society, tends to operate symmetrically within groups between individuals sharing similar characteristics, but it can remain asymmetrical between groups themselves, depending on prevailing social and cultural norms. People who suffer mistreatment often describe their experience in moral terms, through notions such as humiliation, offense or contempt.

These experiences are not merely about material harm or restriction of action, but about injury to one's dignity. The denial of recognition deeply wounds and undermines the individual's self-image. As Axel Honneth argues, sufficient social recognition is essential for personal development and self-esteem. When it is defective, it opens up a psychic breach into which negative emotions such as shame, anger or resentment flow (Honneth, 2013).

In this way, social recognition and vulnerability are intricately linked concepts, particularly in the context of individuals in situation of disabilities. Indeed, as Axel Honneth underlines, recognition is essential to personal development and self-esteem. However, the absence of social recognition can increase vulnerability, particularly when individuals are marginalized or unrecognized in their existence and experiences. Vulnerability, seen as exposure to injury, is exacerbated by the denial of recognition, making it all the more crucial for social struggles to extend forms of recognition and enable real inclusion of vulnerable individuals. Thus, social recognition is not limited to a moral or institutional aspect, but becomes a fundamental lever for surmounting vulnerability and favoring genuine autonomy.

Vulnerability is a term we need to define. Indeed, since the end of the 20^{e} century, we have been in a period marked by the omnipresence of vulnerability due to the multiplication of its experiential forms and the anthropological, philosophical, sociological models for understanding and containing them (Martuccelli, 2014). The use of the term vulnerability has multiplied in the public sphere, but this inflation does not always correspond to a stable definition (Garrau, 2018). Here, vulnerability is seen as a lever in an individual's trajectory, and in the specific context of people in situation of intellectual disabilities, it is intrinsically linked to notions of autonomy and action. Vulnerability is related to the idea of injury (Latin: vulnus), to the fact of hurting, harming, offending (from the Latin verb: vulnerare). The vulnerable is the one who can be wounded, exposed to receiving wounds, blows (Brodiez-Dolino, 2016). It's both the fissure through which the injury can arrive, and the injury itself (Thomas, 2010). Vulnerability refers to the « potential to be wounded » and therefore to heal from wounds. The term vulnerability thus refers to exposure to risk, but also to the ability to overcome these injuries (Brodiez-Dolino, 2015).

The World Health Organization (WHO), as well as legal experts, define vulnerability in the form of a « catalog »[10], juxtaposing it with the label of situation of weakness. As Marc-Henry Soulet has written, vulnerability is characterized as a relationship between individuals and the social context. « Vulnerability underlines a deficit of resources or the lack of framework conditions affecting the individual capacity to face a critical context, at the same time as the capacity to catch opportunities or to use supports to overcome this challenge in order to maintain an existence by oneself » (Soulet, 2014, p.63). The notion's potentiality translates into possible risks, its relational and contextual form: vulnerability is established in a precise context. Its reversible dimension is based on the possibility

[10] International Ethical Guidelines for Biomedical Research Involving Human Subjects, developed by the Council for International Organizations of Medical Sciences (Cioms) in collaboration with the World Health Organization (WHO). Cioms, Geneva, 2003

of acting to modify certain factors. Vulnerability is common but not egalitarian (Brodiez Dolino, 2015). The notion is universal, which presupposes that we are all fundamentally vulnerable, although ultimately the experience of this vulnerability differs from each individual. Indeed, Marlène Jouan highlights the fact that not being identified or categorized as vulnerable is actually anecdotal, because vulnerability is an integral part of the human condition (Jouan, 2016).

Vulnerability refers to a dual reality: exposure to risks and the ability to overcome these impacts. Axel Honneth, for his part, points out the link between vulnerability and social recognition. In his view, the denial of recognition only accentuates people's vulnerability by depriving them of any social validation of their existence and experience. This dynamic is particularly visible in the case of people in situation of disabilities, whose place in the social space is often conditioned by the way they are perceived and recognized (Honneth, 2013).

13.1.5 The place of knowledge and recognition in an inclusive approach

This struggle for recognition also affects experiential knowledge, which is often marginalized in favor of institutional and academic knowledge. The notion of « knowledge » needs to be clarified, as it is too often confused with the notion of « connaissance ». In fact, knowledge refers to the body of knowledge made up of all socially validated beliefs organized into a coherent whole, relating to external or internal phenomena that individuals acquire through experience, observation or study, enabling them to act, either by describing it adequately or by understanding it adequately. Knowledge is a broader category than just knowledge, as it takes different forms: practical, theoretical and experiential.

Practical knowledge makes it clear that knowledge is not based solely on « knowing something » these forms of knowledge are akin to « savoir-faire », which is not acquired solely on the basis of theoretical knowledge, but remains linked to it. These two intertwined forms of knowledge clarify the constitution of « experiential knowledge », which is a complex notion, concerning everyone and forming the fabric of everyday life (Garrau, 2018). This knowledge, based on real-life experience, constitutes a resource for understanding the realities of disability and formulating responses adapted to the needs of the people concerned. They allow us to question the dominant norms and legitimization processes which, by valorizing certain types of knowledge to the detriment of others, contribute in particular to making the experiences of people in situation of disabilities invisibilized. The axis of experiential knowledge allows us to question ourselves on other knowledge, other ways of knowing, on situations resulting in being « otherwise capable ».

Enabling people in situation of intellectual disabilities to express themselves fully also means setting up adapted interviews. These should be both comprehensive (Kaufmann, 2016) and tailored to the specific needs of the participants. A privileged approach would be the informal conversational interview, which relies on questions emerging over the course of natural interactions between interviewer and interviewee. This method, often associated with participant observation, is characterized by its spontaneous flow, where the participant may not be fully aware that he or she is taking part in an interview, thus favoring more authentic responses less influenced by a formal framework (Mactavish et al., 2000).

Furthermore, it is crucial to initiate an ethical reflection with SNCF staff by identifying specific obstacles using the Living Lab method, a simulation-based pedagogical approach that will be offered to field agents. This method will enable agents to better understand and apprehend the obstacles encountered by users in situation of intellectual disabilities when traveling. By « putting themselves in the shoes » of these users, agents will be invited to experience the conditions and environment in which the users travel by train (Dequiré & Fussel, 2018). The recognition of vulnerability and the knowledge that derives from it is both an epistemic and a social process: the aim is to produce a finer understanding of lived realities. However, this knowledge remains marginalized due to the dominant norms and legitimization processes in our society (Gardien, 2017).

This marginalization is part of a larger process of epistemic injustice, as theorized by Miranda Fricker. There are two main forms of such injustice: testimonial injustice, which occurs when an individual's testimony is discredited because of his or her social identity, and hermeneutical injustice, which emerges when a person lacks the conceptual or linguistic frameworks needed to express his or her experience. In both cases, these mechanisms lead to the invisibilization of certain social realities and reinforce inequalities in terms of recognition and participation (Fricker, 2007). These injustices particularly affect people in situations of disability, whose experiences are rarely taken into account in the development of public policies and accessibility measures. They also reveal the structural dependence of individuals on recognition and validation by others (Honneth, 2013). Inclusion, vulnerability and experiential knowledge are therefore essential notions for thinking about the conditions for real and effective participation by people in situation of intellectual disabilities. Their recognition requires a transformation of social and institutional frameworks, in order to overcome the logics of exclusion and enable everyone to take a full part in society.

13.2 Conclusion

Despite the progress made in rail accessibility, many limitations remain. Disparities in implementation persist, with levels of accessibility varying widely between countries and even within national networks, due to inequalities in funding and political prioritization. In addition, organizational barriers are still a major obstacle. Furthermore, current research suffers from a lack of data directly from the people concerned, which limits the relevance of recommendations, particularly for individuals in situation of intellectual disabilities, whose voice is still too rarely taken into account in studies.

In order to overcome these limitations and improve rail accessibility in the long term, a number of research axes deserve to be explored in greater depth. It would be essential to develop universal standards enabling accessibility norms to be harmonized on an international scale, in order to reduce the inequalities observed. A more inclusive approach, integrating the feedback and specific needs of disabled users right from the design stage of infrastructure and services, would also make rail transport more accessible and adapted to all. The question of staff training is also central to the effective implementation of accessibility. Station staff are generally trained to welcome people with reduced mobility, especially wheelchair users, and have well-established procedures (booking assistance services, boarding devices, access ramps). On the other hand, the care of people in situation of intellectual disabilities remains more marginal and insufficiently supervised. Despite the existence of protocols, staff often have to adapt to unprecedented situations, for example when confronted with disoriented passengers who have not been identified as disabled, or who express considerable stress at the time of boarding. In these contexts, agents' ability to improvise and their personal commitment are decisive. This highlights the tension between standardized procedures and the need for individualized adjustments in the field.

Railway staff are at the heart of the accessibility system, acting as the interface between users and the system. Their ability to detect, reassure and adapt their communication is essential, demonstrating that accessibility is not just a matter of technical measures, but also relies on human mediation. Some experienced agents use their practical and intuitive knowledge to respond appropriately to users' needs, which calls into question the place of this experiential knowledge in current professional training courses, that are often too theoretical and homogenized.

Employees with the most years of service develop fine observation and adaptation skills over time, while those with less experience express a greater need for targeted training and concrete tools to support people in situation of intellectual disabilities. A better recognition and valorization of skills in the field therefore seem essential to enhance the efficiency and sensitivity of assistance and support services. From this perspective, it becomes decisive to better understand the difficulties encountered by these travelers in order to improve rail accessibility, focusing on key spaces such as stations, trains and platforms. This approach aims to identify the specific obstacles faced by people in situation of intellectual disabilities when travelling, whether on a daily or occasional. At the same time, an analysis of the training needs of SNCF staff will help identify potential obstacles to a truly inclusive welcome. One of the fundamental aims of this approach is to make rail information not only physically accessible, but also cognitively comprehensible for all users, regardless of their abilities. In this sense, this global reflection will help to reveal the systemic issues and concrete obstacles that currently stand in the way of more comprehensive and effective accessibility within the rail system.

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13.4 Planned activities

This field research is divided into five phases, some of which are interdependent. The first four phases aim to formulate a recommendation document, which is phase 5. The main objective of these different phases is to improve the accessibility of the rail system for people with intellectual disabilities.

The first phase consists of conducting semi-structured interviews with field agents from the railway system in order to stabilise the initial research hypotheses. These discussions cover various topics such as training provided and attended on disability in general, but also intellectual disability, staff experiences in supporting and assisting people with intellectual disabilities, and the procedures put in place by the railway system to provide this support. The overall objective is to understand the different experiences, difficulties and needs of SNCF field staff.

The expected results include an understanding of the different practices used by staff in their daily work. This information is important in order to prepare next phases (2, 3 and 4), notably to develop recommendations adapted to staff members. The second phase, which consisted of a second data collection period, is based on interviews and observation of passengers with intellectual disabilities. These interviews will take place during scheduled journeys, i.e. journeys already planned by passengers outside the context of this research. The aim is to incorporate myself into existing journeys in order to better understand the potential difficulties encountered. For this purpose, discussions are based on a simplified interview guide to enable users to understand the questions as well as possible. Pictograms and Makaton sign language (an alternative communication system) may also be used to facilitate communication. Users give their consent via a consent form. The aim is to enable users to describe their emotions and difficulties, and what they find understandable or not during their trip. This phase, along with phase 4, also aims to ensure that users with intellectual disabilities are able to express themselves and are not exclusively treated as research subjects. The third phase involves "walking interviews". This involves following users as they travel through the station, with the aim of getting them to verbalise or point out, using pictograms, any difficulties or obstacles they encounter during their journey. During this itinerary, the aim is also to observe the environment, such as signage and the tools available to users, and to assess their effectiveness and usefulness for this specific type of public. The fourth phase consists of a participatory workshop in a living lab between field agents and individuals with intellectual disabilities. These workshops aim to increase ethical reflection and good practice skills among railway system staff. The objective is to develop durable practices around the notion of dignity in rail accessibility. To achieve this, it is necessary to establish a learning environment that is also a capacitant environment, providing participants with the resources they need to develop their ability to act in specific situations and contexts. A capacitant environment allows individuals to develop their ability to act in specific situations and then to develop new skills and knowledge through simulation in an authentic context. These workshops will take place within the station and are designed to promote mutual learning. On the one hand, agents will be able to explain how the station works, how to find your way around, how to take the train, who to ask for help and how to alert staff in case of difficulties. On the other hand, individuals with intellectual disabilities will be able to express their needs, demonstrate their difficulties, and explain their disability. The objective is also to raise staff awareness of the different types of intellectual disabilities and the specific difficulties each individual faces. The final field phase (phase 5) aims to produce a protocol setting out “good practices” for supporting and assisting users with intellectual disabilities. This guide could help to fill gaps in staff training and provide a response in more complex situations. This protocol, which is intended to be a recommendation document, will be based on the different field phases (1, 2, 3, 4) and will therefore draw on the experiences of professionals and users, in order to take both points of view into account. The goal is to implement this protocol during my fieldwork in order to conduct a study to assess the level of satisfaction of users who have travelled in an environment where this protocol has been applied. And to make the necessary changes if certain guidelines appear to be less appropriate or difficult to execute for the staff members. The intention is to propose a document that would be adapted to the reality of the field.

14 ICT Platforms for Reliable and Interoperable ERTMS Systems

14.1 A standardized Railway TMS for interoperability

The railway Traffic Management System (R-TMS) is one of the crucial components of railway transportation signalling since it provides train monitoring, Automatic Train Control (ATC) and Automatic Train Protection (ATP), maintenance and more.

In the past, R-TMS were deployed by different countries independently, using different technologies and thus resulting in systems being incompatible and not interoperable. Consequently, in the case of cross-border journeys, rolling stocks would need different onboard systems. However, in the new international scenario, where the need for a highly interconnected infrastructure is increasing, the necessity for efficient and effective cross-border traffic has also risen.

This led to the proposal of a new, standardized and interoperable TMS, the European Railway Traffic Management System/European Train Control System called ERTMS/ETCS or simply ERTMS (European Rail Traffic Management System (ERTMS)).

The expected advantages can be summarized as follows (Bloomfield R. , 2006):

- Cross-border interoperability;
- Improvement of both national and international train safety;
- Allow competition among infrastructure providers in all of Europe;
- Enhance the European Railway Industry.

The current standard of ERTMS is based on two principal subsystems: a common communication protocol, GMS-R, and the standardized European Train Control System, the ETCS (ERTMS in brief - ERTMS — ertms.net).

Particularly, the GSM-R is a protocol based on the Global System for Mobile Communications, commonly known as 2G, and modified for railway networks. Nowadays, its successor has also been defined, and it is the Future Railway Mobile Communication System (FRMCS), that is considered one of the enablers for digitalization in railway transportation (ERTMS in brief - ERTMS — ertms.net).

The ETCS, on the other hand, supervises and controls the train running.

14.2 ERTMS/ETCS – State of the art

The ETCS is the crucial component of ERTMS and encompasses logic for train supervision and movement. It is composed of two main parts: trackside equipment and onboard equipment. The trackside equipment gathers information about train position and speed. This information will then be elaborated in the control room and sent to the driver's cab, where maximum train speed is computed and supervised, providing authorization to the movement, called Movement Authority (MA)

Following, we will describe some of the principal components that constitute the ETCS (Subsystems and Constituents of the ERTMS — transport.ec.europa.eu) that are illustrated in the subsequent figures about the ERTMS implementations (Figure 25, Figure 26 and Figure 27).

14.2.1 Trackside Components

Eurobalise

The Eurobalise is a device installed on the track that is capable of detecting the passage of a train and retrieving data about the rolling stock, such as speed, speed limit, and position. It is a passive element, as it is a train with its antenna that electrifies it and transfers data to it.

Euroloop

It is an intermittent transmission system that provides support for the In-fill information that allows to optimize the train ride by providing information about the next signal in advance.

Interlocking

It is not an ERTMS component, but it is a crucial component since it is directly involved in many ERTMS operations. It guarantees the safety of train operations by ensuring that incompatible routes are not established simultaneously.

Lineside Electronic Unit (LEU)

It is used to deliver the information from the interlocking to the driver. It can retrieve information from the interlocking system and send the appropriate signal through lineside signals and on the Eurobalises which, in turn, can provide the train with the "Movement Authority" (MA).

Radio Block Centre (RBC)

It is used for ERTMS Level 2 and in the future implementation of Level 3 (the different levels of ERTMS implementations will be described in the next section). The train position is sent to the RBC through radio signals rather than Eurobalises. The RBC also interacts with Interlocking to obtain information about the other rolling stocks on the track and provides the MA.

14.2.2 Onboard components

Automatic Train Operation (ATO)

ATO is the system that automatizes the train's operation to the Grade of Automation 2 (GoA2 – see Table 11: Grade of Automation for a complete description of GoA). The ATO can start and stop the train automatically in accordance with the Automatic Train Protection (ATP) functionalities provided by the ETCS.

The ATO is present both on board (ATO-OBU, On Board Unit) and on trackside (ATO-TRK). The latter sends the timetables to the ATO-OBU, which checks some requirements and can decide whether the train can move or must stay still.

Balise Transmission Module (BTM)

It is a module that encompasses an antenna used to receive and process messages from the Eurobalises.

Driver Machine Interface (DMI)

It is the interface between the driver and the ETCS. It presents a touch-screen display that shows information such as MA and speed limit to the driver and allows the driver to authenticate and input data, like the train ID number.

14.2.3 Implementation of the ERTMS/ETCS

Currently, the ERTMS/ETCS works by considering the track as subdivided into fixed pieces called "blocks". Every train can occupy a block and it can receive the MA to the next one only if it is free.

Different implementations have also been proposed for ERTMS/ETCS. In this case, the European Commission defined three signaling levels (Dhahbi, Abbas-Turki, Hayat, & El Moudni, 2011):

ERTMS Level 1

It is based on continuous supervision of the train movement and non-continuous communication. The train position and speed are detected by trackside equipment called "Eurobalises", and the MA is provided through the Lineside Electronics Unit (LEU). To deploy ETCS Level 1 thus, signals on the track are necessary.

Since Level 1 is based on "spot" transmission, the display of the DMI is only updated when the train passes on one of the Eurobalises. Thus, the main disadvantage is that Automatic Train Protection (ATP) can only act on some specific points, neglecting every event that can happen in the middle. For instance, if a red light is detected, the train would be forced to brake by the nearest Eurobalises. This happens even if while the train approaches the traffic light, this becomes green. The driver, even if he knows that the light is green, cannot speed up due to ATP. This effect can be mitigated with the “in-fill”, that consists of the implementation of a communication loop between Eurobalises, allowing a train to receive information in advance, without the train needing to pass on the nearest Eurobalises. The protocol used to deploy the communication of the In-fill is called EURORADIO, and a software implementation of the latter has been proposed, tested and validated in (Cecchetti, Ruscelli, Cugini, Castoldi, & others, 2013), reaching the expected safety standard and passing the conformity test.

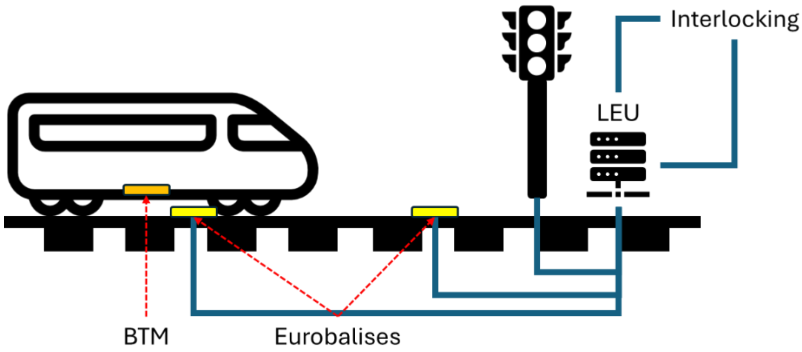

Figure 25: ERTMS Level 1

ERTMS Level 2

This is the next step in the evolution of ETCS. It is based on digital radio communication, thus implementing continuous communication. In this case, the Movement Authority is displayed on board, making the LEU unnecessary. This implementation allows real-time data about train speed and position, which is thus a first step in train automation. This implementation requires the trains to send periodic information about speed and position to the Radio Block Center (RBC), which is also directly connected to the interlocking system, an arrangement of signals to prevent conflictual movement, to retrieve information about the whole area. The RBC can thus determine the train locations on the blocks and provide MA. The communication takes place via GSM-R, and the Eurobalises are used to provide a redundant update about the position to correct possible errors in the radio communication. ETCS L2 is a first step through a centralized architecture from the distributed one of Level 1.

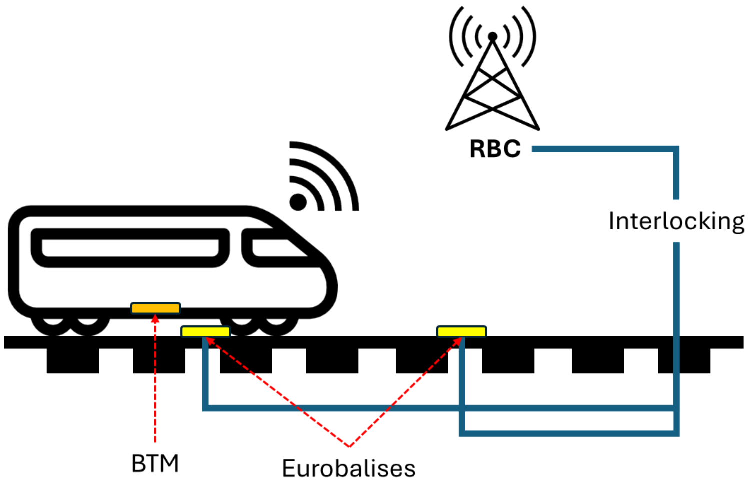

Figure 26: ERTMS level 2

ERTMS Level 3

It is the future implementation of the ETCS. This implementation aims to have a continuous communication Train – RBC via radio and eliminate the Eurobalises. The train integrity check also is performed on board through a component called Train Integrity Monitoring System (TIMS), allowing the elimination of much of the trackside equipment.

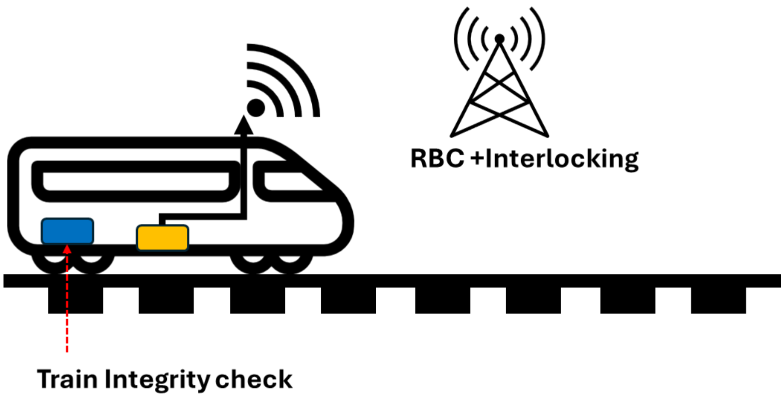

Figure 27: ERTMS level 3

Moreover, continuous communication allows to switch from a mechanism based on fixed blocks for movement authority to one based on moving blocks. Using moving blocks means that the division of the track in blocks is dynamic rather than static and depends on the trains' position. This change of paradigm allows for a better allocation of the line and a more efficient movement of the trains themselves. Due to the high criticality of the messages, and the fact that with this level only radio communication is allowed, it is essential to provide a degraded mode of operation, so that also when radio communication is not available, or is available with degraded performance, the train circulation is not affected and it can operate in a safe way.

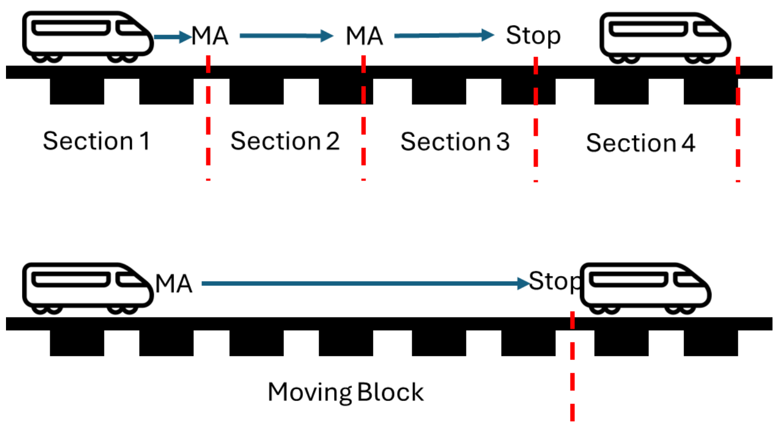

Figure 28: Moving blocks

The three different implementations can be summarized in Table 10:

Table 10: Type of ERTMS and differences

Level	***Transmission***	***Track vacancy/occupancy detection***	***Blocks***
Level 1	Discontinuous, through Eurobalises	Through Eurobalises	Fixed blocks

Level 2	Continuous, though GSM-R with Eurobalises performing checks	Through Eurobalises, that confirmes the trains' position and thus the vacancy of a block on the track	Fixed blocks
Level 3	Continuous, though GSM-R, to be updated to FRMCS	Through on-board equipment that sends their position to RBC	Moving blocks

It is interesting to note that a train can move if and only if it receives an MA, meaning that it can only move when it is sure that the track is free and standing still while there's some sort of doubt. The general approach is that whenever there's no certainty about the track, the train must stop, failing in its purpose of transportation, but still in a safe state, avoiding accidents and harm to people and goods. This approach is indeed called "fail safe".

ERTMS/ETCS Level 2 Hybrid Train Detection (HTD)

While the layer 3 ERTMS implies the progressive elimination of Eurobalises, not every train currently in use has the capability to support such an architecture. Moreover, it is important to consider the case of trains that lose connectivity and become no more visible. Even if the trackside equipment can store the last position of the train, there is no guarantee at all that it will remain in the zone where the authorization has been provided. Hence, there is a need for an intermediate level between 2 and 3 that allows the coexistence of trains with Level 3 capabilities with other old trains without such requirements or trains that, for some reason, lost their radio connection. This level, previously referred to as Hybrid Level 3 (HL3), is now called Hybrid Train Detection (HTD).

The characteristics of the HTD are extensively explored in (ertms.be). This implementation uses two different types of section: Trackside Train Detection Sections (TTD), which can detect a train using trackside equipment, and Virtual SubSections (VSS), which perform train detection using Positive Train Detection (PTD), a train detection mechanism based on information received by the train itself, rather than detected through balises. VSSs are a subdivision of the TDD sections.

Using VSS rather than moving blocks has less impact on the system if compared with the latter, moreover, if VSS small enough are chosen, it is possible to achieve similar performance as moving blocks.

As explained in (Hoang, Butler, & Reichl, 2018), with this solution, trains that can perform PTD and are equipped with TIMS can precisely provide their position and can be thus followed on the previous VSS by any other kind of train. Other trains, on the other hand, being incapable of continuously reporting their position and being then detectable only by trackside equipment, occupy a whole TDD section.

In (Knutsen, Olsson, & Fu, 2024), the authors simulated a real case scenario, considering one of the main railway lines in Sweden to evaluate the capacity of the line using HTD. They calculated in a first test the headway time between different combinations of two high-speed train equipped with L2 ERTMS and L3 ERTMS, and, as expected, the results show that using an L3 train allows to have a chasing train at shorter distance, reducing the headway and enabling a better capacity occupation of the track. Viceversa, an L2 train can't have a chasing train at a short distance. It indeed cannot communicate continuously its position, occupying the whole TDD section, rather than a small VSS. Moreover, in the same work, the authors try to evaluate the capacity occupation and the punctuality of the trains with various percentages of L3 train. In this case, they don't notice any improvement, concluding that, in order to increase the overall capacity of the rail line, the capacity of the platforms must also be increased. The benefit of such a solution thus depends also on the specific line on which it is activated.

This solution then allows the optimization of the track allocation for trains that are capable of performing TIMS on board and of continuously reporting their position, and at the same time, allows the use of old trains with no such capabilities. For this reason, it is considered the most mature implementation of ERTMS so far.

14.2.4 Related works

The characteristics of the ERTMS/ETCS L3 imply that if a message is lost, the train will stop even if the track ahead is free, making the availability of communication a crucial aspect of the overall system. This aspect has been widely and deeply analysed by (Biagi, Carnevali, Paolieri, & Vicario, 2017), who proposed an approach to reduce the breaking of chasing trains based on the MA sent based on the last position report (PR) by the foregoing train, rather than as a reaction to the PR itself. In this way, even if a train misses a packet, the chasing train will still receive the MA if the first is far enough.

Another approach to optimize the efficiency of railway transportation through the MA, is described in (Di Meo, et al., 2019), who introduce the Virtual Coupling. In this case, the MA is more permissive and makes use of the foregoing train's speed. In the current definition of L3 ETCS a train has the authorization to move until the next block, which is defined by the foregoing train position, meaning that the speed of the train must be zero when it comes close to the next train unless another MA is received. The proposed approach defines a speed limit for MA, stating that a train must have a speed *v* equal to the speed of the foregoing train when it reaches the next block (i.e.: the next train). This second approach would increase the efficiency of the travel of the train, introducing a less conservative approach. On the other hand, it would only be possible with very highly dependable communication, ensuring continuous updates and synchronization between trains.

Thus, in this scenario we have also to consider the communication protocol as a fundamental aspect of the ERTMS. In (Smith, Kyriakidis, Majumdar, & Ochieng, 2013), the authors evaluate the impact of GSM-R on the safety of the rolling stocks. Starting from the consideration that most accidents and incidents depend on human reasons, the authors try to estimate the impact of GSM-R on operators' performance. They conclude that not only the presence of GSM-R has no negative influence on operators' performance, but also, although communication errors remain the predominant cause of accidents, their number has been reduced since the introduction of GSM-R, proving thus a beneficial effect on the safety of the railway infrastructure.

In (Ranjbar, 2021), the author tries to provide an answer to some of the challenges about ERTMS, particularly, he questions whether the ERTMS can have better performance if compared with other current Railway TMS. Particularly, using a simulation tool, he compared ERTMS with the Swedish ATC2 to provide a comparative analysis. He concluded that the ERTMS level 2 is no better if compared with the current Swedish TMS. On the other hand, using HTD (here called Hybrid Layer 3 - HL3), he demonstrates that it is possible to reduce headway time, capacity consumption and block occupation.

14.3 Challenges of ERTMS/ETCS Level 3

In ERTMS L2, the trackside equipment such as Eurobalises, is still essential. Therefore, adopting ERTMS on more lines, and with more capacity, also means increasing the amount of equipment to be installed, limiting the scalability of this implementation. Moving to ERTMS L3 could resolve this issue by delivering better capacity with reduced costs, as highlighted in (Furness, Van Houten, Arenas, & Bartholomeus, 2017)

The performance, anyway, isn't the only aspect that we must carefully evaluate for ERTMS. Indeed, railway systems have strict requirements in terms of dependability, and thus, it becomes crucial to assess how safe the ERTMS is. In (Flammini, Marrone, Mazzocca, Vittorini, & others, 2006) the authors use formal methods such as Fault Tree and Beasyan Network to estimate the Mean Time Before Failure (MTBF) and the Unavailability of the components. The analysis reveals that some of the requirements can be achieved by using Components Of The Shelf (COTS) components, allowing to address some design choices from the early stage of the implementation.

(Berger, James, Lawrence, Roggenbach, & Seisenberger, 2017), on the other hand, deals with the problem of experimental validation and verification of ERTMS. After modelling the overall architecture using Real-Time Maude, and performing fault injection, the authors concluded that the main criticality of ERTMS is that, by specification, the safety depends on the correctness of all its components. Indeed, by injecting a fault in the interlocking alone, or in the RBC alone, or in the train alone, the safety requirements are violated, showing how in ERTMS a fault on one of the components cannot be compensated by the others, concluding that it is not a fault-tolerant system.

To achieve ERTMS/ETCS L3, it is crucial to improve the dependability of radio communication. Indeed, one of the goals of ERTMS is to increase the railway capacity, which can be achieved only through fine-grain monitoring of the rolling stock.

In (Furness, Van Houten, Arenas, & Bartholomeus, 2017), the authors address some of the main challenges that the ERTMS/ETCS Level 3 will face:

- Train Integrity Monitoring (TIM): the integrity of the train (i.e.: no fault on any of the cab) becomes a responsibility of the train itself. But currently, ERTMS L3 still lacks a reliable TIM.
- Radio Block Center must know at any time the position of any train. This might not always be possible since a train can be in a degraded operational status where no radio transmission is possible.
- Accuracy of the reported position: the communication delay can cause the sending of outdated information to RBC. In this case, the RBC could not provide other trains on the same line with the MA, causing a degradation of the performance of the whole line.

Besides these technical aspects regarding safety, security is also a topic to be carefully addressed. In (Bloomfield, Bloomfield, Gashi, & Stroud, 2012) the authors try to define the challenges and the possible weaknesses that the next generation ERTMS has to face. The core point of the analysis is that to perform an effective attack on the ERTMS infrastructure, an attacker would need access to the physical layer, therefore the security of ERTMS can be dependent on the implementations that different countries can adopt. Some of the weaknesses highlighted in the paper are listed in the following:

- **Balises:** It is not contemplated the case of an attacker subverting the current balises, or adding new ones on the track on strategic positions. On the other hand, the specification for the balises does not provide any indication about authentication. The ERTMS standard makes a distinction between linked and unlinked balises: the firsts are signalled to the train, and missing some of them can cause the train stop. Unlinked balises are not signalled to the train, which must be always ready to encounter and communicate with one of them. The unlinked balises can send a limited set of messages, but they can still be used to cause some damage, which can be Denial of Service in the less severe case, or a hazardous situation, in the most pessimistic case.
- **GSM-R:** It is based on 2G protocol (second-generation cellular technology) which uses weak encryption algorithms and cannot guarantee the authenticity and confidentiality of the messages. An attacker might then know sensitive information about the rail movement. In this regard, another big challenge of ERTMS is to negotiate and share an encryption key on an international scale.

To boost the process of innovation of the European railway, the European Union founded the Shift2Rail Joint Undertaking (S2R JU), a public-private partnership with the aim of supporting railway research, promoting competitiveness and innovation to enhance and upgrade the railway infrastructure (About S2R - Europe's Rail).

Particularly interesting for our case study is the OPTIMA demonstrator (OPTIMA — projects.shift2rail.org), one of the outputs of S2R OPTIMA project. The OPTIMA project is based on the requirements and the guidelines defined in predecessor project X2Rail-2 (X2RAIL-2 — projects.shift2rail.org, s.d.) and X2Rail-4 (X2RAIL-4 — projects.shift2rail.org, s.d.).

The OPTIMA demonstrator defines a Communication Platform Demonstrator for testing and validation of solutions for new-generation ERTMS.

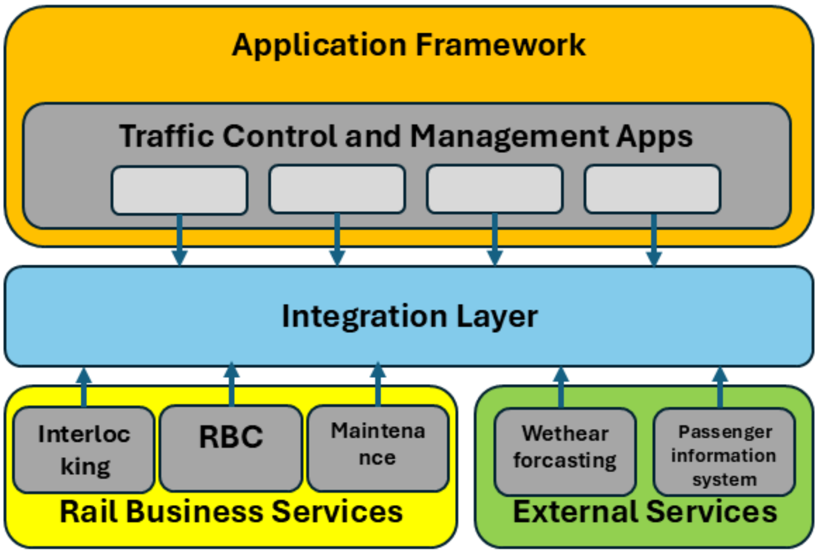

Figure 29: OPTIMA architecture

The core component of the OPTIMA demonstrator is the Integration Layer (IL), a publish/subscribe broker that defines a middleware for the communication between different applications such as Traffic Management, Traffic Control, Maintenance, Energy Control, and signaling (ETCS). Besides, it provides a gateway for external applications. The IL aims to enable seamless data exchange among all these applications by providing standardized data structures. According to the architecture proposed in OPTIMA, all the abovementioned services operate in an environment called "Application Framework" (AF), which provides resource management, monitoring, and separation of big monolithic applications in fine-grained microservices, easier to deploy and maintain if compared with monolithic applications (Optima Project — optima-project.eu, s.d.). The OPTIMA project relies on the "Common Data Model" (CMD), a standardized data structure that enables a seamless data exchange among heterogeneous data sources developed in synergy with EuLynX, a European initiative that aims to create standardized interfaces for signaling systems (https://eulynx.eu/, s.d.). These results have then converged in the MOTIONAL project, which aims to enhance the efficiency, resilience and interoperability of European railway, exploiting the potential of digitalization to build the future of railway infrastructure (Europe's Rail FP1 MOTIONAL shares ambitions for future European rail traffic management, s.d.).

These solutions pave the way to another crucial point in railway infrastructure and ERTMS, namely digitalization. Digitalization has been defined as one of the top priorities of EU's policies about railway infrastructure. The role and importance of digitalization have been investigated in several remarkable works.

This progressive approach to digitalization has been further explored in (Ruscelli, Cecchetti, & Castoldi, Cloud Networks for ERTMS Railways Systems (Short Paper), 2016), where the authors propose to investigate the possibility of cloud computing in ERTMS. As stated in the paper, trackside data, used to compute Movement Authority and ATP, are not integrated with onboard data, which are sent to the ground station only for monitoring purposes. Data from different sources could be jointly used to simulate train circulation and detect anomalies and possible delays in advance. In this scenario, cloud computing might be the enabling technology to allow that kind of computation, thanks to its intrinsic capability of sharing the load and providing shared access to the different data sources. This approach is further investigated and extended by the same authors in (Ruscelli, et al., 2019) where, besides the cloud infrastructure, it is also proposed a more deep softwarization, through the use of Network Function Virtualization (NFV) and Software Defined Network (SDN) to increase the dependability of the network and enable an easy wat to configure or reconfigure the network. This research has been then further deepened in (Ruscelli, Cecchetti, & others, Service Orchestration and Network Function Virtualization for Information Systems

Maintenance Service in Railway Systems, 2024) where the authors proposed the combination of NFV and microservices to enable a highly flexible and reconfigurable architecture, improving the overall efficiency. In (Atanasov, Pencheva, Trifonov, & Kassev, 2024), the authors propose a model that encompasses cloud-based microservices to improve the safety and QoS of railway transportation. The authors mention Artificial Intelligence (AI) to solve problems related to train automation, maintenance, forecasting of train dwell time, improvement of energy efficiency and more. The deployment of such an architecture would be possible thanks to the computational power given by cloud infrastructure leveraging virtualization. Moreover, 5G and FRMCS would enable fast and reliable networking to deal with the distance between the physical railway and the cloud infrastructure itself. The authors point at the fundamental role of a proper orchestration of the cloud infrastructure to deal with problems related to reliability, security and isolation and propose a Railway Management Automation and Orchestration (RMAO) platform based on microservices as a part of the railway control system to manage cloud functions and resources.

In (Arnaudov, 2022), the author states that enhanced digitalization can improve the effectiveness of train transportation, making it a much more appealing choice, especially when it comes to freight. Moreover, it can also provide supplemental operation to preserve the safety, security and reliability of transportation. Overall, the author points to the ERTMS as the enabling technology for deploying advanced digitalization in railway architectures.

In the article (Poliński & Ochociński, 2020), the author stressed the importance of digitalization in railway infrastructure, including the implementation and deployment of ERTMS among the crucial actions to take. According to the authors, in order to deliver an infrastructure with improved safety and efficiency, it is necessary to integrate ERTMS with innovative full-automation train operation. The main areas of focus are ATO, train positioning, smart train operation, and operating expenses.

Some of the most important digital technologies for the railway sector are explored in (Möller, et al., 2022). Here, the author mentions, among others, Cloud Computing, Containers, Big Data Analytics, and Artificial Intelligence/Machine Learning. Overall, despite the lack of trust and the resistance of some domains, like the railway itself, to adopt new cutting-edge technologies, the authors agree on the fact that some of them are becoming crucial to ensure competitiveness and development.

The point of view described in (Sarp, Kuzlu, Jovanovic, Polat, & Guler, 2024) is particularly interesting. Here, the authors explain the benefits of a deep digitalization of the railway infrastructure, also describing the enabling technologies. Among the benefits cited by the authors, one of the most interesting is the possibility of more advanced maintenance. Thanks to the support of sensors, Internet of Things (IoT), and cloud computing, it is easy to gather and manage data from different sources and perform data analysis and AI to predict failure, allowing for predictive maintenance and thus reducing the cost of corrective and scheduled maintenance.

In (Milburn & Erskine, 2019) an approach to reach higher level of automation in railway using Automatic Train Operation over ETCS (AoE) is proposed. This approach involves a closed loop between AI, data gathering and the AoE. In this system, AoE generates and sends data that will eventually be combined with other sources (e.g., environmental data). This data will be processed by AI methods and the results will be used to perform ATO within the limits imposed by the ETCS. This means that the ATOs are always more or equally restrictive than the boundary given by ETCS through MA.

14.4 Contributions

Given the study of the state of art, we conclude that currently one of the main hot spots of railways is the limited support for digitalization.

Digitalization in railway infrastructures would consistently improve the current state of the services, increasing the reliability of the infrastructures, creating a self-aware domain based on Real-Time data processing to avoid dangerous failures and expensive maintenance, and would, eventually, enable a higher degree of Grade of

Automation (GoA). Currently indeed, Level 2 ERTMS/ETCS only supports GoA 2 (see Table 11: Grade of Automation for a description of the different degrees), but in the last few years, AI and data analytics have become a mature and reliable field of study, ready to be used also in safety critical domains.

Table 11: Grade of Automation

Grade of automation	**Train operations**	**Train start**	**Train driving**	**Door closure**	**Accident prevention**
GoA 1	ATP with driver	Driver	Driver	Driver	Driver
GoA 2	ATP and ATO with driver	Automatic	Automatic	Driver	Driver
GoA 3	Driverless	Automatic	Automatic	Train attendant	Train attendant
GoA 4	Unattended (UTO)	Automatic	Automatic	Automatic	Automatic

New generation ERTMS, therefore, cannot disregard the deployment and utilization of the most advanced ICT technologies to exchange, integrate and elaborate data from all the possible sources. This is indeed a key aspect for boosting the railway sector and providing a service that is reliable, efficient and safe.

Moreover, Through digitalization and softwarization it is possible to deliver a product that is flexible and easy to manage, allowing the possibility of upgrading and further extending the systems in the future without the need for expensive component replacements and impactful unavailability time.

The purpose pf PhD 10 is to provide a dependable and interoperable platform that leverages the most recent technologies to deploy an ERTMS with the highest standard of safety and that can be extended to provide new fundamental functionalities, like predictive maintenance or a growing GoA, in the present as well as in the future, thanks to the intrinsic flexibility introduced by software that complies with the software engineer rules.

To deliver an architecture that satisfies the aforementioned requisites, we will leverage container-based virtualization to obtain a system that is reliable, flexible and extensible. This kind of approach would allow to have different and isolated applications, reducing the risk coming from interferences of different components. At the same time, we aim to optimize the utilization of resources using virtualization to consolidate the hardware utilized. Virtual machines, moreover, can be moved and rescheduled on different physical machines, improving the resilience to failures. Particularly, containers can be seen as lightweight virtual machines, allowing for fast deployment and rescheduling in case of fault of the underlying hardware.

14.4.1 Activities of the PhD

During the first year, the main activity concerned the study of the state of the art, reported in this document, and the deepening of the knowledge about ICT through related PhD courses.

After a careful review of the state of the art and a gap analysis, the second phase started: the activities will focus on the implementation and testing of experimental platforms able to host and improve the next generation ERTMS. Those platforms will act as a starting point to define which technologies, and which approach are suitable to become the pillar of the future ERTMS.

In the development of this kind of platform, the interaction with industry, specifically Rete Ferroviaria Italiana (RFI), will be crucial to point out which are the use cases of major interest, providing support in defining the direction of the research. Moreover, the collaboration with one of the major rail infrastructure providers in Europe will allow the team to obtain real-world data, fundamental to testing and designing realistic platforms, and constructive and precise feedback. Particularly, RFI, provided us with data log from their platform “MISTRAL”, a real-time monitoring of railway traffic.

Particularly, the proposed experimental systems for the deployment of new generation ERTMS will involve the usage of Real-Time frameworks to meet the temporal constraints of the railway system and virtualization technologies to leverage their feature of isolation and flexibility.

Relevant findings will be published in related conferences and peer-reviewed journals in the process. Eventually, in the last phase, a wrap-up of the research will be generated to propose an architecture able to improve the current ERTMS implementation, and in particular for the deployment for a refined application potentially integrated into the MISTRAL platform.

The activities can be summarized as follows:

1. **Phase 1, Literature review**: A systematic review of the work and the achievements in research and deployment of ERTMS. The review is carried out both on scientific papers and on project deliverables. Particularly, in this last category, the outcomes of projects like Shift2Rail OPTIMA projects are considered.
2. **Phase 2, Gap analysis:** In this phase, the aim of PhD 10 is to find the gap currently existing in ERTMS implementation. During this phase, some experimental solutions have been proposed to overcome current limitations.
3. **Phase 3, Dissemination:** The findings of Phase 1 and the proposal of Phase 2 are summarized in papers and presented at various conferences and submitted to scientific journals.
4. **Phase 4, Data gathering and industry collaboration:** In this phase, the collaboration with industry will be tightened. The team will acquire relevant data from real-world use cases, enabling the possibility of further studying the state of the art of ERTMS from the point of view of the industry. The feedback and communication with the industry will be crucial for data understanding and acquiring information to better exploit it.
5. **Phase 5, Statistical Analysis of industry data:** The data provided by the industry will be analyzed, and whenever possible, statistical analysis will also be performed. Data gathered from the industry will enrich the knowledge acquired from the literature review and will allow the team to better understand the gap in the current ERTMS implementation.
6. **Phase 6, Development of ERTMS applications using real-world data:** the acquisition of data during the previous phase will be used to propose and develop new applications able to enrich the current ERTMS. Possible applications include the usage of AI tools and data analysis to propose improvements and optimizations of the current ERTMS, for instance applying them in predictive maintenance.
7. **Phase 7, synthesis and integration:** the different results obtained from the previous phases will be integrated into one application, which includes different processes, eventually delivering a working system that respects the requirements of flexibility, extensibility, and interoperability needed for the next generation ERTMS.

At the end of Phase 5, the deliverable D2.10 will be produced, using the data acquired from the literature review and the interaction with industry. Also, the knowledge acquired will be used to produce journal articles.

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15 Conclusion

The PhDs EU-Rail Deliverable 1.1 shown a preliminary, though impressively rich and articulated, state of art in the railway domains that represent the working environment of the ongoing PhDs.

The findings across the chapters demonstrate that the current state of infrastructure and existing technological solutions still require substantial efforts to overcome barriers, foster innovation, and ensure the successful implementation of technological advancements in railways. These efforts are crucial to advancing decarbonisation initiatives within the transport sector.

In parallel, , it has become clear that there is a profound gender inequality in the railway sector, as well as in the other industries related to the transport sector. This inequality happens transversally in the three dimensions studied: women as workers, as potential workers and as users.

Concern the education and training in railway the deliverable indicates that while substantial progress has been made through European projects and institutional initiatives to modernize railway education, existing curricula often lag behind the pace of technological change and industry evolution. Fragmented approaches, outdated content, and inconsistent evaluation models hinder the sector's capacity to produce a future-ready workforce

Furthermore, urban logistics and night train operations emerge as promising avenues for sustainable modal shift. The study proposes a novel approach to urban freight distribution by providing a model that allows freight movement between cities using rail to a micro hub where it is then sorted and further distributed to their last-mile locations by eco-friendly last-mile delivery modes such as cargo bikes, electric vans, crowd shipping.

The analysis of KPIs in rail research and the development of interoperable ICT platforms point to the importance of data-driven governance and standardization. Such tools are critical to monitor impact, guide investment, and scale successful innovations across Europe.

Altogether, this deliverable lays the intellectual and strategic groundwork for each PhD project. It identifies research gaps, methodological needs, and practical considerations that will guide the next phases of investigation. As these doctoral works evolve, they are expected to generate actionable insights, prototype solutions, and policy recommendations that collectively support the EU-Rail Joint Undertaking's vision for a connected, green, and inclusive European rail network

Beyond the importance in the PhDs research activities, this state-of-the-art is a powerful multidisciplinary pillar for the railway research that PhDs EU-Rail projects make available to the EU-Rail Joint Undertaking and to the entire railway community to strengthen the concept that the railway is a system and its harmonic development must proceed with the involvement of all involved human and technological components.

The present state-of-the-art will be further implemented during the research work and important steps beyond it will be provided by the ongoing PhDs research activities.