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D2.2 Position Paper on Research Gaps

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3 Executive Summary

European railway research is a cornerstone of advancing transportation infrastructure, enhancing sustainability, and maintaining Europe's global leadership in railway innovation. As rail transport becomes an important contributor to Europe's decarbonization and digital transformation goals, there is a need for academic research activities to align with those of the broader railway sector. This position paper identifies key gaps in current research efforts, highlights findings from the UIC 12 Capabilities assessment and academic surveys on Future Research Area, and outlines strategic actions to address these challenges, ensuring long-term development and competitiveness for the European railway sector.

The Shift2Rail (S2R) initiative and the transition to Europe's Rail Joint Undertaking (ERJU) have driven significant advancements in railway research and innovation. S2R projects were structured around five key Innovation Programs (IPs) addressing distinct aspects of railway technology, including cost-efficiency, traffic management, infrastructure, IT solutions, and freight technologies. As S2R transitioned to the ERJU, the focus shifted toward achieving higher TRLs and market uptake of innovative solutions **(Section 2)**.

To understand whether these projects provide sufficient coverage of the near- and long-term research and development needs of the European railway sector, a comprehensive review of these projects was completed **(Section 2)**. Academic surveys and brainstorming sessions with ERRAC **(Section 3)** revealed persistent gaps in research focus, particularly in areas requiring long-term foundational studies, interdisciplinary collaboration, and exploration of emerging technologies.

Identified Gaps

- **Lack of Support for Fundamental Research**

Current funding priorities emphasize projects with mid-to-high Technology Readiness Levels (TRL), limiting the foundational, multidisciplinary research crucial for long-term railway innovation from the European project perspective. Strategic, long-term EU support for fundamental research at lower TRL is needed to foster disruptive technological advancements **(Section 2)**.

The brainstorming of the applicability of the UIC 12 Capabilities assessment highlighted the mismatch between TRL and areas of emerging research in areas like wheel-rail contact efficiency, innovative manufacturing, and predictive maintenance. The academic community noted that current funding tends to prioritize applied research, and higher TRL research with demonstrators over exploratory studies, creating a potential gap in some fundamental research areas.

- **Multidisciplinary Research Deficit**

There is inadequate focus on system-level challenges requiring multidisciplinary approaches. Enhanced collaboration across engineering, data science, environmental studies, and policy development is essential and has been outlined by the EU Strategic Transport Research and Innovation Agenda (STRIA) however there is limited cross-sector collaboration.

The academic community stresses the need for cross-functional research, integrating expertise from diverse fields to address complex railway challenges. For example, the integration of AI-driven decision-making in multimodal traffic management requires insights from computer science, operational conditions from road, rail, nautical, and air transport, as well as integrating human factors.

- **Increasing Research of Emerging Technologies**

Projects exploring high-speed technologies including Hyperloop and Maglev are largely absent from the main ERJU Projects. Investment in these areas is rising globally, particularly in the Asia-Pacific region, which poses a risk of marginalization of European partners in the high-speed sector **(Section 3).**

The UIC 12 Capabilities assessment found that Hyperloop and Maglev technologies were not addressed despite their growing global interest. The lack of dedicated funding and research focuses on these technologies' places Europe at a disadvantage in shaping the future of high-speed rail.

- **Insufficient Integration of Artificial Intelligence**

AI applications in railway operations, maintenance, and safety remain underprioritized, despite their transformative potential and their increased usage in adjacent sectors, notable road applications for decision support and automation. Greater integration of AI methodologies, as demonstrated by the RAILS project **(Section 4)**, is essential to enhance railway efficiency and reliability.

Survey results indicated that AI research received lower priority despite its potential to revolutionize rail systems. Respondents highlighted the need to move beyond proof-of-concept applications and integrate AI tools into real-world operations, such as predictive maintenance and traffic optimization. Likewise, in-situ AI test beds are needed to allow for the deployment and certification of AI in the context of safety and automation.

- **Imbalance in Research Focus (Rail Freight)**

The survey of Future Rail Research Areas indicates that passenger rolling stock innovation requires greater attention to align academic research with industry and societal needs. Meanwhile, Mobility as a Service and seamless passenger experiences have low research priority and urgency, despite their significance for enhancing railway attractiveness. Therefore, it is suggested that increased exploration in this sector should be considered for future research areas.

Moreover, though projects prioritizing freight and infrastructure have been particularly focused in the areas of asset reliability and sustainability, the survey responses seem to highlight that while increased attention to passenger-related research is necessary, freight also deserves a stronger and more focused approach. In fact, when comparing current efforts, it's clear that the attention given to freight must be significantly enhanced. A striking example of this gap is the recent ERRAC student submission pool (MSc and PhD prize), which received 58 submissions, none of which focused on freight. This is a telling sign: it suggests that ERJU's freight projects did not sufficiently engage universities, research centers, or students in industry. While this alone is not conclusive, it strongly indicates a lack of visibility or appeal in freight-related research initiatives. The mismatch between academic research focus and the current needs of freight related rolling stock, operations, and infrastructure sector indicated research stagnation which may lead to long term, systemic challenges in the European freight sector.

- **Underrepresented Research Fields**

Areas such as advanced manufacturing and materials, railway education, EU integration and interoperability, railway economics, and data handling practices are insufficiently explored, with fragmented academic research and development at both the regional and EU levels **(Section 5).** These fields are generally researched at local levels, however, there currently are limited opportunities to address these topics, particularly at railway systems level.

Data handling is also highlighted as an emerging research gap, with calls to treat data as a strategic asset and improve data-sharing mechanisms. There are limited contexts for academic researchers to access data from industrial partners, leading to a lag between the pace of academic research and the industrial development. The academic community advocates standardized data governance frameworks to facilitate cross-border, cross-institutional data interoperability to enable data-driven insights for improving railway operations.

Recommendations

Increasing Support for Fundamental and Multidisciplinary Research

- Allocate dedicated funding for projects addressing system-level railway challenges,
- Support long-term research agendas particularly those with lower TRL in strategic areas,
- Encourage projects exploring early-stage research, such as advanced manufacturing and materials, predictive maintenance, and sustainable infrastructure. Creating open access *research sandboxes* could provide testing grounds for experimental ideas and foster collaboration between researchers and practitioners.

Prioritize Emerging Technologies and AI Integration

- Establish dedicated research streams for emerging technologies including Hyperloop, Maglev, and AI and data-driven railway solutions,
- Promote the adoption of AI tools across all facets of railway operations, with a focus on the adoption and testing of AI tools following the RAILS Roadmap (**Section 4**),
- Create accessible demonstrator projects to assess technical applications in safety-critical systems and real-world environments. Emphasis should be placed on developing AI-driven digital twins for simulating railway networks and optimizing traffic management. These demonstrators should prioritize small and medium Sized Enterprises (SMEs) and research incubators to encourage the grassroots development of new railway tools.

Address Imbalances in Research Focus

- Rebalance funding to include rolling stock innovations with a focus on passenger rolling stock advancements and freight system optimization,
- Address the urgent need for additional freight research in European universities to strengthen the European good transportation network across all sectors including innovative rolling stock, improved operations, sustainable infrastructure, and efficient maintenance,

- Encourage studies considering the entire railway ecosystem, in particular research in railway economics, railway materials and circularity, environment and green energy, and innovative freight solutions for efficient and optimized good transport,
- Develop standardized methods for integrating passenger needs into railway innovation strategies. Prioritizing user experience design, accessibility, and multimodal connectivity could enhance the attractiveness of rail transport for diverse passenger segments.

Foster Systematic Benchmarking and Reporting

- Implement regular benchmarking against global railway research efforts to understand the state of rail research and development and the alignment of academic research goals to broader railway system goals,
- Introduce systematic reporting of academic outputs and emerging research trends to track progress and identify emerging trends (Section 6),
- Establish reoccurring fora for academic and industry exchange, including the development of a virtual cluster to support the information and decision-making information flows between ERRAC, ERJU, and EURNEX (Section 7).

Strengthening Data Collaboration

- Treat data as a strategic asset, enhancing data sharing across industry, academia, and policymakers,
- Establish guidelines for data standardization, storage, and exchange to streamline cross-stakeholder collaboration. Building interoperable data platforms would enable seamless integration of diverse data sources, facilitating real-time decision-making and predictive analytics.

Addressing these gaps is imperative to maintaining Europe's leadership in railway research. A concerted effort to support fundamental research, embrace multidisciplinary approaches, and invest in emerging technologies will ensure Europe remains at the forefront of railway innovation, delivering sustainable, efficient, and future-proof transport solutions.

By implementing these recommendations, Europe can cultivate a dynamic research environment, foster groundbreaking discoveries, and build a railway network that meets the demands of the future.

4 Introduction

Europe's Rail Joint Undertaking (ERJU) is the European partnership on railway innovation, with the mission to deliver a high-capacity integration of European railway network by eliminating barriers to interoperability and providing solutions for the full integration of the system. The partnership involved developments in traffic management, vehicles, infrastructure, and services with the aim of achieving faster uptake and deployment of innovative project solutions. The partnership should leverage advancements in digitalization and automation to reduce the cost of railway systems, with the goal of increasing capacity and flexibility, while maintaining reliability [1].

The missions of the ERJU are supported by research and development by academic, industrial, and regulatory partners in the European railway system. These partners are organized into flagship areas which are directed to realize specific objectives and thematic research areas outlined by ERJU.

To support the goals of ERJU the Academic4Rails (Ac4R) research project is established to align the research needs and goals of the scientific community with the goals of the ERJU and to the railway stakeholders. The Ac4R community is comprised of members of the academic scientific community with representation of 27 academic and research institutions.

To assist in these tasks, the following paper outlines the (1) current state of railway research, (2) activities performed by the Ac4R to assess the current state of research and assess the alignment of the research to European activities, and (3) the discussion of research gaps and the prioritization of future European research activities.

It is anticipated that this document will **provide a comprehensive outline into the state of European railway research and provide guidelines on how to assess research activities in Europe**. Likewise, this work will provide a **framework for the systematic analysis research gaps, based on the inputs from the academic community**. Finally, the work will provide **recommendations on activities between ERRAC, ERJU, and the academic community to meet the research gaps**, with a focus on how to integrate emerging research fields into future railway research.

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5 Review of European Rail Research Themes: State of the Art, Challenges and Opportunities

5.1 Horizon 2020 – Shift2Rail

The research activity was based on the Shift2Rail (S2R) projects focused on research and innovation (R&I). The projects were structured around five asset-specific Innovation Programmes (IPs). These Programmes covered all the different structural (technical) and functional (process) subsystems of the railway system and is shown below in Figure 1.

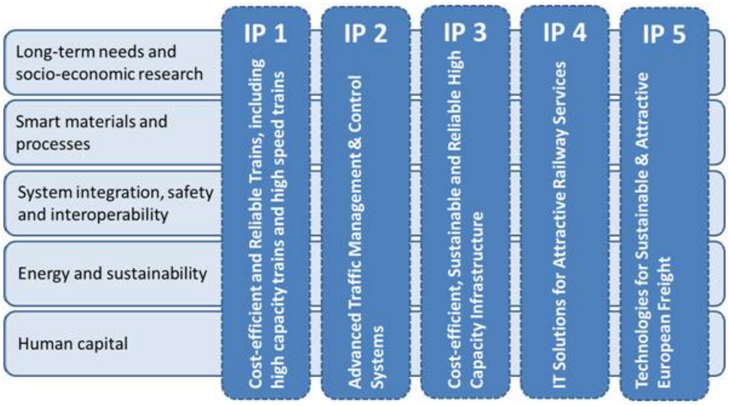

Figure 1: Interactions between the various IPs

(source: https://rail-research.europa.eu)

5.1.1 *Innovation Programme 1* (IP1) Cost-efficient and Reliable Trains

Research activities of IP1 were focused on promoting the competitiveness of rail transport in relation to other modes of transport. The focus was on vehicle design, on increasing comfort and reliability, on affordability and accessibility, but also on meeting the requirements of railway undertakings and operators. The projects addressed the use of new materials and technologies, the energy and economic performance of rail operations, the implementation of intelligent systems, the development and integration of more efficient technologies, etc. IP1 was differentiated into several technical demonstrators:

- TD 1.1 Traction system,
- TD 1.2 Train control and monitoring system (TCMS),
- TD 1.3 The new generation of car body shells,
- TD 1.4 Running gear,
- TD 1.5 New braking systems,
- TD 1.6 Innovative doors,
- TD 1.7 Train modularity in use,

- TD 1.8 Heating, Ventilation, Air conditioning and Cooling (HVAC) systems.

An overview of IP1 is presented below in Figure 2.

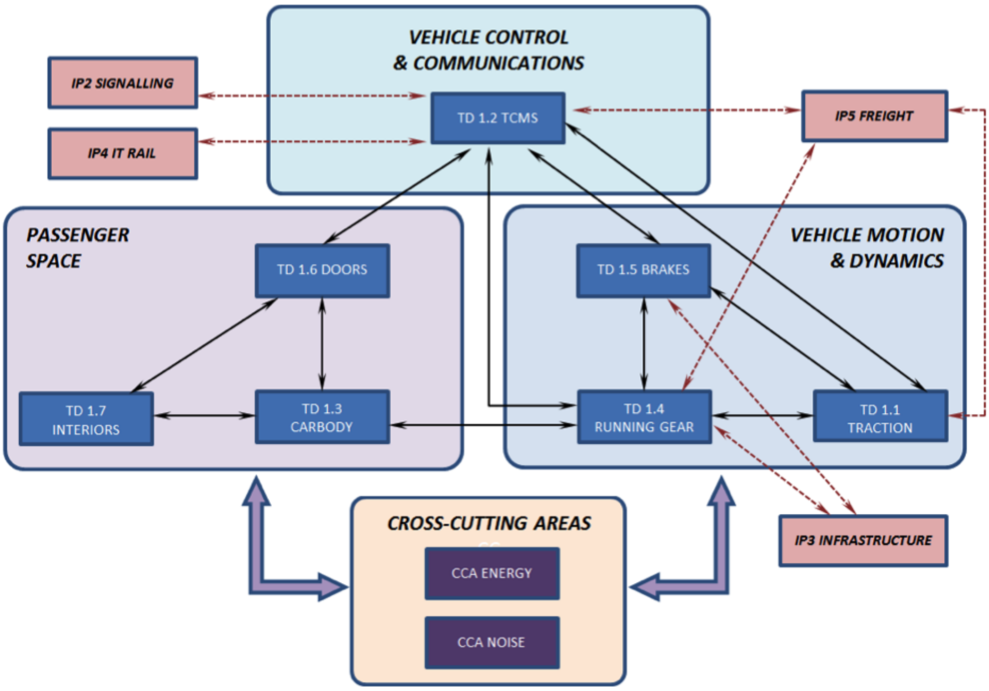

Figure 2: IP1 Research and Innovation relationships

(source: https://rail-research.europa.eu)

The following Table 1 provides an overview of the IP1 projects, indicating the start and end dates of the various projects. It is noted that several projects have the -2 or -3 ending which indicates a continuation of the project within the IP.

Table 1: The overview of projects in S2R Innovation Programme 1

Project	Duration from	Duration to
Pinta	09/ 2016	12 / 2018
Connecta	06 / 2016	09 / 2018
Safe4Rail	10 / 2016	12 / 2018
Run2Rail	09 / 2017	09 / 2019
Mat4Rail	10 / 2017	09 / 2019
Pivot	10 / 2017	12 / 2019
Pinta2	09 / 2018	02 / 2021
Safe2Rail2	10 / 2018	07 / 2021
Connecta-2	10 / 2018	07 / 2021
Pivot2	10 / 2019	03 / 2023
NextGear	12 / 2019	02 / 2022
Carbodin	12 / 2019	02 / 2022
GearBodies	12 / 2020	06 / 2023
Pinta3	12 / 2020	05 / 2023
Connecta-3	12 / 2020	07 / 2023

Recet4Rail	12 / 2020	09 / 2023
Safe4Rail-3	12 / 2020	07 / 2023

In the area of cost-efficient and reliable trains, the 17 projects of IP1 of the Shift2Rail R&I Programme, which lasted from 2016 to 2023, were explored in more detail. The projects were investigated for their content and, above all, their achieved Technical Readiness Level (TRL), as presented in Table 6. The necessary information was obtained from the Shift2Rail website or the projects' own websites.

The achieved TRLs ranged from 2 to 7, mostly from 4 to 7.

Table 2: The projects of the Innovation Programme 1 (S2R) and achieved TRL

Project	TRL
Pinta	2,3,4,5
Connecta	2,3,4,5,6
Safe4Rail	2,3
Run2Rail	2
Mat4Rail	4,5
Pivot	3,4
Pinta2	5,6
Safe2Rail2	4,5
Connecta-2	5
Pivot2	7
NextGear	5,6
Carbodin	5,6
GearBodies	5,6
Pinta3	7
Connecta-3	7
Recet4Rail	3
Safe4Rail-3	6,7

Note:
TRL 2 (Technology concept formulated) is defined as gaining an increase knowledge of technologies, materials, and interfaces, investigating and an improving new concept, assessing feasibility or defining preliminary technical specifications for laboratory test. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions.
At TRL level 4 (Technology validated in lab), the technology is tested in a laboratory environment. The core technology components are integrated to verify their compatibility and collective performance. Key Performance Indicators are measurable. The results provide evidence that performance targets can be achieved based on the projected or modelled systems.
TRL 7 (System prototype demonstration in operational environment). The integration of upstream and downstream technologies has been verified and validated. The manufacturing approach is defined. Compliance with relevant environment conditions, authorisation issues, local/national standards is guaranteed, at least for the demo site. The prototype is tested in a real operational environment. This stage is crucial to assess the technology's performance in practical conditions.

The percentages of achieved TRLs are shown graphically in Figure 3.

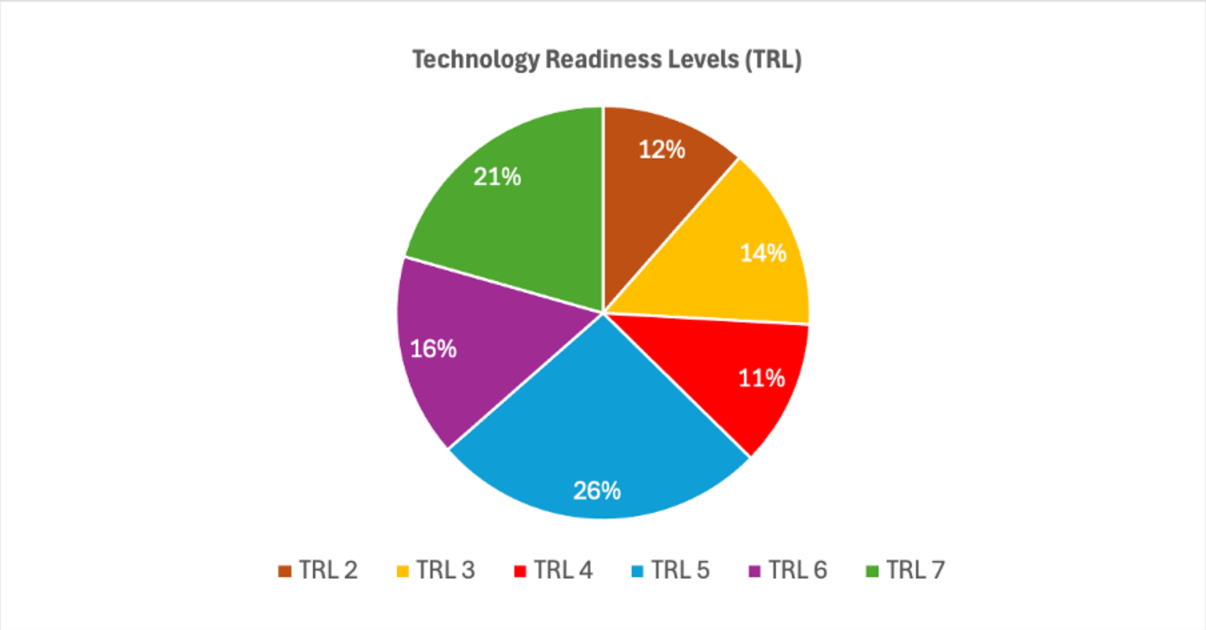

Figure 3: The percentage of TRL represented in the monitored projects IP1

5.1.2 *Innovation Programme* 2 (IP2) Advanced Traffic Management and Control Systems

A key challenge for IP2 was to enhance the advanced traffic management and control systems, therefore a flexible, real-time, intelligent traffic management and decision support system. Shift2Rail activities should support the rapid and broad deployment of advanced traffic management and control systems, by offering improved functionalities and standardized interfaces based on common operational concepts, facilitating migration from legacy systems, cutting overall costs, and adapting them to the needs of the different rail segments as well as to the needs of a multimodal smart mobility system. The technical demonstrators were as follows:

- TD 2.1 Communication System,
- TD 2.2 Automatic Train Operation (ATO),
- TD 2.3 Moving Block,
- TD 2.4 Safe Train Positioning,
- TD 2.5 Train Integrity,
- TD 2.6 New laboratory test framework,
- TD 2.7 Standardized engineering and operational rules,
- TD 2.8 Virtual Coupling,
- TD 2.9 Traffic Management System,

- TD 2.10 Smart radio-connected all-in-all wayside objects,
- TD 2.11 Cyber Security.

An overview of IP2 is presented in Figure 4.

Table 3 provides an overview of the IP2 projects, indicating the start and end dates of the various projects. It is noted that several projects have the -2 or -3 ending which indicates a continuation of the project within the IP.

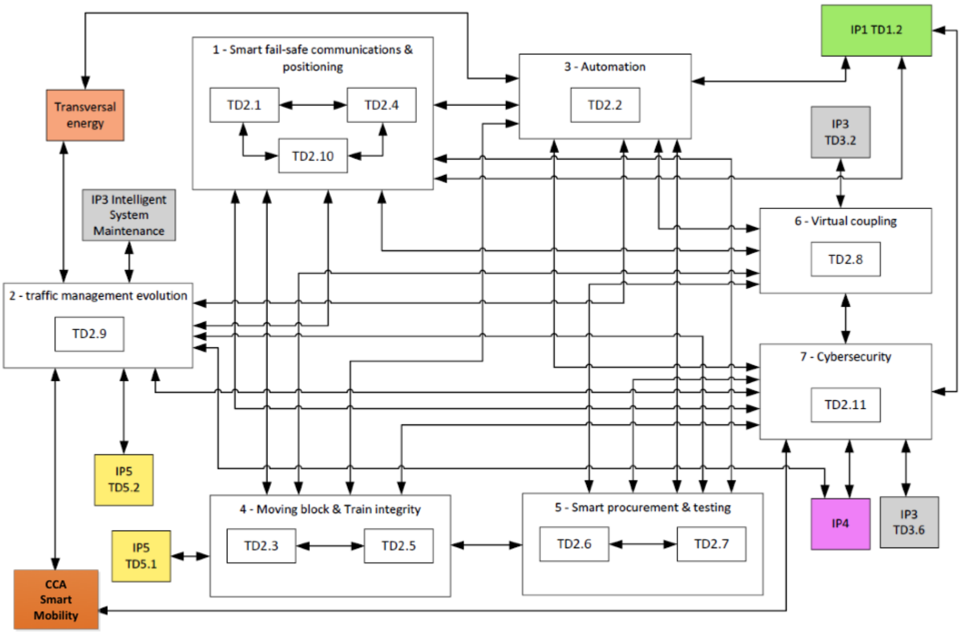

Figure 4: IP2 Research and Innovation relationships

(source: https://rail-research.europa.eu)

Table 3: The overview of projects in S2R Innovation Programme 2

Project	Duration from	Duration to
In2Rail	05 / 2015	04 / 2018
X2Rail	09 / 2016	06 / 2021
CYRail	10 / 2016	09 / 2018
Vite	11 / 2016	12 / 2018
Mistral	11 / 2016	10 / 2018
Etalon	09 / 2017	02 / 2020
ASTRail	09 / 2017	10 / 2019
X2Rail2	09 / 2017	04 / 2021
Gate4Rail	12 / 2018	02 / 2021
MovingRail	12 / 2018	12 / 2020

EmulRadio4Rail	12 / 2018	12 / 2020
X2Rail3	12 / 2018	11 / 2021
Optima	12 / 2019	02 / 2023
4SecuRail	12 / 2019	11 / 2021
X2Rail4	12 / 2019	02 / 2023
PerformingRail	12 / 2020	06 / 2023
X2Rail5	12 / 2020	10 / 2023
AB4Rail	01 / 2021	12 / 2022

In the area of advanced traffic management and control systems, the 18 projects of IP2 of the Shift2Rail R&I Programme, which lasted from 2015 to 2023, were explored in more detail. The projects were investigated for their content and, above all, their achieved Technical Readiness Level (TRL), shown in Table 4. The necessary information was obtained from the Shift2Rail website or the projects' own websites.

The achieved TRLs ranged from 2 to 7, mostly from 4 to 7.

Table 4: The projects of the Innovation Programme 2 (S2R) and achieved TRL

Project	TRL
In2Rail	3,4,5
X2Rail1	4
CYRail	3
Vite	4
Mistral	2,3
Etalon	4
ASTRail	3
X2Rail2	5
Gate4Rail	3
MovingRail	3
EmulRadio4Rail	5,6
X2Rail3	6
Optima	6
4SecuRail	4,5
X2Rail4	7
PerformingRail	3,4
X2Rail5	7
AB4Rail	4,5

The percentages of achieved TRLs are shown graphically in Figure 5.

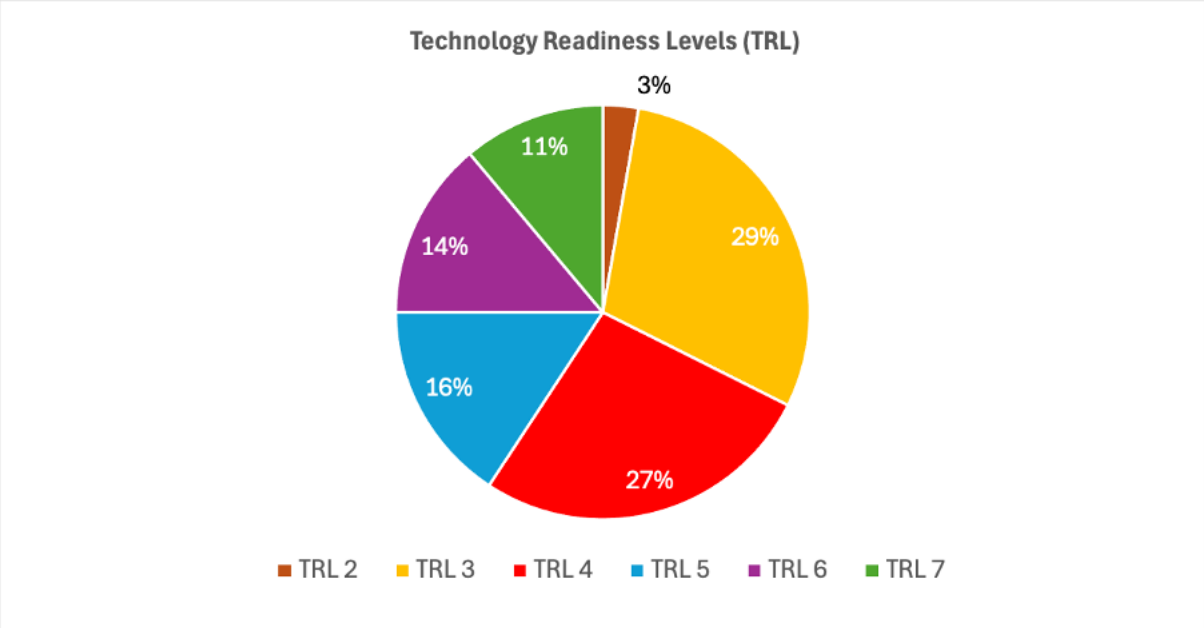

Figure 5: The percentage of TRL represented in the monitored projects IP2

5.1.3 *Innovation Programme* 3 Cost-efficient and Reliable High-Capacity Infrastructure

The challenges of IP3 include ensuring a secure and reliable, cost-effective, and sustainable infrastructure. The focus was on the design, construction, operation, and maintenance of rail network infrastructure. The research activities of the projects were primarily aimed at activities that support the ensuring of interoperability and elimination of network diversity furthermore support of the reduction of maintenance costs and life cycle costs and solutions that can be deployed quickly and efficiently, using smart technologies and comprehensive approaches.

The technical demonstrators of IP3 (Figure 6):

- TD 3.1 Enhanced Switch & Crossing System,
- TD 3.2 Next Generation Switch & Crossing System,
- TD 3.3 Optimized Track System,
- TD 3.4 Next-Generation Track System,
- TD 3.5 Proactive Bridge and Tunnel Assessment, Repair and Upgrade,
- TD 3.6 Dynamic Railway Information Management System (DRIMS),
- TD 3.7 Railway Integrated Measuring and Monitoring System (RIMMS),
- TD 3.8 Intelligent Asset Management Strategies (IAMS),

- TD 3.9 Smart Power Supply,
- TD 3.10 Smart Metering for Railway Distributed Energy Resource Management System,
- TD 3.11 Future Stations.

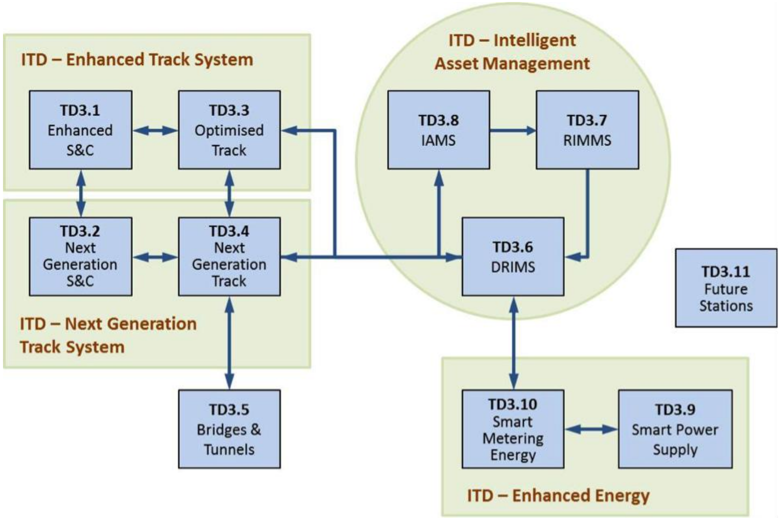

Figure 6: IP3 Research and Innovation relationships

(source: https://rail-research.europa.eu)

In the area of infrastructure, the 16 projects in IP 3 of the Shift2Rail R&I Programme (Table 5), which lasted from 2015 to 2023, were explored in more detail. The projects were investigated for their content and, above all, their achieved Technical Readiness Level (TRL), as shown in Table 6. The necessary information was obtained from the Shift2Rail website or the projects' own websites.

Table 5: The overview of projects in S2R Innovation Programme 3

Project	Duration from	Duration to
In2Rail	05 / 2015	04 / 2018
In2Smart	09 / 2016	10 / 2019
In2Track	09 / 2016	04 / 2019
S-Code	11 / 2016	10 / 2019
In2Stempo	09 / 2017	03 / 2023
FAIR Stations	09 / 2017	12 / 2019
Momit	09 / 2017	10 / 2019
In2Dreams	09 / 2017	10 / 2019
In2Track2	11 / 2018	02 / 2022
Assets4Rail	12 / 2018	12 / 2021
In2Smart2	12 / 2019	05 / 2023
Fundres	12 / 2019	11 / 2021
DayDreams	12 / 2020	05 / 2023
In2Zone	12 / 2020	05 / 2023
Stream	12 / 2020	05 / 2024
In2Track3	01 / 2021	12 / 2023

The achieved TRLs ranged from 2 to 7, mostly from 4 to 7. The TRLs for two projects (Fair Station and Momit) were not determined (Table 5).

Table 6: The projects of the Innovation Programme 3 (S2R) and the achieved TRL

Project	TRL
In2Rail	3, 4, 5
In2Smart	4
In2Track	4
S-Code	4, 5, 6
In2Stempo	4/5
FAIR Stations	-
Momit	-
In2Dreams	5, 6/7
In2Track2	5, 6
Assets4Rail	5, 6, 7
In2Smart2	4
Fundres	4, 5
DayDreams	5/6
In2Zone	6
Stream	5, 6, 7
In2Track3	2, 3

The percentages of achieved TRLs are shown graphically in Figure 7.

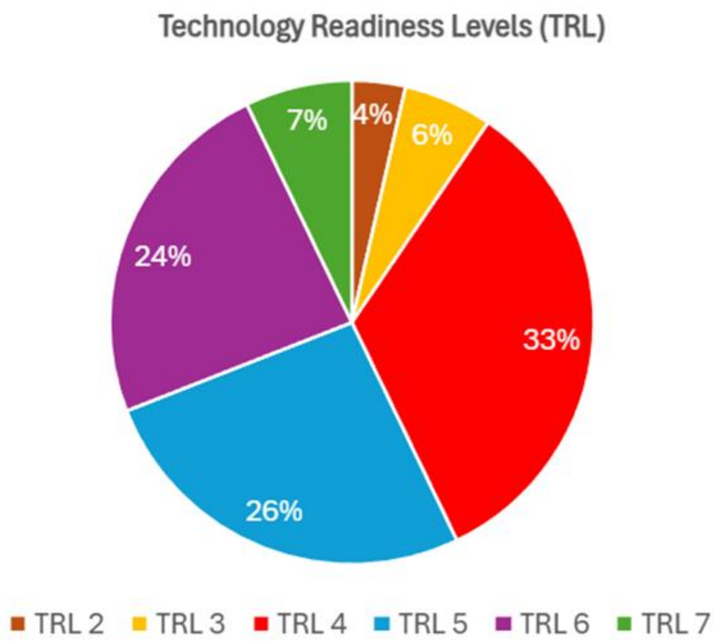

Figure 7: The percentage of TRL represented in the monitored projects IP3

5.1.4 *Innovation Programme* 4 IT Solutions for Attractive Railway

The research interests were focused on interoperability with other transport modes. The research activities were based on the availability of European Global Navigation Satellite Systems (GNSS)-based locations, the advances in cloud computing, big, linked, and open data and the propagation of internet and social media. Improved information technology, management and exploitation, and cross-industry collaboration make transfers easy, comfortable, and reliable.

IP4 was differentiated into several technical demonstrators (Figure 8):

- TD4.1 Interoperability Framework,
- TD4.2 Travel Shopping,
- TD4.3 Booking & Ticketing,
- TD4.4 Trip-tracker,
- TD4.5 Travel Companion,
- TD4.6 Business Analytics.

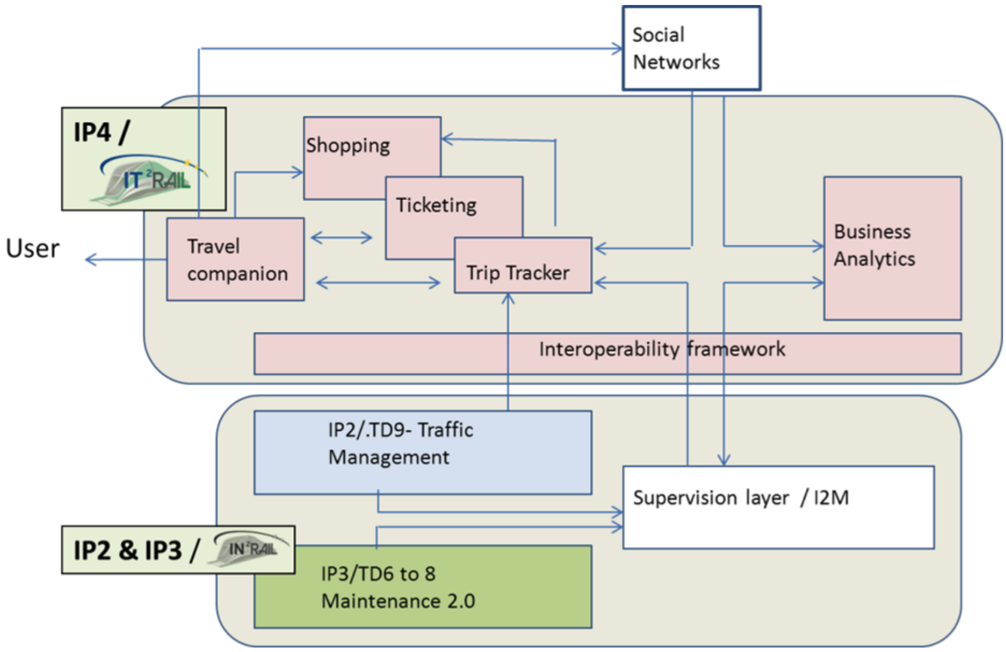

Figure 8: IP4 Research and Innovation relationships

(source: https://rail-research.europa.eu)

The 14 projects within the Innovation Programme 4 are listed in Table 7.

Table 7: The overview of projects in S2R Innovation Programme 4

Project	Duration from	Duration to
IT2Rail	05 / 2015	04 / 2018
Co-Active	09 / 2016	05 / 2019
Attracktive	09 / 2016	05 / 2019
GOF4R	11 / 2016	10 / 2018
ST4RT	11 / 2016	10 / 2018
Cohesive	09 / 2017	12 / 2022
Connective	09 / 2017	06 / 2023
MY-Trac	09 / 2017	12 / 2020
MaaSive	11 / 2018	07 / 2021
Shift2Maas	12 / 2018	06 / 2021
Sprint	12 / 2018	02 / 2021
Ride2Rail	12 / 2019	04 / 2023
IP4Maas	12 / 2020	05 / 2023
Extensive	12 / 2020	06 / 2023

In the area of solutions for attractive railway, the 13 projects of IP4 of the Shift2Rail R&I Programme, which lasted from 2016 to 2023, were explored in more detail. The projects were investigated for their content and, above all, their achieved Technical Readiness Level (TRL), as shown in Table 8. The necessary information was obtained from the Shift2Rail website or the projects' own websites.

The achieved TRLs ranged from 2 to 7, mostly from 4 to 7.

Table 8: The projects of the Innovation Programme 4 (S2R) and achieved TRL

Project	TRL
Co-Active	5,6
Attracktive	3,4,5,6
ST4RT	2,3,4
Cohesive	6
Connective	6
MY-Trac	4,5
MaaSive	6
Shift2Maas	4
Sprint	4
Ride2Rail	5
IP4Maas	6,7
Extensive	7

The percentages of achieved TRLs are shown graphically in Figure 9.

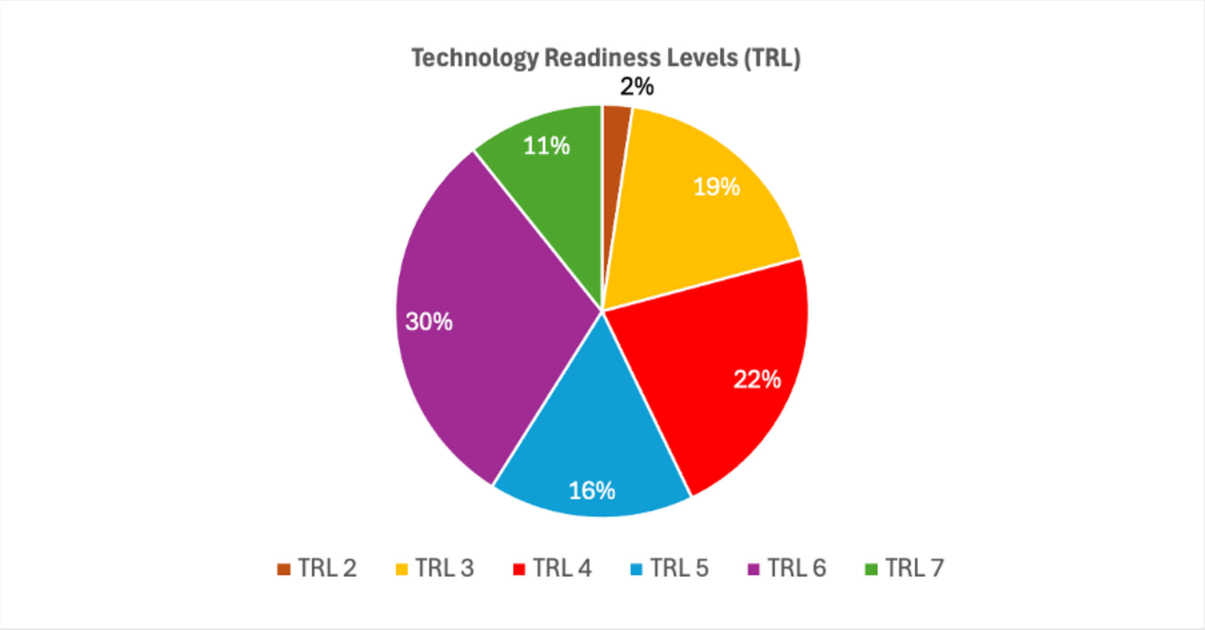

Figure 9: The percentage of TRL represented in the monitored projects IP4

5.1.5 Innovation Programme 5 Technologies for Sustainable and Attractive European Rail Freight

The IP5 focused on improving the competitiveness and reliability of freight transport services (excellence in on-time delivery at competitive prices, interweaving its operations with other transport modes, offer of innovative value-added services, fostering technology transfer from other sectors into rail freight). Activities included the development of the intermodal transport segment and the wagon load/block train activity segment, which relies on the use of specific freight wagons. Among the other objectives belong to better operating in conjunction with passenger traffic, to maximize the utilization of existing networks. Improving rail freight performance also implies addressing the critical issues of rail noise and the continued improvement of its environmental performance, e.g. through electrification/hybrid propulsion.

The technical demonstrators for this programme were:

- TD 5.1 Fleet Digitalization and Automation,
- TD 5.2 Digital Transport management,
- TD 5.3 Smart Freight Wagon Concepts,
- TD 5.4 New Freight Propulsion Concepts,
- TD 5.5 Business analytics and implementation strategies.

The 16 projects within the Innovation Programme 5 are listed in Table 9.

Table 9: The overview of projects in S2R Innovation Programme 5

Project	Duration from	Duration to
SmartRail	05 / 2015	04 / 2018
ARC	09 / 2016	04 / 2021
FFL4E	09 / 2016	07 / 2019
FR8Rail	09 / 2016	08 / 2019
Smart	10 / 2016	09 / 2019
FR8RAILII	10 / 2016	09 / 2019
Innowag	11 / 2016	06 / 2019
Dynafreight	11 / 2016	06 / 2018
FR8HUB	09 / 2017	02 / 2021
OptiYard	10 / 2017	09 / 2019
Marathon2Operation	12 / 2018	12 / 2020
FR8RAILIII	09 / 2019	06 / 2023
Locate	11 / 2019	04 / 2022
Smart2	12 / 2019	11 / 2022
FR8RAILIV	07 / 2020	03 / 2023
Daccelerate	06 / 2021	12 / 2022

In the area of technologies for sustainable and attractive European rail freight, the 13 projects of IP5 of the Shift2Rail R&I Programme, which lasted from 2016 to 2023, were explored in more detail. The projects were investigated for their content and, above all, their achieved Technical Readiness Level (TRL), as shown in Table 10. The necessary information was obtained from the Shift2Rail website or the projects' own websites.

The achieved TRLs ranged from 2 to 7, mostly from 4 to 7.

Table 10: The projects of the Innovation Programme 5 (S2R) and achieved TRL

Project	TRL
FFL4E	3,4,5
FR8Rail	3,4,5
Smart	3,4,5
FR8RAILII	6
Innowag	3,4,5
Dynafreight	2,3,4
FR8HUB	4,5,6
OptiYard	4
Marathon2Operation	5
FR8RAILIII	7
Locate	5,6
Smart2	6,7

The percentages of achieved TRLs are shown graphically in Figure 10.

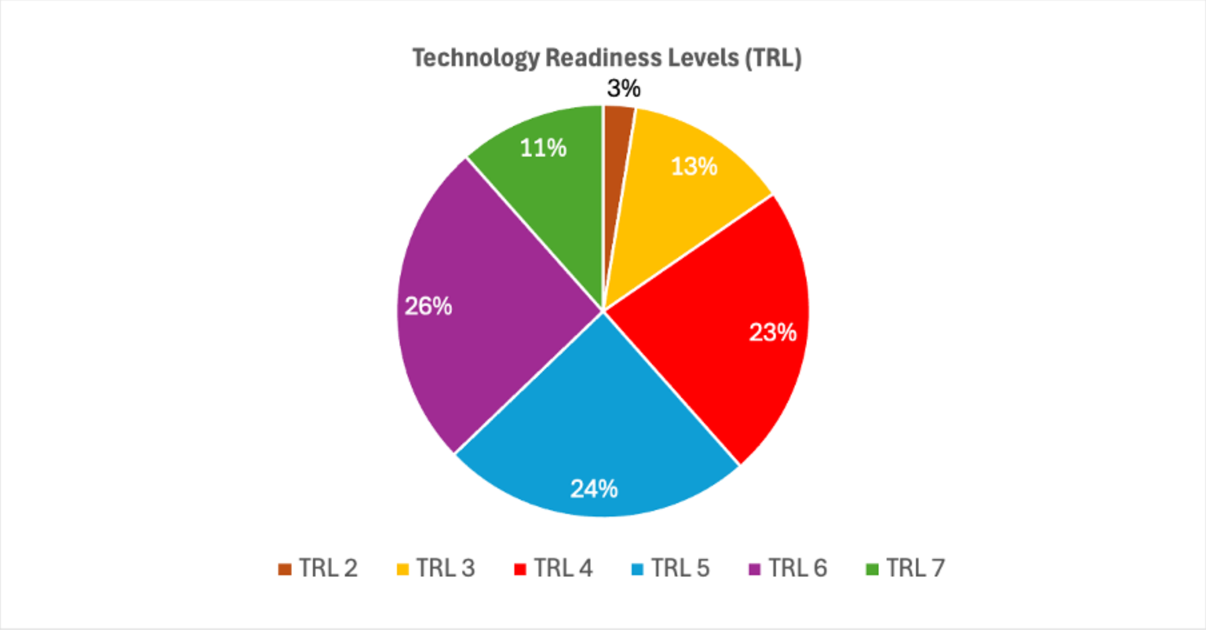

Figure 10: The percentage of TRL represented in the monitored projects IP5

5.1.6 CCA Research and innovation areas to achieve the CCA objectives

The CCAs ensured that R&I activities within the different IPs were closely aligned in terms of their objectives and requirements, as well as in terms of the methodologies used for evaluating and assessing the expected impacts. It is the activities: energy and noise management, safety, standardization, overall traffic management, maintenance, and virtual certification, as well as long-term societal effects and human capital management.

CCA work included six work areas (Figure 11):

1. Socioeconomics,
2. KPI,
3. Safety, Standardization & Smart Maintenance,
4. Smart Mobility,
5. Energy and sustainability,
6. Human capital.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement: HORIZON-ER-JU-2022-ExpIR-04

Europe's Rail

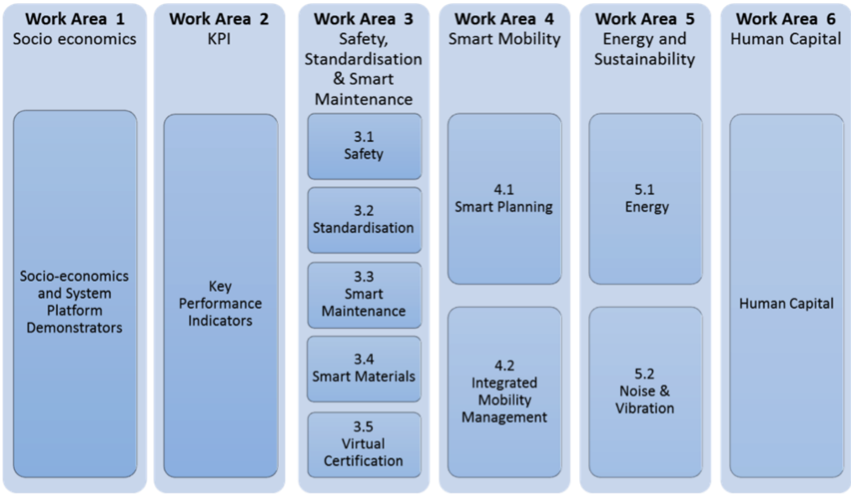

Figure 11: An overview of the various work areas in the CCAs

(source: https://rail-research.europa.eu)

The 17 projects within the Innovation Programme 5 are listed in Table 11.

Table 11: The overview of projects in S2R Innovation Programme CCA

Project	Duration from	Duration to
In2Rail	05 / 2015	04 / 2019
Roll2Rail	05 / 2015	04 / 2017
SmartRail	05 / 2015	04 / 2018
Fine-1	09 / 2016	10 / 2019
Impact-1	09 / 2016	04 / 2018
Plasa	09 / 2016	08 / 2018
GoSafeRail	10 / 2016	09 / 2019
Near2050	10 / 2016	04 / 2018
Destinate	11 / 2016	10 / 2018
Opeus	11 / 2016	10 / 2019
Impact-2	09 / 2017	12 / 2022
SMARTE	09 / 2017	10 / 2019
Plasa-2	09 / 2018	12 / 2020
Fine-2	12 / 2019	05 / 2023
Transit	12 / 2019	02 / 2023
SilvarStar	11 / 2020	02 / 2023
Ben@Rail	09 / 2021	05 / 2022

In the area of cross-cutting activities, the 16 projects of CCA of the Shift2Rail R&I Programme, which lasted from 2015 to 2023, were explored in more detail. The projects were investigated for their content and, above all, their achieved Technical Readiness Level (TRL), as shown in Table 12. The necessary information was obtained from the Shift2Rail website or the projects' own websites.

The achieved TRLs ranged from 2 to 7, mostly from 4 to 7. The TRLs for two projects (Roll2Rail and SmartRail) were not determined.

Table 12: The projects of the Innovation Programme CCA (S2R) and achieved TRL

Project	TRL
In2Rail	3,4,5
Fine-1	3,4,5
Impact-1	3
Plasa	3,4,5
GoSafeRail	3,4,5
Near2050	1,2,3
Destinate	3,4,5
Opeus	3,4,5
Impact-2	4,5
SMARTE	4
Plasa-2	3
Fine-2	6
Transit	4
SilvarStar	5

The percentages of achieved TRLs are shown graphically in Figure 12.

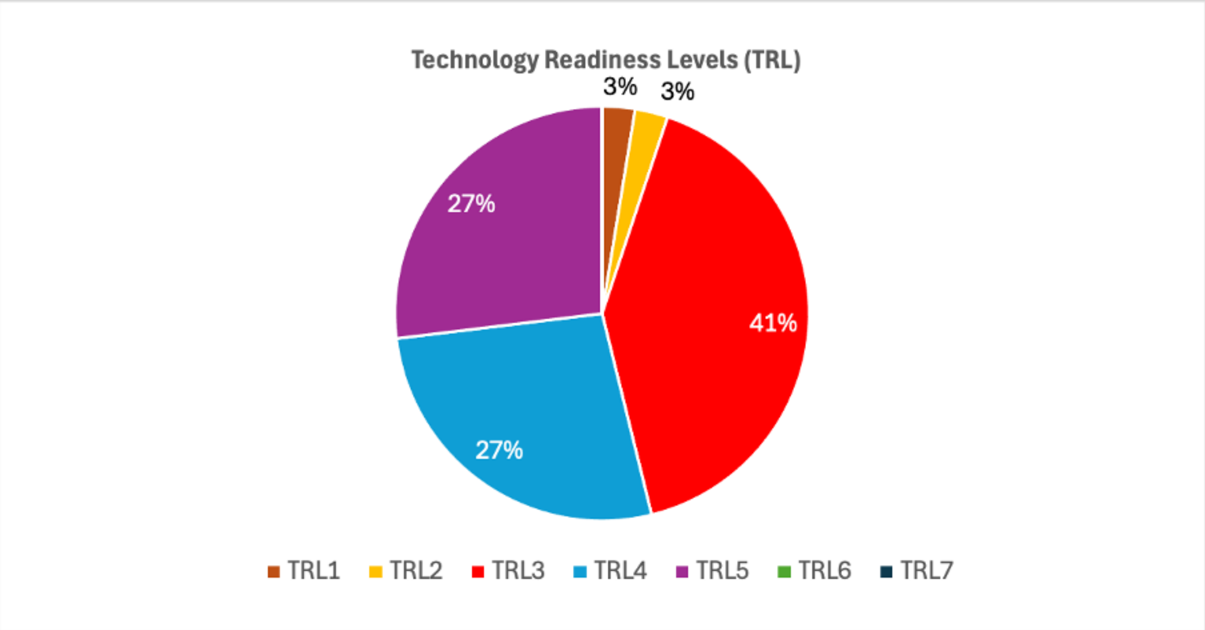

Figure 12: The percentage of TRL represented in the monitored projects CCA

IPX explored the impact of new technologies and sciences (Blockchain, Artificial Intelligence, and Internet of Things, with a view towards their implementation in rail applications).

The 10 projects within the Innovation Programme 5 are listed in Table 13.

Table 13: The overview of projects in S2R Innovation Programme IPX

Project	Duration from	Duration to
B4CM	12 / 2018	11 / 2022
FLEX-RAIL	12 / 2018	05 / 2021
TER4RAIL	12 / 2018	11 / 2020
MVDC-ERS	12 / 2018	04 / 2022
Hypernex	12 / 2019	02 / 2022
Linx4Rail	12 / 2019	11 / 2022
Rails	12 / 2019	11 / 2022
Translate4Rail	12 / 2019	11 / 2021
Linx4Rail2	12 / 2020	05 / 2023
Tauro	12 / 2020	05 / 2023

In the area of new technologies and sciences, the 7 projects of IPX of the Shift2Rail R&I Programme, which lasted from 2018 to 2023, were explored in more detail. The projects were investigated for their content and, above all, their achieved Technical Readiness Level (TRL), as shown in Table 14. The necessary information was obtained from the Shift2Rail website or the projects' own websites.

The achieved TRLs ranged from 2 to 7, mostly from 2 to 5. The TRLs for three projects (B4CM, TER4RAIL and MVDC-ERS) were not determined.

Table 14: The projects of the Innovation Programme IPX (S2R) - IPX and achieved TRL

Project	TRL
FLEX-RAIL	2
Hypernex	2,3
Linx4Rail	3,4
Rails	2,3
Translate4Rail	5,6,7
Linx4Rail2	3,4
Tauro	5

The percentages of achieved TRLs are shown graphically in Figure 13.

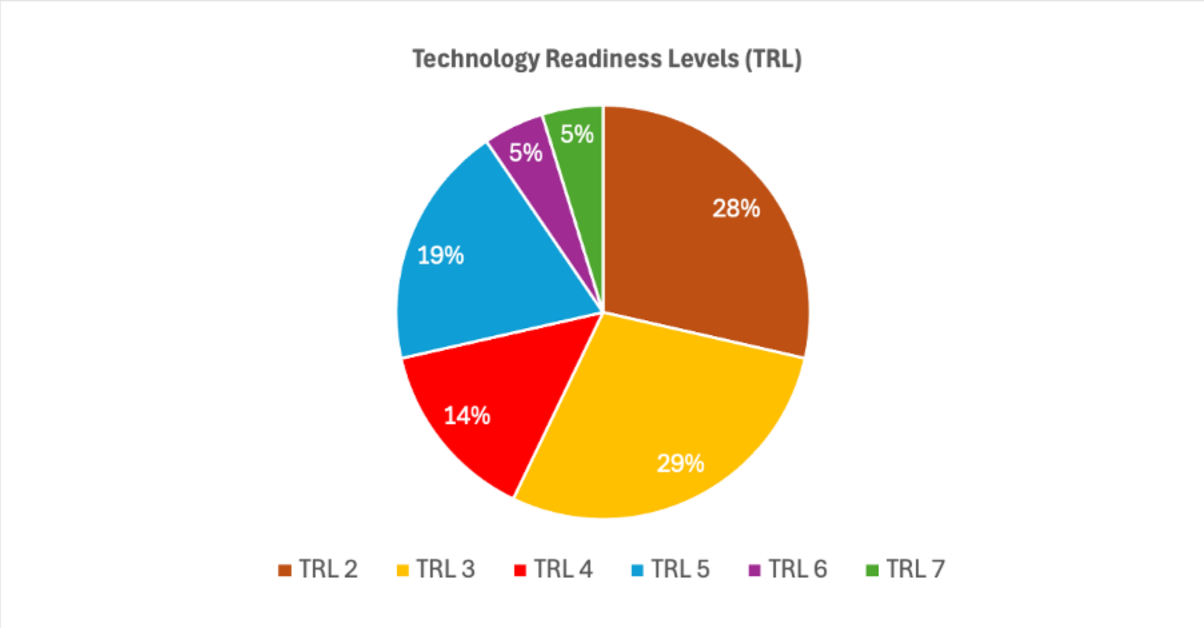

Figure 13: The percentage of TRL represented in the monitored projects IPX

In total, 97 projects were analysed for TRL in Shift2Rail. Information was obtained from the Shift2Rail website, in particular the Annual Work Plans. In some cases, TRL data on project outcomes was also obtained from the projects' own websites. However, it should be noted that the websites of a large number of projects are not updated and often not available at all.

The achieved TRLs ranged from 1 to 7. The percentages of achieved TRLs are shown graphically in Figure 14. The TRL4 level, which can be considered as the first phase of R&D, covered 47% of the projects.

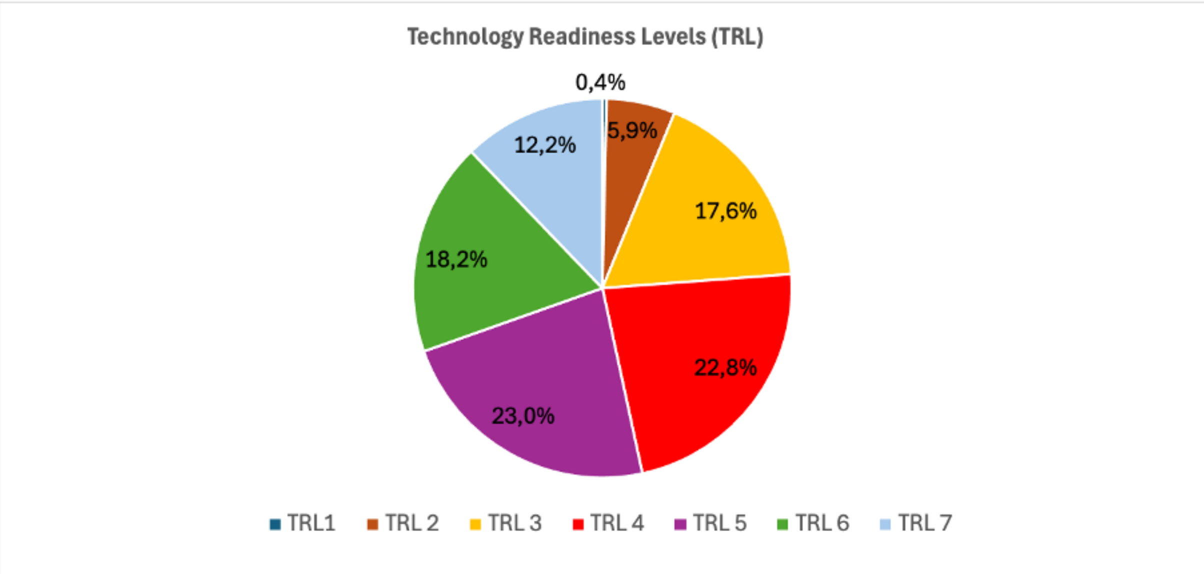

Figure 14: The percentage of TRL represented in the monitored 97 projects S2R

5.2 Horizon Europe – Europe's Rail JU

https://rail-research.europa.eu/latest-news/keeping-trains-track-and-infrastructure-in-tip-top-condition/

The follow-up programme of Shift2Rail is the EU-Rail JU programme. The EU-Rail database, specifically the Catalogue of Solutions, was also examined. Research topics focused on infrastructure were selected:

- Keeping trains, track, and infrastructure in tip-top condition,
- Making rail transport more sustainable, comfortable, and quieter,
- Optimising the rail track system,
- Ensuring safety, enhancing reliability.

5.2.1 Keeping trains, track, and infrastructure in tip-top condition

Under EU-Rail, new innovations were demonstrated for integrating autonomous systems/machines and worker' physical support (exoskeleton) in railway maintenance, including their Cost-Benefit Analysis and assessments against Key Performance Indicators (KPIs).

Demo: On-Track Autonomous Multipurpose Mobile Manipulator (OTA3M) (TRL 6)

Research plan

The goal was to achieve accurate control of the OTA3M, a robotic version of a human-operated on-track machine (OTM), which can manipulate heavy rail infrastructure components and materials, and has a reach of several metres.

Solution

Enhanced operation of autonomous road-rail excavator, thanks to new software (trajectory scaling algorithms; fast-reacting Inertial Measurement Units; autonomous running modes and safety systems).

Demo: Occupational Back-support Exoskeleton (OBSE) (TRL 6)

Research plan

The prototype fitted with sensors and IoT capabilities, helps workers lift and carry. Musculoskeletal loading is reduced by up to 50%, improved worker productivity and safety.

Solution

Exoskeleton to be worn by railway workers handling heavy tasks, to minimise muscular fatigue and enhance job safety.

Demo: Unmanned Ground Vehicle (UGV) and End Effector (TRL 6/7)

Research plan

Autonomous vehicle equipped with command-and-control system; and a Robotic device that screws and unscrews rail fasteners. Better obstacle detection accuracy and maintenance cycle times; reduced ergonomic risks; produces up to 302.5 sleepers per hour.

Solution

A command-and-control system for unmanned ground vehicles and end effectors, enhancing the efficiency of railway maintenance.

INTELLIGENT ASSET MANAGEMENT

Intelligent Asset Management System (IAMS) is a means to manage, monitor, maintain and optimise the rail assets (from trains to track and all associated infrastructure).

Demo: Italian Urban Metro System IAMS (TRL 6/7)

Solution

The Intelligent Asset Management System (IAMS) can be successfully used in urban areas to facilitate the work of train operators and reduce passenger disruptions.

Demo: Digital Twin for Railway Asset Management: Application to the French and Spanish Railway

Network (TRL 7)

Solution

A digital twin to help asset managers with railway assets management, including renewal of track and catenary components.

Demo: Anomaly Detection for Rail Fastener Systems (TRL 6/7)

Solution

Lindometer (differential Eddy Current sensor) updated to detect anomalies more quickly in rail fasteners.

Demo: Remote Condition Monitoring Maintenance Reduction Interventions and Decisions: In Field Validation (TRL 7/8)

Solution

Automated data collection and intervention in an alarm system on railways, calling on algorithms, to reduce the overall number of unnecessary alarms raised and to facilitate decisions on which assets need maintenance now.

Demo: SMART maintenance on rail freight corridor Rhine-Alpine (TRL 6/7)

Solution

Digital representation of a track (digital twin), to better detect anomalies in the rail surface and track design, as well as a smart maintenance planning tool.

Demo: Integrated Asset Management for Civils – Track (TRL 6/7)

Solution

On-Track Machine Decision-Support Tool to identify the most appropriate maintenance action for track geometry (tamping or stone-blowing) and to prepare priority maintenance plans.

Demo: Integrated Asset Management for Civils – Bridges (TRL 7/8)

Solution

Life Cycle Engineering (LCE) tool to optimise maintenance and replacement planning for urban railway bridges.

Demo: Operational Asset Management in a Dutch environment (TRL 6/7)

Solution

Six modules for acquiring data, data analytics and decision support on carrying out rail network maintenance.

Demo: Track Maintenance Decision Support Tool for a Swedish Heavy Haul Railway Line (TRL 6/7)

Solution

Integrated Maintenance Decision Support Platform (IMDSP) to provide a maintenance schedule for improving the track's performance.

5.2.2 Making rail transport more sustainable, comfortable, and quieter

https://rail-research.europa.eu/latest-news/making-rail-transport-more-sustainable-comfortable-and-quieter/

ENERGY AND SUSTAINABILITY

Energy-efficient solution and future railway system with respect to energy solution

HVAC systems, including innovative systems with heat pumps and natural refrigerants.

Auxiliary power of the train, excluding Heating, Ventilation, and Air Conditioning (HVAC).

Battery-Powered Electrical Multiple Units (BEMU), with reference parameters for trains/ infrastructure.

Generic thermal model of the carriage body, with thermal reference parameters.

Freight trains with updated reference parameters for aerodynamic losses/energy consumption.

Evaluation of energy KPIs (Key Performance Indicators)

Several energy-saving topics investigated in the Shift2Rail programme are being covered in flagship projects (FP) under the EU-Rail Joint Undertaking, with the aim of achieving a higher TRL. These projects explore the energy-saving potential of innovations, through demonstrators in real operation. They include automatic train operation with energy-optimised driving (FP1, FP2 and FP6), a Traffic Management System allowing smoother traffic and fewer unplanned stops (FP1 & FP6), substitution of diesel trains by battery and hydrogen-powered trains (FP4 and FP6), an airless train with airless brakes, suspension, pantograph and doors (FP4), and HVAC solutions with alternative natural refrigerant with higher Coefficient of Performance (FP4).

NOISE AND VIBRATION

Simulation Tool for Vibrations

Solution

Validating the vibration prediction tool's ability to predict vibrations from railway traffic in buildings next to the track.

Software tools for Auralisation and Visualisation (TRL 5)

The goals of the acoustic validation were to ensure the:

- Quality of the A&V system.
- Correctness of the calculated noise environment.
- Feasibility and applicability of the A&V system for the use case communication of mitigation measures (mandatory) and optional for the use case *perception studies* (depending on final realisation in the project).
- A good correlation between the synthetically generated sound and sound recorded and measured in field tests. This also included auditory perception during extensive listening tests with test persons, to ensure that the physics was correlated and the human perception of observers.

5.2.3 Optimising the rail track system

https://rail-research.europa.eu/latest-news/optimising-the-rail-track-system/

Enhanced switch & crossing system demonstrator (TRL 6, 7)

The main objective of the TD is to improve the operational performance of existing S&C designs, delivering new S&C subsystems with enhanced Reliability, Availability, Maintainability and Safety (RAMS), LCC, sensing and monitoring capabilities, self-adjustment, noise and vibration performance, interoperability, and modularity.

Next generation S&C system demonstrator (TRL 4, 5, 6)

The main objective of the TD was to provide radical new S&C system solutions. By embracing new designs that use completely new methods for switching trains between tracks, these S&C system solutions aim to drastically improve capacity and performance and reduce costs, all while maintaining safety as an overriding factor.

Optimised track system technical demonstrator (TRL 6, 7)

With the goal of improving the operational performance of existing track systems, the optimised track system TD aimed to fundamentally challenge track construction assumptions that are implicit in current European track design.

The TD explored how new construction designs can make use of modern materials to provide high levels of sustainability, capacity, and LLC savings relative to existing construction types. In addition to investigating innovative products, processes, procedures, and construction methods, the TD also looked at ways to renew existing track assets.

Next generation track system technical demonstrator (TRL 4 – 7)

Like the optimised track system TD, the next generation track system TD identified and evaluated innovative track solutions. However, unlike the optimised track system TD, the solutions developed in this TD have a targeted horizon of around 40 years beyond the current state-of-the-art.

Thus, instead of prioritising harmonisation with today's railway system, this TD prioritised step changes in performance. This allowed the TD to focus on providing key railway functionality without being restricted to current practices.

5.2.4 Ensuring safety, enhancing reliability

https://rail-research.europa.eu/latest-news/ensuring-safety-enhancing-reliability/

Safety starts with assessing the risks (TRL 3)

- The developed safety risk management model is based on a risk assessment method and uses a decision support tool.
- Risk Assessment: The JU's developed method focusses on the human centric aspects of safety and includes system functionalities to create scenarios as close to reality as possible. The method uses a decision model to identify the main parameters, which can then be applied to optimise safety, functionalities (e.g. availability, capacity), and system costs.
- Decision support tool: By identifying risks and taking a holistic view, the developed decision support tool allows decision makers to quickly react to a safety situation. The parametric approach can be generalised and applied to a wide range of decisions across the entire railway system – meaning both the design and operation of a system can be adapted to the risk assessment. The tool can also combine safety with costs and/or the level of service provided, meaning users can optimise cost efficiency without sacrificing safety.

Smart planning at the crossroads of safety and reliability (TRL 3)

- Optimised network and traffic management contribute to increasing the safety, reliability, and performance of the European railway system.
- PROTON (*Punctuality and Railway Operation Simulation*) is a simulation tool designed to improve the planning quality of timetables.
- The simulation model is particularly well-positioned to reduce delays caused by secondary sources or planning management.
- Further improvements to the simulation model could be made by including dispatching decisions (if resources are not available at the planned departure time). PROTON's scope could also be extended by writing interfaces to other data formats and tools. Furthermore, by specifying an integration layer, the model's infrastructure information could be translated into an internal data format.

Integrated mobility management (TRL 3)

- Integrated Mobility Management (I2M) is a key solution for rail traffic management and has the potential to increase:
  - Operational reliability in freight,
  - Operational performance for passenger services,
  - Efficiency of rail freight operations,
  - Efficiency of passenger-focused operations,
- With the aim of leveraging I2M's full potential within rail, EU-Rail developed a portfolio of prototypes, each using the TMS to support high efficiency freight operation:
  - Dangerous goods management application,
  - ATO-application for freight trains,
  - Functions to support better management of freight operations,
  - Conflict detection and resolution,
  - Driver advisory functionality,
  - Design concepts for annual and ad-hoc timetable planning,
  - Automatic router adaptations related to providing automatic routing for manoeuvres

at stations/depots,
- Freight functionalities and resource mapping for management of dangerous goods integrated into freight operations.

Advanced business services

EU-Rail also developed an advanced business services (ABS) concept to increase the efficiency of passenger-focused operations.

5.3 Key Outcomes from S2R and ERJU review

The review of the previous S2R and ongoing ERJU project shows significant research activity from European project work in infrastructure, rolling stock, and operational contexts. The innovations pillars from S2R focus on five topics: Cost efficiency and System reliability of rolling stock, Advanced Traffic management and control, Cost Efficiency and sustainable and reliable infrastructure, IT solution for railway services, and technologies for sustainable and attractive freight. These topics were covered across many subtasks, resulting in the development of subsequent projects with multiple continuations for the topics.

In the ERJU, the objectives of the innovation pillars have continued, however the ERJU innovation pillars have more focused goals. The ERJU innovation pillars include (1) European rail traffic management and supporting rail's key role in a multimodal transport system, (2) Digital and Automated Train Operations, (3) Sustainable and Digital Assets, (4) Competitive Digital Green Rail Freight, (5) Smart Solutions for Low Density Traffic Lines (cost-efficient regional railways), (6)Transversal topics: data and digital enablers and (7) Exploratory research and paradigm shifts.

It is noted that in the ERJU there is a new focus on exploratory research areas, which is used to direct research activities towards areas of emerging research interest. These exploratory areas, include work in infrastructure interoperability (InBridge4EU), Stations as a sustainable city provider (RAIL4CITIES), web-based services and the development of web-based platforms (EEP4FREIGHT), raw materials and the assessment of sufficiency for ERJU Projects (LEADER2030), the DAC delivery program (DACcord), and the creation of the community of rail researchers and academics (Academics4Rail). These topics are associated with the innovation pillars from the ERJU however the focus of these projects is towards a targeted solution or outcome. Although these topics are derived from the ERJU MAWP there has been limited assessment of the alignment of these activities with the broader rail research community and in particular understanding whether these are the appropriate for the current rail research directions.

6 Alignment of Research to European Research Goals

One aim of this position paper is to identify the research gaps in the European railway sector and how the research priorities of the academic community align with the broader European railway ecosystem. In the previous section, Shift2Rail and Europe's Rail Joint Undertakings were analyzed to understand the current state of research, based on top-down research objectives outlined by these joint undertakings.

In parallel, there are also goals and objectives outlined by other bodies in the European railway ecosystem, including regulatory and advisory bodies like the UIC, industrial representative bodies like UNIFE, and broader EU directives like STRIA. These bodies outline goals and strategies for the railway and the broader transportation sector where there is significant overlap between these goals and the research interests of the railway sector. As these bodies have significant interest in railway research, it is important for the academic community to (1) systematically survey the current goals and objective of the railway industry, (2) identify the gaps these goals, (3) provide recommendations on the rail research priorities.

To understand the opinion of the current broader research and innovation priorities from the academic community perspectives, two surveys were performed in Fall of 2024. The first survey reviews the UIC 12 Capabilities, published in 2017 [2]. The second survey reviews the UIC Future Research Areas, which is a working document with pending approval in March 2025. These documents are the basis for the research and innovation goals in the railway sector therefore there is a need to understand the alignment between these stated goals and the research and development activities and perspectives from the academic community.

6.1 UIC 12 Capabilities Brainstorming Workshop Summary (Qualitative Analysis)

In collaboration with partners at the EURNEX, a brainstorming session was held at the 2024 Ac4R annual meeting. The meeting was held in Bilbao, ES, on 17 September 2024. The goal of the brainstorming session is to assess the UIC 12 Capabilities [2] and identify the gaps based on discussion within the academic community. The discussion was conducted in groups of 5-10 individuals, and each group was free to choose which of the 12 Capabilities based on their expertise and relevance to their field of research. In these groups, the discussions were recorded on slides to collate the results or further analysis.

6.1.1 Assessment format

To guide the discussion, the following questions were formulated and presented to the discussion members. These questions were presented for each of the UIC 12 Capabilities.

Question 1: What is the Current State of Art Developed by S2R/ Past EU Projects?

Question 2: What are the Results/ Benefits achieved by ERJU?

Question 3: Are there Gaps/ Future Opportunities after ERJU?

Question 4: Are there relevant National/Regional Research outside of EU Projects related to this topic?

From the discussion for the academic partners, the following conclusions and research gaps were identified.

6.1.2 Capabilities 1: Automated Train Operations

Automated Train Operation refers to the method of operating trains automatically where the driver is not required or required for supervision for most train duties. The participants noted that mid TRL goals were achieved, particularly in Automatic train operation (ATO) and intelligent trains systems. The participants also note that the ongoing ATO research topics, transferred from the from S2R to the ERJU projects, indicate a continued desire from both the academic, regulatory, and industrial partners.

Identified Gaps: No Gaps were explicitly identified by the participants.

6.1.3 Capabilities 2: Mobility as a Service

Mobility as a service refers to the development of a customer-oriented rail system where services are tailored to the individual needs. The UIC notes that two choke points are found (1) the connection between different transport nodes and (2) the efficient and user specific information dissemination. From the discussion, the participants find that limited research at the academic level is performed in this area for both passenger and freight services.

Identified Gaps: Creation of a single platform for passenger travel bookings and the creation of tools for freight operators to identify the demand within the system. It is also noted that mobility as a service is primarily focused on passenger transport, with limited development in freight operation.

6.1.4 Capabilities 3: Logistics on Demand

Logistics on demand refers to the development of customer-driven freight alternatives. The survey shows that significant research was completed across a variety of European projects, including transversal research from S2R and Horizon 2020. The survey participants have identified research projects in ESEP4Freight (S2R), SYNCHRO-NET (H2020), and AUTOMOTIF (CINEA) that have worked towards these goals.

Identified Gaps: There is a need for improved user experience and user organization, where there are increased channels between customers and freight transportation providers. There is also an identified gap in staff training.

6.1.5 Capabilities 4: More Value from Data

For data values, the survey participants note that there is ongoing research using data for safety and security protection, including the SAFETY4RAILS project, which was part of Horizon 2020. Within this project both cyber safety and cyber-physical safety are assessed. Current research focuses on artificial intelligence (AI) and Data driven operations and maintenance. For AI. it is primarily through the RAILS project, which was funded by S2R, which shows the potential of AI. in the railway sector, with the focus on proof of concepts for signaling, operational intelligence, and network management. For data driven operations and maintenance, the work has been driven by the IN2DREAMS projects which aimed to use energy and asset data or support asset management and prescriptive maintenance procedures.

Identified Gaps: Data security, Cyberattacks, Use of AI in real environments, and user-oriented software for data accessibility.

6.1.6 Capabilities 5: Optimum Energy Usage

Optimum energy usage includes the development of low energy solutions for the railway system, in both design and operational contexts. Previous work has developed solutions for alternative energy drive systems, including the Hydrogen gas station project: FutuReFP4 and FCH2RAIL: Hydrogen train successfully tested in Portugal. Regional projects have also integrated Automatic Driving systems to support energy efficiency.

Identified Gaps: Migration plans for standardized electrical grids in Europe, aerodynamic optimization of freight wagons for energy savings, and the further development of the railway electrical substations to both give and accept energy (bidirectional substations from regenerative braking).

6.1.7 Capabilities 6: Service timed down to the second

To meet service down to a second, this requires situational awareness, and knowledge of each train's location and speed in real time. This results in enhanced service frequency and service flexibility based on vehicle location. The primary focus of this work has been in parallel with Capability 4, where the vehicle data is leveraged to better position the location of the trains. Virtual Train Coupling (VTC) has significant advancements, with current Ac4Rail Projects focused on developing solutions for radio communication between trains.

Identified Gaps: Self-healing of the railway system, particularly after service disruptions.

6.1.8 Capabilities 7: Low-Cost Railways

Newer models are required to deliver efficient and affordable infrastructure, rolling stock, and operations to service areas with lower demand. There is a need to create lower cost solutions to revitalize the rural economy with explicit calls for shared solutions with other modes of transport. The participants find that there has been significant, ongoing research in this field including the Low-cost electrification (NetiRail) and the ERJU Future flagship area which focuses on the development of total solutions for low cost, efficient vehicles. It is noted that RSSB in the UK has extensively investigated capillary line access and the revitalization of regional efforts.

Identified Gaps: Participants note that analysis of schedules and socio-economic conditions of areas needs to be performed to select the necessary railway lines. Likewise, there is a need for data driven cost analysis to understand the prioritization of the solution to best meet the needs of the area of interest. Lower TRL research (in all areas) in topics outside of the research completed in S2R and ERJU (wheel-rail contact efficiency, innovative manufacturing and design, predictive maintenance) needs to be performed so that ongoing innovative solutions can be created to meet a greater demand.

6.1.9 Capabilities 8: Guaranteed Asset Health and Availability

Optimized maintenance leads to a more efficient railway system, where disruptions are minimized, and the asset health is actively managed. The optimized maintenance is monitored using an array of sensors connected through IoT with the further goals of using AI for decision support. The participants identify ongoing research in this field, in particular the ERJU IAM4RAIL flagship area which addresses these research and innovation challenges.

Identified Gaps: Cybersecurity and IoT devices need detailed assessment. The use of AI for decision support needs further field studies and in-situ results. Data sharing guidelines between academic and maintenance providers needs further discussion to aid in the validation of solutions created from academic research.

6.1.10 Capabilities 9: Intelligent Trains

Intelligent trains refer to trains that are self-managing, aware of the surrounding and passenger loads and able to adjust the journey to meet passenger demands. This concept builds on the *Digital Twins* of trains and allows for the autonomy between trains and decision making by the trains, based on the condition of the vehicle and system. The participants notes that there is pre-existing work in this area, particularly the development ERTMS Level 3 for autonomous driving, the integration of GNSS for train positioning, and the remote condition monitoring for vehicle health monitoring from maintenance centers.

Identified Gaps: The interactions between Humans- Trains, with a focus on accessibility for all users and all abilities. This interaction extends with the design to ensure that there is appropriate human interaction of safety critical systems and unexpected situations. Global connectivity and the application of these systems across networks outside Europe also prove challenging, with a focus on standards and norms.

6.1.11 Capabilities 10: Stations and smart city mobility

Stations should act as a transportation hub, where multi-modes of transportation can seamlessly interact and interchange. The design of the infrastructure should provide easy access for passengers and platform and flow management systems can be used to guide passengers safely to their destinations. The participant notes previous work in the S2R projects: FAIRSTATIONS and IN2STEMPO which explored safety and energy solutions for stations.

Identified Gaps: Participants note that there is limited continuing research in the ERJU flagship areas in stations and smart city mobility. There are gaps in information accessibility for all users. Likewise, physical barriers are still challenging for stations when switching between different modes of transport. Energy efficiency of stations has also not been strongly explored; how alternative energy systems should be integrated into the station infrastructure.

6.1.12 Capabilities 11: Environmental and Social Sustainability

Railways provide energy efficient means to transport goods and people. As rail makes an increasing contribution to the transportation mix, the system must provide efficient service with low carbon footprint and circular economy principles to reduce waste. It is noted that there is an ongoing need to reduce noise pollution and particle emissions. The participants have identified significant research from European projects. ERJU FA4 RAIL4EARTH, ERJU FA6 FUTURE, which focuses on emissions, hydrogen adaptation of vehicles, and optimize energy efficiency of vehicles. ResCOM from the European commission has dedicated studies for resource conservative manufacturing in the railway sector. Circularity has been studied at multiple levels including at the EU commission [3] and in the design of the new HS2 line in the UK. For carbon neutrality, there have been many local efforts including the 2025 carbon neutrality for the Copenhagen City Ringen.

Identified Gaps: Despite the major advances and contributions in this field across a variety of sectors, many research projects are in the prototype phase. To ensure the delivery of these solutions, there should be focused on how each solution can be evaluated and integrated into the railway system. Likewise, as climate change impacts become more localized and severe, there is a need for flexible solutions that can be used in different contexts and the rapid delivery of solutions in vulnerable areas.

6.1.13 Capabilities 12: Rapid and Reliable R&D Delivery

The Research and development ecosystem needs to be supported with a focus on technology demonstration and rapid integration of these technologies into the railway sector. A focus should include the development of centers of excellence in specific research areas, where technologies are researched across various technology levels. Likewise testing should integrate both in-situ and virtual testing techniques to ensure that there are multiple methods to test and deploy innovative solutions. The participants note that these goals are supported by ERJU projects, in particular the Academics4Rail projects and the 10 PhD projects which support the leading-edge research in railways research. It is also noted that virtual testing has been supported in ERJU IAM4Rail.

<u>Identified Gaps:</u> They exist in railway training and skills, where there is a skills gap in the railway industry for new talent combined with limited opportunities for doctoral level railway researchers to transfer and implement knowledge on an industrial basis. The participants also note that there is still limited collaboration between industrial partners and academic partners, particularly in the sharing of relevant data which can be used to validate research findings. Physical testbeds are also limited to larger organizations, therefore there is a call for open test beds and research *sandboxes*, where researchers can openly collaborate.

6.1.14 Conclusions from UIC 12 Capabilities Assessment

From the discussion and collaborative brainstorming on UIC 12 Capabilities, the following conclusions can be expressed.

There is a significant overlap between the UIC 12 Capabilities and academic research activity across different European projects and regions. The participants were able to identify S2R and ERJU projects for all the UIC 12 Capabilities. This indicates strong alignment between the current European Level research and development activities and the broader railway sector. This also indicates that the UIC 12 Capabilities remain a viable reference document for current and short-term research initiatives in Europe.

Participants noted that emerging technologies including Hyperloop, Maglev derived technologies, advanced contact modelling, and AI which are currently being explored in the ERJU are not addressed by the 12 Capabilities. These projects have significant research and development activity in other regions (Asia Pacific) and thus pose a possible strategic gap in the 12 Capabilities

The UIC 12 Capabilities were interpreted as focused on implementation of solutions and higher TRL projects. The results from fundamental, early-stage railway research, including the 10 PhD projects supported by ERJU Academics4Rails are not clearly mapped in the UIC 12 Capabilities. This creates a potential **research topic gap** and an increased likelihood that these topics are not acknowledged or continued by the wider railway sector.

Most respondents note that there is limited clarity on the next steps following the ERJU and how the current projects can continue to progress in TRL, which increased from S2R to ERJU, resulting in limited opportunities for academic research, and in particular fundamental research to play a significant role in future railway development and innovation. Historically strong collaboration between the academic community and the industrial partners has led to a robust railway sector. However, due to the segmentation of the railway sector and the privatization of railways there is a potential for a **long-term strategic gap** in the railway sector in the development of fundamental railway research and innovations.

6.2 UIC Future Capabilities Assessment

The UIC is in the discovery phase for the next set of railways capabilities. These new goals, known as the *UIC Future Research Areas,* are anticipated to expand the scope of the 12 Capabilities and ensure that they are relevant based on trends that are expected to influence the European railway sector. The Ac4R project was invited to observe these activities and provide feedback on the draft capabilities, listed in Table 15.

Table 15: UIC Future Research Areas

Assets for Automatic and Autonomous Operation	Early Disaster Warning Systems
Railways Digital Twin, Simulation and Virtualization	Pandemic
Smart Asset management	Enhancement of Reliance of Railway Infrastructure
Smart integration for Door-to-Door (D2D) Mobility	Development of new generations of propulsion systems for trains (BEMU, HEMU)
Multi-mobility System for Pods	Development of new solutions for energy conservation (onboard trains and in substations)
Environmentally Friendly and Attractive Sustainable Mobility	Development of safety/security standards and risk assessment techniques to manage risk associated with adoption of AI solutions
Green Freight Logistic Chain (Note that only data from the second question was accessed)	Enhancement of cybersecurity of IT and OT systems
Network Management Planning and Control	Development of new solutions protecting railway infrastructure and rolling stock against vandalism and theft

The feedback from the academic community was gathered through an online survey which was shared in Fall 2024. The survey was comprised of the following questions.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement: HORIZON-ER-JU-2022-ExpIR-04

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

<u>Question 1:</u> Which of the following fields will remain the focus of your Research and Development activities within the next 5 years or longer? Please indicate the priority: Level 1: Top Priority, Level 2: Important to catch up near future trends, and Level 3: Important to gain fundamental knowledge.

An example of the survey is shown below in Figure 15. In the response, multiple levels can be selected for each research priority.

Which of the following fields will remain the focus of your Research and Development activities within the next 5 years or longer? Please indicate the priority

Please select the level for the described research priority

	Level 1 Top Priority	Level 2 Important to catch up near future trends	Level 3 Important to gain fundamental knowledge
Assets for Automatic & Autonomous Operation	☐	☑	☐
Railways Digital Twin, Simulation & Virtualization	☐	☑	☐
Smart Asset Management	☐	☑	☐
Smart Integration for Door to Door (D2D) Mobility	☐	☑	☐

Figure 15: Question 1 on the Future Research Capabilities

<u>Question 2:</u> Briefly describe what kind of research activities will be held in these research fields, which remain in the focus of your R&D plan?

Please classify the research according to the following:

<u>Type of Work</u>

- FRA - Fundamental research activities are focused on obtaining new knowledge, without having in mind new possibilities for applications.
- ARA - Applied research activities are focused on obtaining new knowledge, having in mind new applications.
- ED - Experimental development is the testing phase of development and it aims at achieving new or improved products, services or processes in a systematic way.

<u>Research Area</u>

- I - Infrastructure
- P - Rolling Stock Passenger
- F - Rolling Stock Freight

Please select the level for the described research priority.

An example of the survey is shown below in Figure 16. In the response, Multiple types of work and multiple research areas can be selected. Under the research priority, the text box allows the survey participant to add additional comments for clarification.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement: HORIZON-ER-JU-2022-ExplR-04

	Research Priority	Type of Work	Research Area
1	Assets for Automatic & Autonomous Operation	Type of Work FRA - Fundamental research activities are focused on obtaining new knowledge, without having in mind new possibilities for applications. ARA - Applied research activities are focused on obtaining new knowledge, having in mind new applications. ED - Experimental development is the testing phase of development and it aims at achieving new or improved products, services or processes in a systematic way. ☐ FRA ☐ ARA ☐ ED	Research Area I - Infrastructure P - Rolling Stock Passenger F - Rolling Stock Freight ☐ I ☐ P ☐ F

Figure 16: Question 2 on the Future Research Fields

The survey was sent to the Academics4Rails participants. 20 responses were recorded. Each subsection summarizes the results from each Future Research Field.

6.2.1 Future Research Field 1: Assets for Automatic and Autonomous Operation

The summary of the responses to the questions for the Future Research Field 1 is shown in Figure 17.

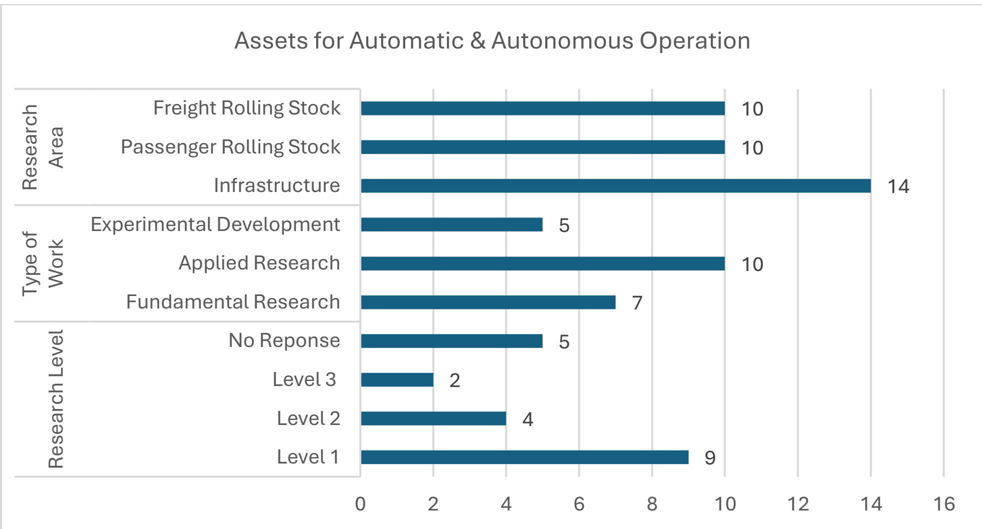

Figure 17: Future Research Field 1: Collected Responses (*N*=20)

The results show a strong emphasis on infrastructure, which may reflect its critical role in enabling autonomous operations. There is balance between applied, experimental, and fundamental activities indicating comprehensive research approaches. Level 1 is the most common level, indicating a strong research priority in this field, however the decreasing response with increasing research level indicates lower priority on fundamental research.

6.2.2 Future Research Field 2: Railways Digital Twin, Simulation and Virtualization

The summary of the responses to the questions for the Future Research Field 2 is shown in Figure 18.

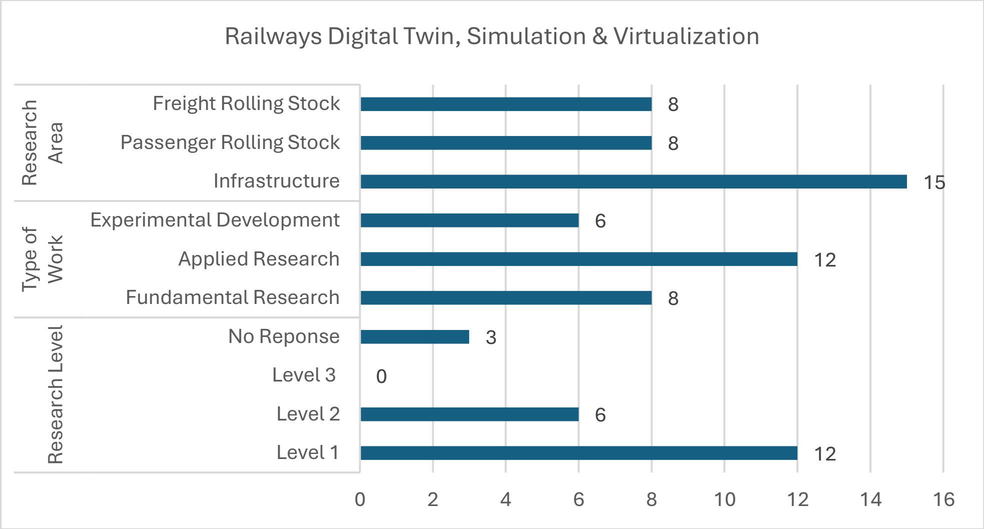

Figure 18: Future Research Field 2: Collected Responses (*N*=20)

The survey shows that the ongoing research in this area is focused on primary research (Level 1), with future research focusing on applied research and infrastructure-related projects. The results show a strong emphasis on infrastructure, which may reflect its critical role in enabling autonomous operations. It is noted that applied research is the primary type of work indicating a strong focus towards development and implementation with digital twins' tools. Level 1 is the most common research level, indicating a high research priority in this field. However, the decreasing response with increasing research level indicates lower priority on fundamental research.

6.2.3 Future Research Field 3: Smart Asset Management

The summary of the responses to the questions for the Future Research Field 3 is shown in Figure 19.

The survey shows that the Smart asset management remains a top priority for research, with balanced work in all types of research (experimental, applied and Fundamental). Research is primarily focused on infrastructure related projects. This research level is concentrated at level 1, which indicates that this research area is top priority with limited current fundamental research in this field.

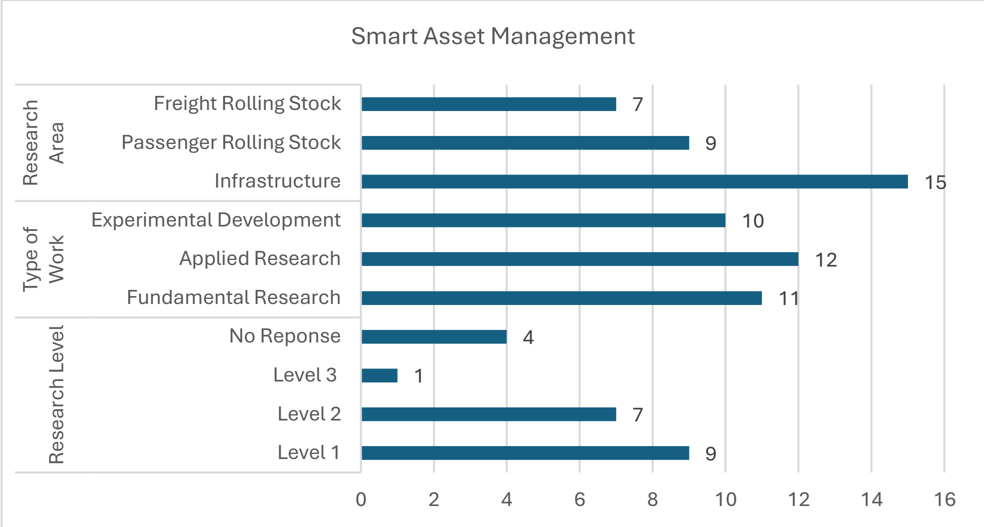

Figure 19: Future Research Field 3: Collected Responses (*N*=20)

6.2.4 Future Research Field 4: Smart integration for Door-to-Door (D2D) Mobility

The summary of the responses to the questions for the Future Research Field 4 is shown in Figure 20.

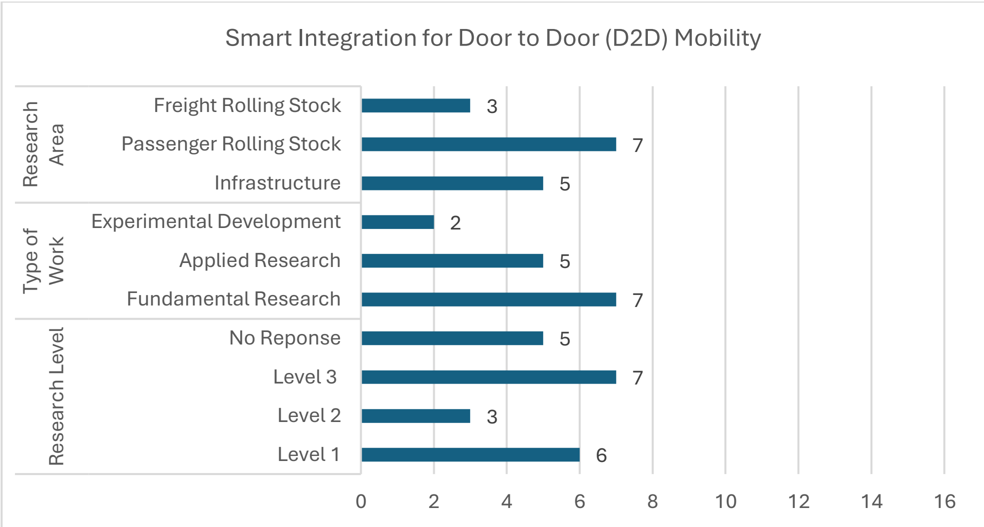

Figure 20: Future Research Field 4: Collected Responses (*N*=20)

The survey shows that there is a lower overall response to this question. Ongoing research in this area is mixed with focus on both level 1 and 3 research which indicates that both high priority and fundamental research needs are balanced for this field. Future research focuses on all types of research (experimental, applied and Fundamental) and passenger rolling stock related projects. It is noted that the respondents identify that this area of research is primarily in passenger rail.

6.2.5 Future Research Field 5: Multi-mobility System for Pods

The summary of the responses to the questions for the Future Research Field 5 is shown in Figure 21.

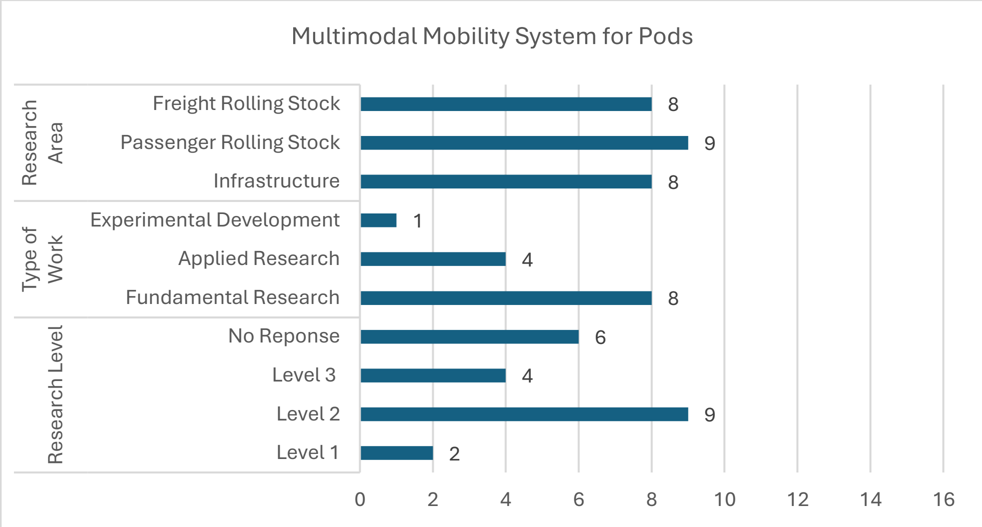

Figure 21: Future Research Field 5: Collected Responses (*N*=20)

The results show that the research priority in this field is focuses on level 2 research, or the focus on catching up with future trends. This indicates a mid-level priority for this research. It is noted that the respondents find that the type of research in this field will include fundamental research balanced across all research areas. Thus, this indicates that there is likely a significant impact for the entire railway sector as this research area progresses.

6.2.6 Future Research Field 6: Environmentally Friendly and Attractive Sustainable Mobility

The summary of the responses to the questions for the Future Research Field 6 is shown in Figure 22.

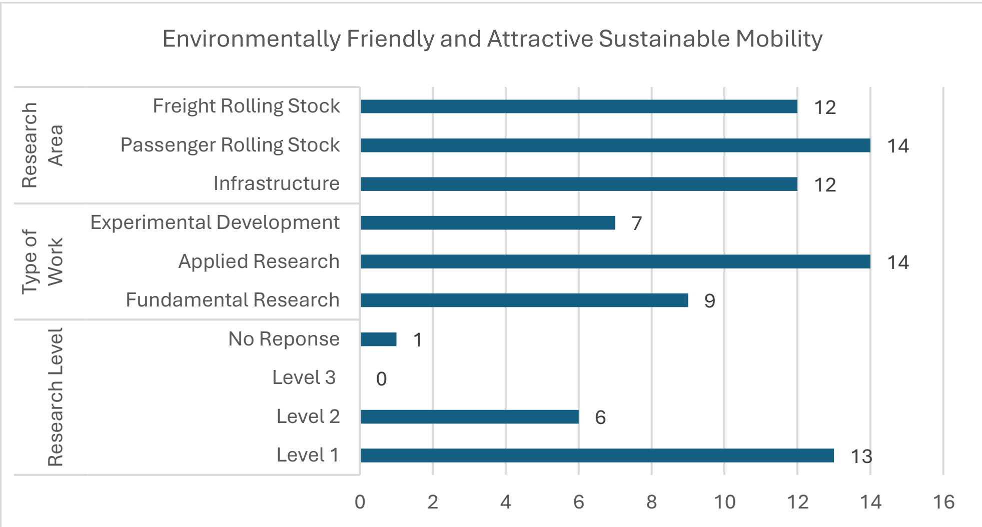

Figure 22: Future Research Field 6: Collected Responses (*N*=20)

The survey shows high current, top level research in this field, as indicated by the high amount of level 1, top priority type research. Future research focuses on all types of research (experimental, applied and Fundamental) and for all types of projects (infrastructure and rolling stock). This indicates that there is significant interest and activity in this research field with a high potential impact on developed solutions to expand environmental friendliness and sustainability mobility across the sector

6.2.7 Future Research Field 7: Green Freight Logistic Chain

The summary of the responses to the questions for the Future Research Field 6 is shown in Figure 8. Note that due to errors in the data collected, only data from the second question was accessible.

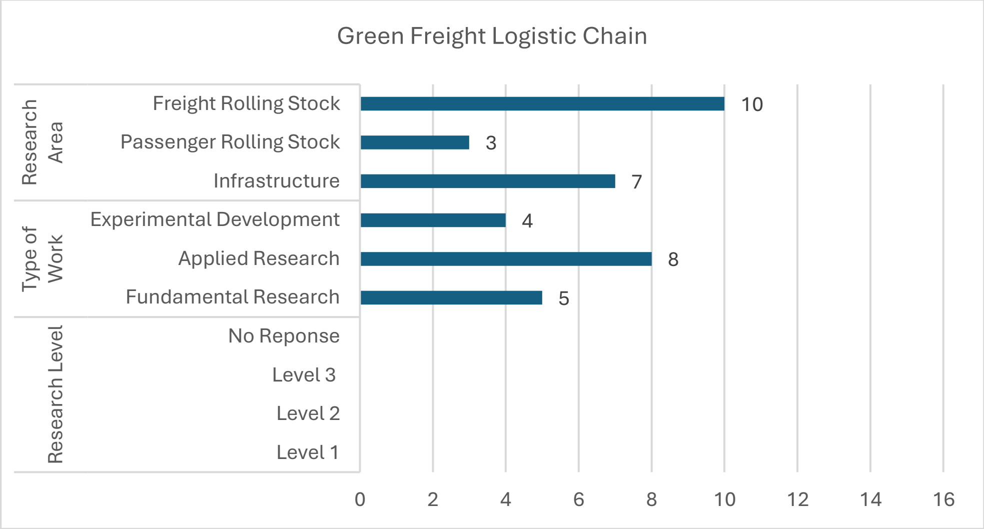

Figure 23: Future Research Field 7: Collected Responses (*N*=20)

The future research in this field includes applied research, with goals for new applications, with a particular focus on fright rolling stock and infrastructure types of research. It is noted that this research is primarily in the fright rolling stock area combined with applied development, indicating that this research is primarily focused on innovation and development projects in this field, with a specific and defined focus.

6.2.8 Future Research Field 8: Network Management Planning and Control

The summary of the responses to the questions for the Future Research Field 8 is shown in Figure 24.

The survey responses show mixed levels for research priority for the given topic, with research priority at all three levels. Similarly, the type of research activity in each field is equally distributed, where there is research in experimental, applied, and fundamental work types. It is noted that for this research, the respondents foresee most of the research focused on infrastructure/ operational contexts which aligns with the description of this research field.

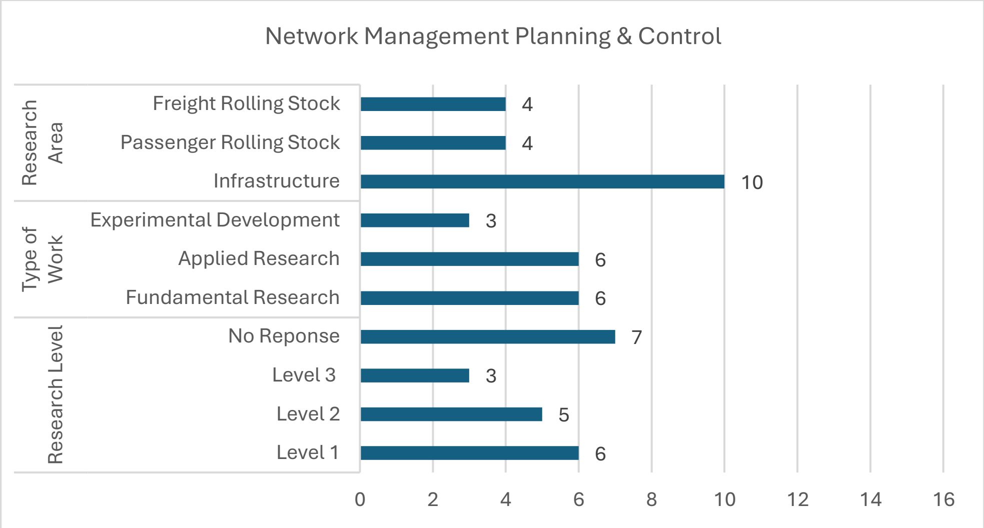

Figure 24: Future Research Field 8: Collected Responses (*N*=20)

6.2.9 Future Research Field 9: Early disaster warning systems

The summary of the responses to the questions for the Future Research Field 9 is shown in Figure 25.

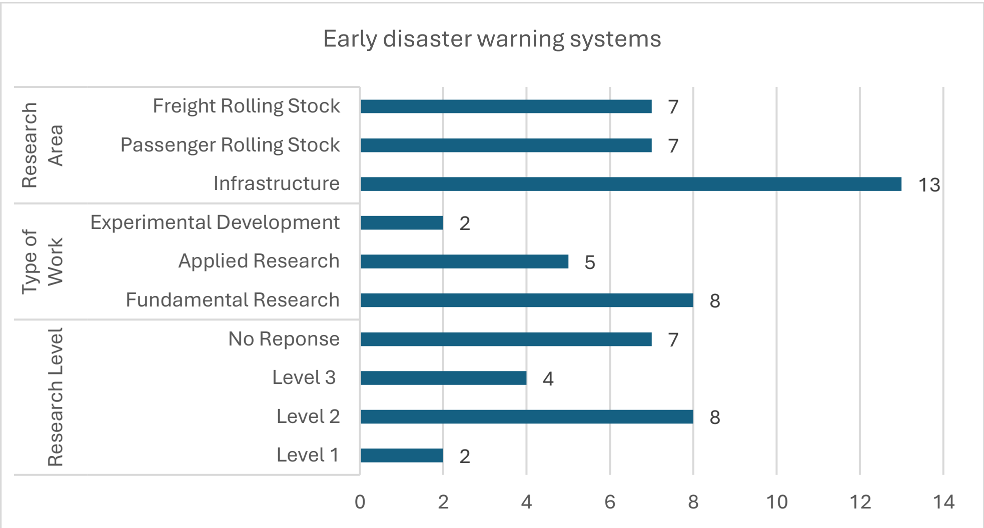

Figure 25: Future Research Field 9: Collected Responses (*N*=20)

The survey responses show mixed levels for research priority for the given topic, with a strong research priority at level 2, indicating the need to catch up with research trends. Similarly, the type of research activity is strongly skewed towards fundamental research. It is noted that for this research, the respondents foresee most of the research primarily focused on infrastructure/ operational contexts, with secondary research in rolling stock contexts. These results indicate that this is an emerging research field, with some preexisting fundamental work that likely needs support towards future research needs.

6.2.10 Future Research Field 10: Pandemic

The summary of the responses to the questions for the Future Research Field 10 is shown in Figure 26.

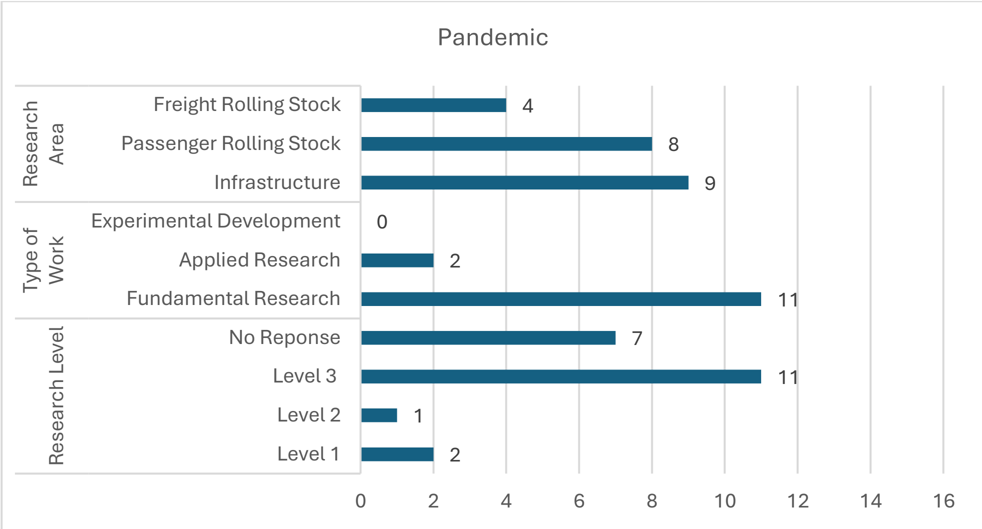

Figure 26: Future Research Field 10: Collected Responses (*N*=20)

The results show that the primary level of research is in level 3, which corresponds with fundamental knowledge. It is also noted that most of the research is related to fundamental research. For the types of research, it is interesting to note that there are research activities in both passenger and infrastructure contexts.

6.2.11 Future Research Field 11: Enhancement of resilience of railway infrastructure

The summary of the responses to the questions for the Future Research Field 11 is shown in Figure 27.

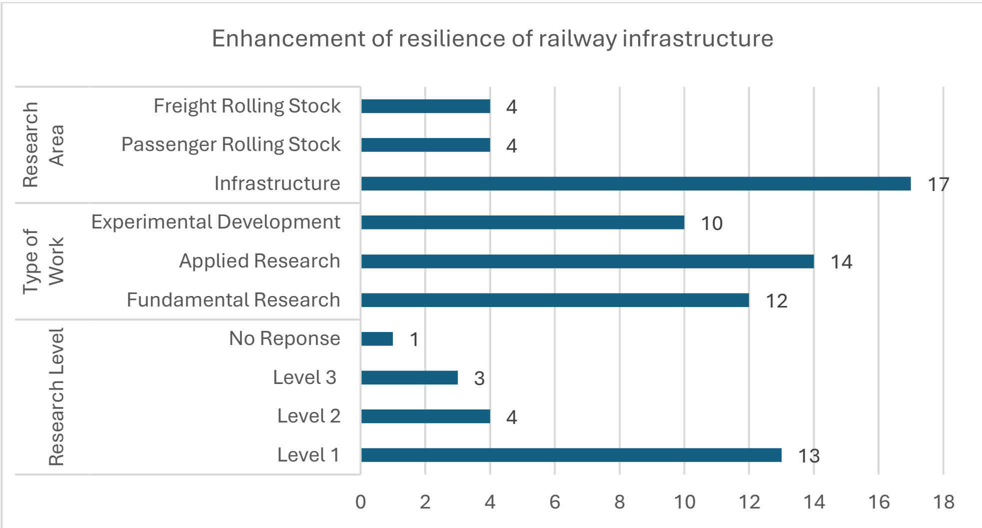

Figure 27: Future Research Field 11: Collected Responses (*N*=20)

The survey responses shows that this research field is Top priority for the respondents. It is noted that the research areas are strongly focused on infrastructure, which aligns with the overall research description for this field. The types of work identified by the survey respondents span all types of work with many responses for each type of work, indicating high levels of current and future research activity in this field.

6.2.12 Future Research Field 12: Development of new generations of propulsion systems for trains (BEMU, HEMU)

The summary of the responses to the questions for the Future Research Field 12 is shown in Figure 28.

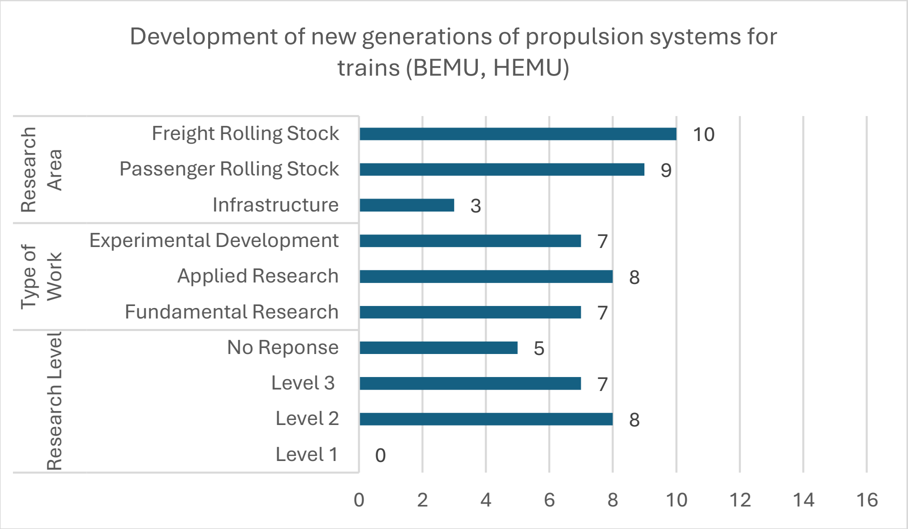

Figure 28: Future Research Field 12: Collected Responses (*N*=20)

The survey results show that the level for this topic is primarily in 2 and 3, indicating catching near future trends and the fundamental knowledge. The respondents have shown moderate research work across all work types with the research area, however there is a strong focus on rolling stock areas (passenger and freight) areas. This response indicates that there is low priority current priority in this field but significant potential research to catch up with trends and fundamental types of research activities.

6.2.13 Future Research Field 13: Development of new solutions for energy conservation (on board of trains and in substations)

The summary of the responses to the questions for the Future Research Field 13 is shown in Figure 29.

The survey results show that the level for this topic is primarily in 1 and 3, indicating research is considered a top priority with an emphasis on fundamental knowledge. The respondents indicate moderate research work across all work types with the research areas focused on both rolling stock and infrastructure.

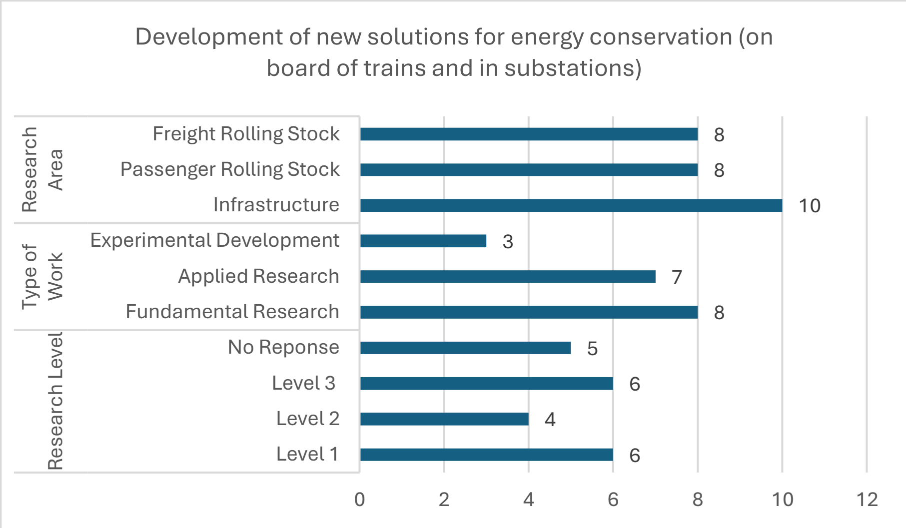

Figure 29: Future Research Field 13: Collected Responses (*N*=20)

6.2.14 Future Research Field 14: Development of safety/security standards and risk assessment techniques to manage risk associated with adoption of AI solutions

The summary of the responses to the questions for the Future Research Field 14 is shown in Figure 30.

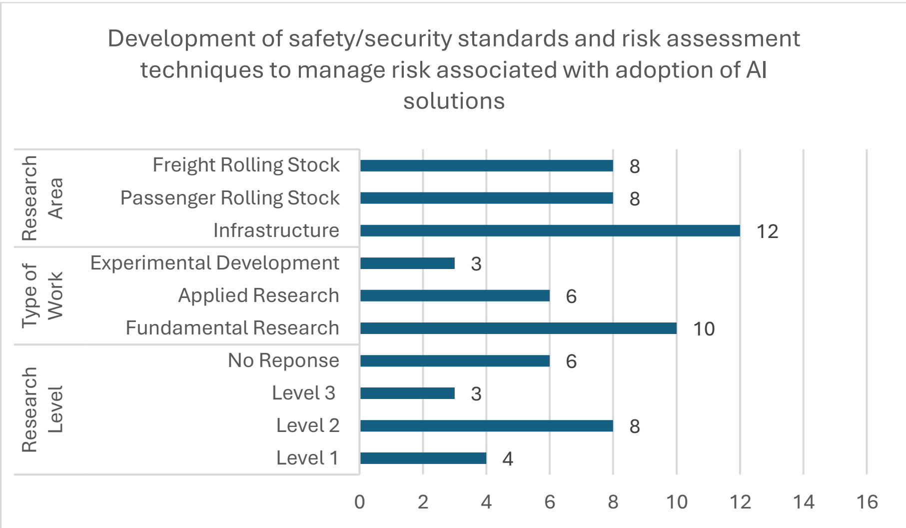

Figure 30: Future Research Field 14: Collected Responses (*N*=20)

The survey results show that the level for this topic is primarily in level 2, indicating the need to catch near future trends. Respondents have shown that the type of work remains in fundamental research in the area, for rolling stock and infrastructure areas. The larger number of responses in fundamental research coupled with the larger number of research areas indicates potentially high near-term research activity.

6.2.15 Future Research Field 15: Enhancement of cybersecurity of IT and OT systems

The summary of the responses to the questions for the Future Research Field 15 is shown in Figure 31.

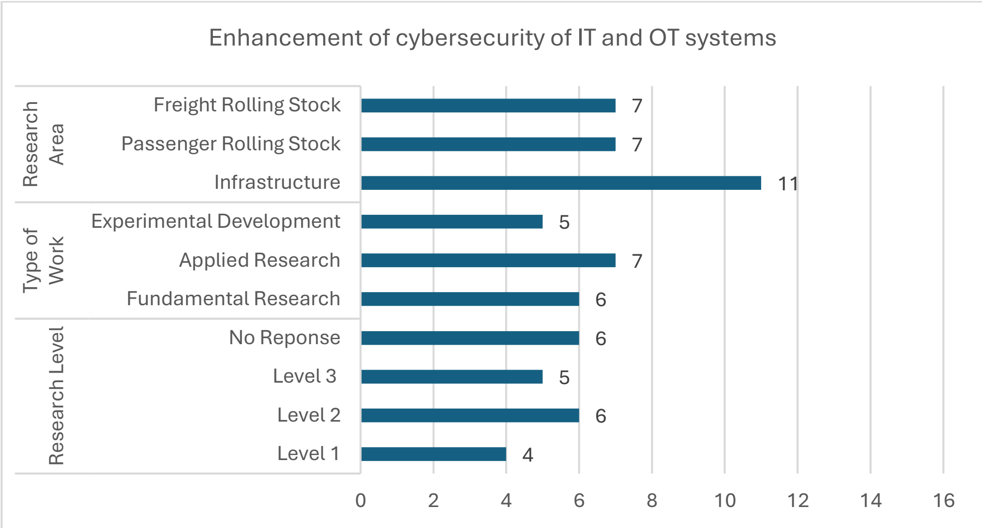

Figure 31: Future Research Field 15: Collected Responses (*N*=20)

The survey results show that the level for this topic is at all research levels, with no clear priority for the types of research. There is a trend towards research in the infrastructure areas. It is noted that AI will be further discussed in 7: Analysis of the results and deliverables produced by the RAILS project of this report.

6.2.16 Future Research Field 16: Development of new solutions protecting railway infrastructure and rolling stock against vandalism and theft

The summary of the responses to the questions for the Future Research Field 15 is shown in Figure 32.

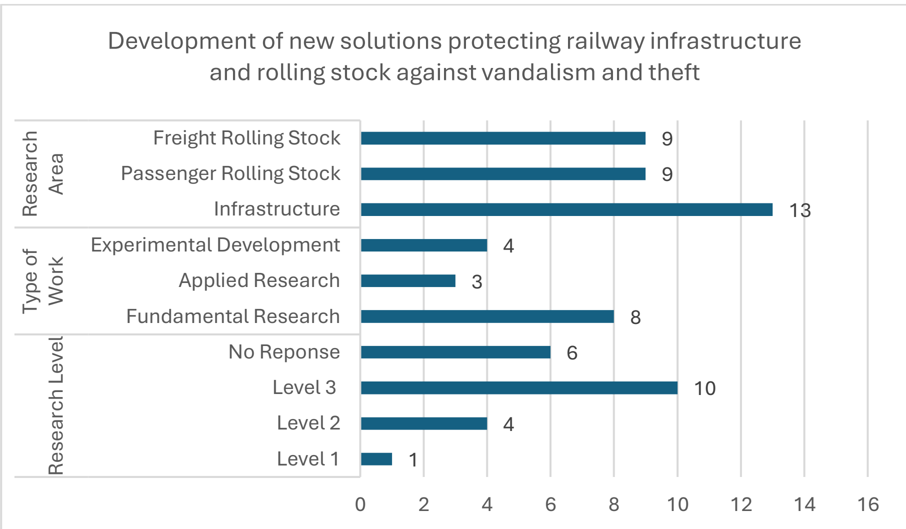

Figure 32: Future Research Field 16: Collected Responses (*N*=20)

The survey results show that the level for this topic is primarily in level 3, indicating the need for research in gaining fundamental knowledge. The survey results show that the research will primarily be focused on the context of infrastructure.

6.2.17 Other Future Research Fields

In the survey, participants were provided with the opportunity to indicate topics outside of the Future Research Areas and indicate priority. The results are presented below in Table 16.

Table 16: Future Research Field 16: Open Responses

Comment Topics		Research Priority			Type of Work			Research Area		
		Top Priority	Cath up to near future trends	Gain fundamental knowledge	Fundamental	Applied	Experimental	Infrastructure	Passenger	Freight
1	Enhancement of cybersecurity of IT and OT systems	L1								
2	Development of new solutions protecting railway infrastructure and rolling stock against vandalism and theft	L1						I		
3	Seamless Connectivity				FRA			I		
4	Economic impact assessment of technical innovations				FRA	ARA	EXP			
5	Use of carbon fibre and recycling materials to reduce the weight and increase sustainability.				FRA	ARA	EXP	I	P	F
6	Circular economy principles				FRA	ARA		I		
7	New Materials				FRA			I	P	F
8	Safe train location based on GNSS	L1				ARA	EXP	I	P	F

9	Zero-carbon trains, to make the rail sector the backbone of interconnected, sustainable, low-carbon, resilient and sober mobility. Reduce negative externalities (noise, vibrations, local pollution).	L1			FRA	ARA	EXP	I	P	F
10	Climate adaptation of railways	L1			FRA	ARA		I		
11	Cenelec is already working in Development of safety/security standards and risk assessment techniques to manage risk associated with adoption of AI solutions									
12	Although we have not been able to join the research team, the Spanish infrastructure Manager is testing and improving the variable gauges designs. Our contributions in this field could have been the synthesis of wheel profiles optimized for simultaneous use on two different track gauges and/or two different rail profiles or cants.	L1					EXP			F
13	Optimization of railway station design (also regarding PRM)	L1				ARA	EXP	I		
14	Easy to use for all	L1			FRA	ARA	EXP	I	P	F
15	Freight Friendly	L1			FRA	ARA	EXP	I	P	F
16	Low emissions	L1			FRA	ARA	EXP	I	P	F
17	optimized train operations:	L1			FRA	ARA	EXP	I	P	F
18	Cost efficient solutions to decarbonize and/or modernize, branch and regional lines	L1			FRA	ARA	EXP	I	P	F
19	Sustainability in railway infrastructure	L1			FRA	ARA	EXP	I		
20	Reuse of materials	L1			FRA	ARA	EXP	I		

These open survey results indicate significant research activity and descriptors of possible fields and research topics outside of the UIC Future Research Fields. The additional context for research is in the fields of Sustainability, Green Technologies, and Digitization. For sustainability, the survey respondents highlight the use of new materials, material circularity, and the reuse of materials to meet these sustainability goals. It is noted that these sustainability actions are focused on infrastructure related projects. For green technologies, specific projects mentioned include zero-carbon trains and the development of zero-carbon technologies for capillary traffic lines. These activities reflect the activities of ERJU, FP6 FutuRe which is not explicitly addressed in the current UIC Future Rail Research areas.

The survey responses also highlight two principal areas of research which are unexplored in both the UIC 12 Capabilities and UIC Future Rail research areas: (1) Railway economics and (2) Advanced Materials and manufacturing. Railway economics includes the economic impact to rail transport and how enabling technologies influence railway system usage. For advanced materials and manufacturing, these respondents indicate research interest and priority in the usage of new materials, like carbon fiber solutions for lightweight designs, and the reuse of materials and circularity principles. It is noted that, for these categories, the indicated impact areas are across all the railway areas and include all types of work.

6.3 Comparative Analysis of Future Railway Research Fields

6.3.1 Research Priorities Analysis

The ranking of the total number of responses and the research level for each UIC Future Research field is shown in Figure 33. The ranking shows that Infrastructure Resilience, sustainability, and digitalization are the highest priorities. Energy efficiency, smart mobility, and AI safety require future-oriented strategies. Cybersecurity, vandalism protection, and disaster warning systems are key for long-term resilience but not top immediate concerns. Some topics have balanced importance across all three levels, indicating ongoing evolution and need for both short-term and long-term research strategies.

The comparative analysis shows that the highest priority areas (indicated in blue) include *Enhancement of resilience of railway infrastructure*, *Environmentally Friendly and Attractive Sustainable Mobility*, and *Railways Digital Twin, Simulation & Virtualization*. These topics have the largest number of responses that indicate that these topics are top priority, indicating that they are critical research areas with **immediate research needs**. *Smart Asset Management*, *Development of novel solutions for energy conservation* and *Development of new generations of propulsion systems for trains (BEMU, HEMU)* have a strong representation in Level 2 (important to catch up on future trends). This indicates that while they are not the most urgent priorities, they are crucial for adapting to future developments and likely have **near future research needs**. *Development of new solutions protecting railway infrastructure and rolling stock against vandalism and theft*, *Enhancement of cybersecurity of IT and OT systems*, and *Early disaster warning systems* are primarily classified under Level 3, or fundamental research needs. This suggests that stakeholders consider them important for foundational knowledge but not immediate priorities and have **long term research interest**.

Figure 33: Research Priority: Comparative Analysis for UIC Future Research Areas

Development of safety/security standards and risk assessment techniques for AI adoption and *Smart Integration for Door to Door (D2D) Mobility*, are distributed relatively evenly across all three levels. This indicates that they require balance research with a high likelihood of long-term ongoing research activity. *Pandemic* and *Early Disaster Warning systems* have smaller bars in Level 1 but noticeable representation in Levels 2 and 3. This suggests that while they are not seen as immediate priorities, they are still recognized as important for future planning and knowledge development. *Assets for Automatic & Autonomous Operation* and *Smart Asset Management* and *Railways Digital Twin, Simulation & Virtualization* have the highest proportion of level 1 (Top Priority) research which indicates high current research priority.

Figure 34 categorizes research topics into three types: Fundamental Research, Applied Research, and Experimental Development. *Enhancement of resilience of railway infrastructure* has the highest number of responses, with significant contributions from all three research categories. This suggests a diverse mix of fundamental research, applied studies, and experimental development and an area where significant research activity occurs. *Smart Asset Management* and *Environmentally Friendly and Attractive Sustainable Mobility* have a high number of total responses and with a bias towards applied research, indicating areas with a strong focus towards development and innovation related activities.

6.3.2 Research Fields Analysis

Figure 34: Research Type: Comparative Analysis for UIC Future Research Areas

For **experimental development** focused research activities, the following fields have the highest relative number of responses: Enhancement of resilience of railway infrastructure, Environmentally Friendly and Attractive Sustainable Mobility, Green Freight Logistic Chain, and Development of novel solutions for energy conservation, as indicated by the high proportion of the experimental development responses in these research areas. For **applied research** focused research activities, the following areas have the most relative activity: Railways Digital Twin, Simulation & Virtualization, Assets for Automatic & Autonomous Operation, and Development of safety/security standards for AI risk assessment. For fundamental research, the topics with highest relative proportion of responses are Pandemic, Multimodal Mobility System for Pods, Early disaster warning systems and Development of innovative solutions protecting railway infrastructure and rolling stock against vandalism and theft.

The survey response shows that the general topics in railway resilience, sustainability, and digitalization are moving toward real-world implementation. Autonomous operation, AI safety, and propulsion systems require both applied research and experimental studies before large-scale deployment. Some areas like security and multimodal mobility are still in the early research phase.

Figure 35 shows the comparative survey results for the different research areas in the railway sector, categorized into three groups: Infrastructure (Blue), Passenger Rolling Stock (Orange), and Freight Rolling Stock (Green). *Environmentally Friendly and Attractive Sustainable Mobility* and *Assets for* *automatic and autonomous operation* have the greatest number of responses. *Environmentally Friendly and Attractive Sustainable Mobility* has the highest number of overall responses, with a significant contribution from Freight Rolling Stock. *Development of new solutions protecting railway infrastructure and rolling stock against vandalism and theft* also has a high number of responses, with Freight Rolling Stock being the dominant category.

6.3.3 Research Area Analysis

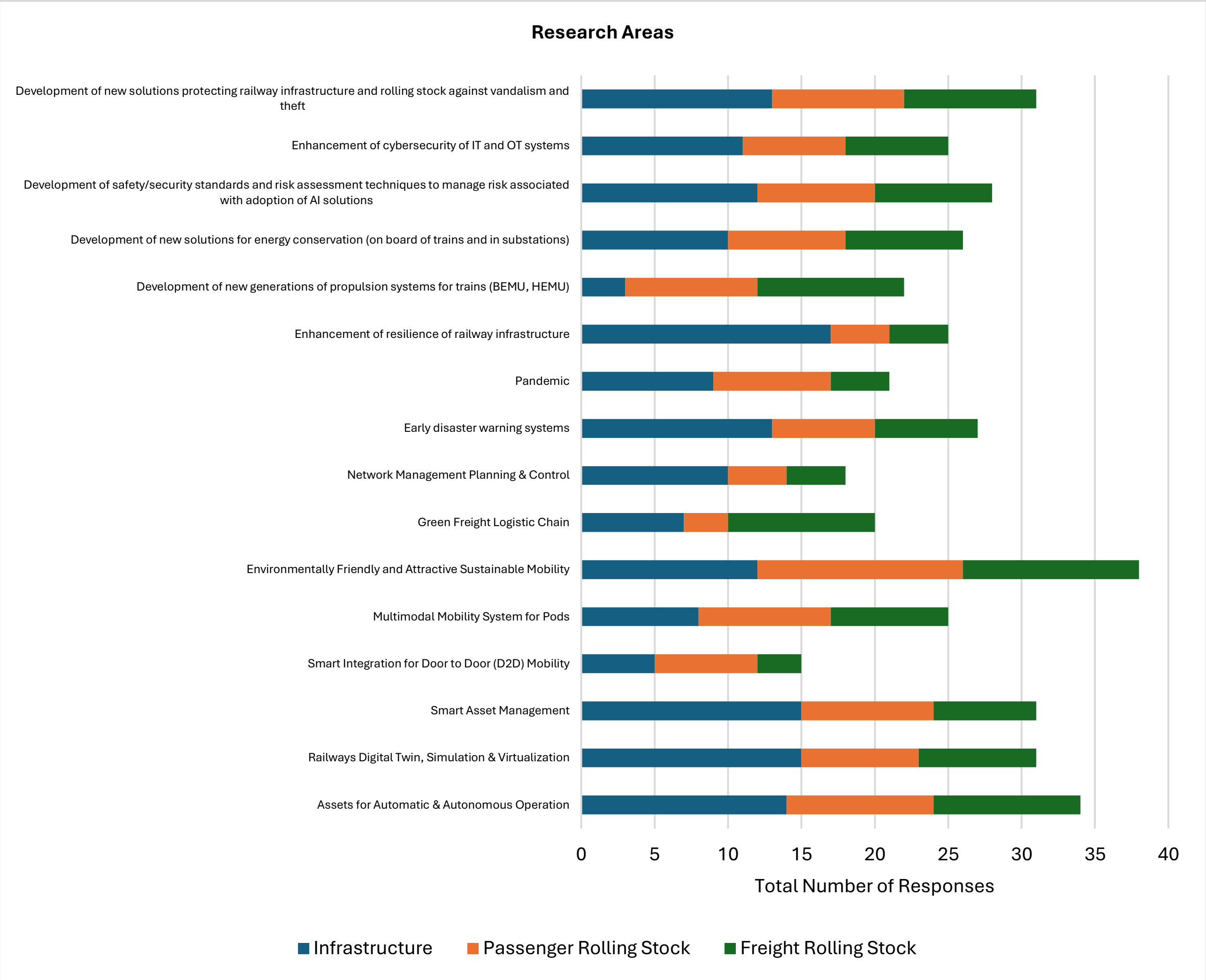

Figure 35: Research Type: Comparative Analysis for UIC Future Research Areas

Environmentally Friendly and Attractive Sustainable Mobility, *Development of safety/security standards and risk assessment techniques to manage risks associated with AI adoption*, *Development of New Solutions for energy conservation*, and *Enhancement of cybersecurity of IT and OT systems* how a balanced distribution of responses in each research field, indicating fields where there are widespread benefits for research. *Multimodal Mobility System for Pods*, *Smart integration of D2D Mobility*, and *Network Management Planning & Control* have fewer responses overall which may indicate an emerging research field, and in particular a possible field where enhanced activity may be needed.

Assets for Automatic & Autonomous Operation, *Railways Digital Twin, Simulation & Virtualization*, and *Smart Asset Management show* a strong focus on Infrastructure. *Environmentally Friendly and Attractive Sustainable Mobility*, have a high interest in the Freight and Passenger Rolling Stock category. It is noted that although the rate of passenger rail uptake in Europe has been increasing tremendously, railway research is primarily focused on freight rolling stock, which has more overall responses compared to the passenger rolling stock category. While there is no cause or correlation between the rise in passenger rail, this indicates a possible mismatch in the railway research areas and a possible area of research underinvestment.

7 Analysis of the results and deliverables produced by the RAILS project

7.1 Introduction to RAILS Project

RAILS (Roadmaps for AI Integration in the Rail Sector) has been the first international research project investigating the potential and limitations of Artificial Intelligence (AI) in railways, with the goal of *providing recommendations for next-generation railways and contributing to the definition of roadmaps for future research*. In RAILS, three principal areas have been addressed: Railway Safety and Automation (WP2), Predictive Maintenance and Defect Detection (WP3), and Traffic Planning and Management (WP4). Through relevant case-studies, researchers have shown the practical usage of machine learning with appropriate datasets for AI training and testing.

In the following sections, the main findings of the project will be summarized to provide pointers to relevant deliverables and technical papers.

7.2 The RAILS Road mapping Process and Outcomes

In RAILS, researchers focused on the development of roadmaps for strategic planning [4] for each of the technical work packages (i.e. WP2, WP3, and WP4). Table 17 provides a map between the roadmap steps, the project outcomes, and related publications (deliverables[1] and technical papers).

In the first phase of the road mapping process (WP1), researchers defined a reference taxonomy for AI in railways and analyzed the State-of-the-Art of scientific literature and worldwide projects, and the State-of-Practice through a survey involving stakeholders (Steps 1 and 2 in Table 17). Following the outcomes of the first phase, two pilot case studies were identified for each technical WP (Step 3 in Table 1):

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

For each case-study, an experimental Proof-of-Concept (PoC) has been provided to investigate AI applications (Steps 4, 5, and 6 in Table 17), including unsupervised Deep Learning (DL) for anomaly detection on rail tracks, Deep Reinforcement Learning for intelligent control in Virtual Coupling, and DL-based Graph Embedding techniques for train delay prediction.

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

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

Table 17: RAILS Roadmap Steps, Outcomes, and Publications

Step	Outcomes	Publications
1. Identify concrete railway problems	Taxonomy of AI for railways, Identification of Railway problems, Review of AI applications to Railway problems, Identification of research directions and uncharted areas emerged from the analysis of the state-of-the-art.	D1.1, D1.2, [5], [6], [7], [8], [9]
2. Identify constraints, applicability issues, and requirements.	Review of EU guidelines, Regulations and directives on AI, Explainable AI, Criticalities and milestones, Ethical and Privacy aspects, Urgent Issues, and Strategic Application areas.	D1.1, D1.3, [5]
3. Speedy technology areas pilot case studies, and operational scenarios.	AI Emerging Technologies in sectors other than Railways, Transferability guidelines, Pilot Case studies identification, Scenarios Definition.	D1.3, D2.1, D3.1. D3.2. D4.1, D4.2
4. Transform requirements into technology drivers.	Basic AI Usage Guidelines, Enabling Technologies, Reference datasets, and Machine Learning (ML) Models.	D1.3, D2.1, D2.2, S3.1, D3.2, D4.1, D4.2, [10], [11]
5. Develop AI-powered approaches, Identify alternative, and their timelines.	PoCs for the selected scenarios: KPIs, ML models, Experiments, results, and Possible alternatives.	D2.3, D3.3, D4.3 [12], [13]
6. Identify innovation needs and recommended improvements.	Results of a SWOT* Analysis of the PoCs, Recommendations, and Innovation Needs.	D2.4. D3.4, D4.4
7. Create the Technology Roadmap Report	Timeline indications derived from: 1) previous steps, ii) relevant stakeholders' opinions, and iii) further available analysis results. Current criticalities and suggested research directions for innovation.	All above, D5.3
DX.Y stands for work package X, deliverable Y References refer to specific works published under RAILS agreements *SWOT: Strengths, Weaknesses, Opportunities, and Threats [14]		

7.3 Fully Autonomous Trains in Open Environments

In RAILS, researchers investigated the use of AI in *open environments* compared to *segregated environments* (i.e., railway tracks protected by means of physical barriers) [15]. They addressed the threats affecting safety that can be mitigated using appropriate Safety Envelopes [16]. In this context, the RAILS project addressed the main challenges listed below.

Conceptual Shift. Grades of Intelligence (GoIs) were identified, which, building upon the Grades of Automation (GoA), define a gradual integration of AI in autonomous trains [11]: i) *limited or no autonomy (GoI1)*, where AI is not adopted in safety-critical functionalities but can be used to optimise the use of resources; ii) *partial autonomy (GoI2)*, where AI is used to improve train operation or train protection; iii) *full autonomy (GoI3)*, where AI is adopted to optimise both operations and protection, e.g., in Virtual Coupling [12]; iv) and *full autonomy in fully connected environments (GoI4)*, where advanced AI functionalities are added to GoI3 through dynamic learning and adaptation.

Structural Needs. To move towards *GoI4*, Levels of Intelligence (LoIs) were defined based on edge, fog, and cloud computing, to provide a reference architecture for the distribution of AI functionalities (Figure 36).

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

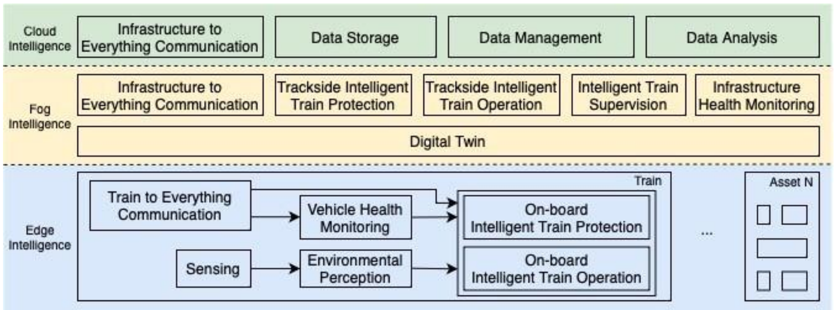

Figure 36: Example Architecture for GoI4 Railway Lines.

7.4 Intelligent Infrastructure Inspection

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

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

AI-aided DTs. AI extends DTs allowing for the deployment of intelligent services such as predictive maintenance; also, it provides the capability of emulating the behaviour of their physical counterpart. An example architecture for AI-aided DT is discussed in [10], including implementation guidelines. Researchers showed that non-intrusive sensors combined with data processing based on AI can extract specific information that is crucial for the successful implementation of DTs.

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

7.5 Route embedding for Arrival Delay Prediction on Service Basis

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

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

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

Recommendations. Taking these aspects into account, the recommendations identified in RAILS refer to the i) implementation of the Structural Deep Network Embedding approach and then integrating it with dimension decomposition methods. To generate route embedding vectors as information entropy condensed features, contributing to the subsequent arrival delay prediction. ii) Transfer learning in railway networks, i.e., applying knowledge from one network to another, which is valuable when data is scarce or for newly built networks. iii) Ensemble methods in machine learning, combining multiple models to enhance prediction accuracy and reliability. Different models have strengths and weaknesses, but ensembles leverage their collective wisdom, particularly when models are diverse.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement: HORIZON-ER-JU-2022-ExpIR-04

8 Assessment for Rail Research Needs and Prioritization

8.1 Thematic Research Grouping

As a result of the activities outlined in Sections 2-4, multiple definitions of research topics have been proposed. These definitions include research and development focused categorizations like the S2R and ERJU flagship areas, and innovation and development focused categories like the UIC 12 Capabilities and Future Research Fields. Concurrently there is overall transportation research goals outlined by STRIA and Horizon Europe provide multi-sector and broader research objectives.

To simplify the discussion of research topic gaps, the research topic descriptors were mapped to 13 research thematic groups. as shown below in Figure 37. These 13 research themes are the amalgamation of the previous research descriptions, and each theme provides overlaps to each of the research topics. The purpose of academic research themes is to provide a broader academic context for railway research areas and less dependency on solution driven research objectives.

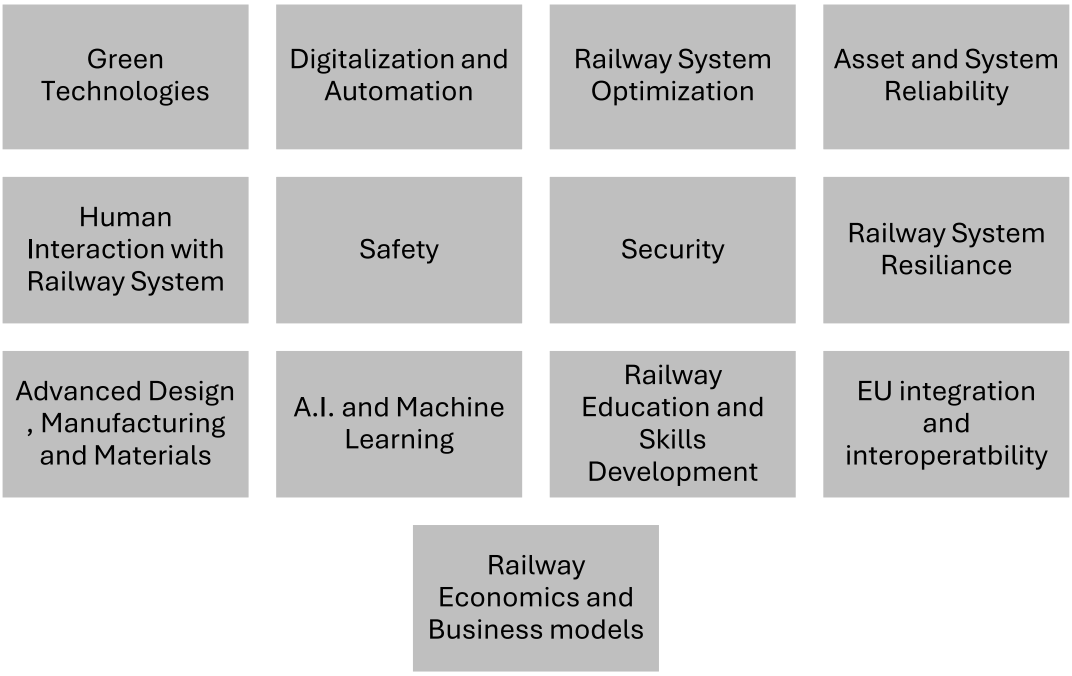

Figure 37: Research Themes for Rail Research needs and prioritization analysis.

<u>Green Technology</u>

This research theme focuses on the development of sustainable, eco-friendly technologies to reduce the environmental footprint of railway operations and contribute to carbon emission reduction targets. Specific areas of research include the development of alternative energy sources for powering trains, reducing overall energy consumption, and analyzing emissions and environmental impacts at both the component and system levels. This theme also examines the lifecycle impact of railway assets to create a more sustainable and circular approach to rail infrastructure and operations.

Digitization and Automation

This theme aims to address systemic challenges in the railway sector by leveraging digital tools to enhance efficiency, safety, and system management. Research covers multiple railway functions, including operations, signalling, maintenance, and rolling stock. A key area of focus is the digital transformation of traditional manual processes, with particular attention to automated train operations (ATO), which promises increased efficiency and safety through automation. Digitization research also explores the potential of smart infrastructure, data-driven decision-making, and predictive analytics to enhance system reliability and performance.

Railway Systems Optimization

Research in this area seeks to optimize the utilization of existing railway infrastructure and resources to increase capacity and efficiency. By developing advanced management tools and technologies, this theme aims to improve the allocation of rolling stock, enhance infrastructure usage, and balance demand fluctuations. Importantly, the emphasis is on practical solutions that can be implemented within the current railway system, including dynamic scheduling, traffic management, and optimization algorithms to address bottlenecks and improve overall system throughput.

Asset and System Reliability

This theme focuses on improving the predictability and availability of railway system by advancing tools and technologies for predictive maintenance and condition monitoring. Research aims to reduce unplanned downtime, extend asset lifecycles, and enhance operational resilience by detecting and addressing potential failures before they occur. In addition to physical asset reliability, this research examines how the railway system can adapt to operational changes and demand variability, ensuring reliable service delivery.

Human Interaction with the Railway System

This multidisciplinary theme explores how passengers and stakeholders engage with the railway system and how railways interact with the broader transportation network. Research may investigate how railway operations influence social, political, cultural, and geographic behaviour, with a particular emphasis on user experience, accessibility, and public perception. This theme also considers the integration of railways into multimodal transportation systems to improve connectivity and passenger satisfaction.

Safety

Safety research investigates methods to protect the railway system from unexpected risks, accidents, and operational failures. This theme focuses on risk assessment, risk reduction strategies, and the implementation of safety protocols to mitigate hazards. Research also addresses remediation and recovery processes to ensure that railway operations can resume quickly and safely after disruptions.

Security

This theme examines the protection of railway assets, both physical (e.g. stations, rolling stock, infrastructure) and digital (e.g., data networks, operational systems), from targeted threats such as cyberattacks, vandalism, and terrorism. Given the broad range of potential vulnerabilities in the railway domain, security research often involves interdisciplinary collaboration. Key areas of focus include cybersecurity, infrastructure protection, and data integrity, with an emphasis on developing proactive threat detection and response capabilities.

System Resilience

Resilience research investigates how the railway system can adapt to and recover from disruptions, both internal (e.g., network failures, operational changes) and external (e.g., extreme weather events, long-term climate impacts). This theme explores short-term response strategies, such as real-time timetable adjustments, as well as long-term adaptation to changing environmental conditions. Research in this area also examines the temporal aspects of resilience, assessing how railways can maintain functionality under varying stressors and support sustainable, climate-resilient infrastructure.

Advanced Design, Manufacturing, and Materials

This theme emphasizes the development of innovative materials, manufacturing processes, and design methodologies to enhance railway components, assets, and systems. Research focuses on areas such as lightweight materials, resilient structures, safety-critical components, and sustainable product development. The concept of circularity is a key cross-functional aspect, with studies examining the full lifecycle of railway components to minimize waste and improve resource efficiency.

Artificial Intelligence (AI) and Machine Learning (ML)

AI and ML are integral to advancing decision-making capabilities across the railway sector. Research focuses on applying these technologies to areas such as predictive maintenance, traffic management, automation, and system optimization. AI and ML tools are expected to play a critical role in enhancing operational efficiency, safety, and passenger experience by enabling real-time data analysis, anomaly detection, and automated control systems.

Railway Education and Skills Development

This research theme examines best practices for improving the attractiveness of railway careers through education, training, and skills development. Research explores how digitization and automation are reshaping the skillsets required in the railway sector and how current workers can be upskilled to meet these evolving demands. Additionally, studies may assess how the European educational system can better promote railway-related careers to attract future researchers, engineers, and operational staff.

EU Integration and Interoperability

This theme focuses on enhancing cooperation, standardization, and interoperability across European railway networks. Research aims to reduce technical, operational, and regulatory barriers between operators, traffic administrators, and maintenance providers. Key objectives include the harmonization of standards, the adoption of best practices, and the development of interoperable technologies, such as the Digital Automatic Coupler (DAC), to improve cross-border railway operations and meet evolving market demands.

Railway Economics and Business Models

Research in this area investigates the economic sustainability and profitability of railway systems. Key areas include the development of new economic assessment tools to evaluate the impact of digitization, circularity, and sustainability on railway operations. Additionally, research explores how social, environmental, and economic drivers influence railway demand and how innovative business models can enhance the sector's competitiveness and attractiveness as a future transportation solution.

The mapping of the research topic descriptors to the research themes are shown in the following Figure 38 and Figure 41. To distinguish the origin of each theme, the color of each box refers to a different research topic descriptor source. The color key is as follows: blue for S2R, green for ERJU, orange for UIC 12 Capabilities, purple for UIC Future Research fields, and black for EU STRIA objectives.

8.1.1 Discussion on Research themes Mapping.

From the mapping of the research descriptors to the research themes, it is observed that all research themes contain multiple research topic descriptors. The mapping shows three topics where there are the most associated research topic descriptors: (1) Digitization and Automation, (2) Railway System Optimization, and (3) Green Technologies. Within these themes there is representation from all five sources indicating high ongoing activity with significant future research interest.

Conversely, the mapping shows emergent themes that have fewer associated topics, including (1) Railway System Resilience, (2) Railway Education and Skills Development, and (3) Security. Of the research descriptors that are associated with the themes, most of the contributions are from current research plans indicating that these topics may have current relevance but have low research activity. Therefore, there is likely a need from the railway industry to further define specific research objectives in these fields.

Themes with moderate activity with moderate research activity include (1) Human Interaction with the railway System, (2) AI and Machine Learning, and (3) Asset and System Reliability. Like the previously mentioned themes there are topic descriptors from all five sources, however the total number of research topic descriptors in each theme is lower. Therefore, these topics have moderate research activity with planned future research trends. The moderate activity in these research themes suggests that there are opportunities for increased research in these fields to define specific research goals.

In conclusion, the mapping shows significant research descriptors across all the research themes. However, there is an imbalance in the number of topics associated with each theme. Digitization, Automation, System optimization and green technologies remain at the forefront of the current European research. However, there are still significant gaps in research topics, in particular the emergent themes where there are limited research descriptors indicating the lack of focused research activities in these fields which may limit the long-term research and excellence in these themes.

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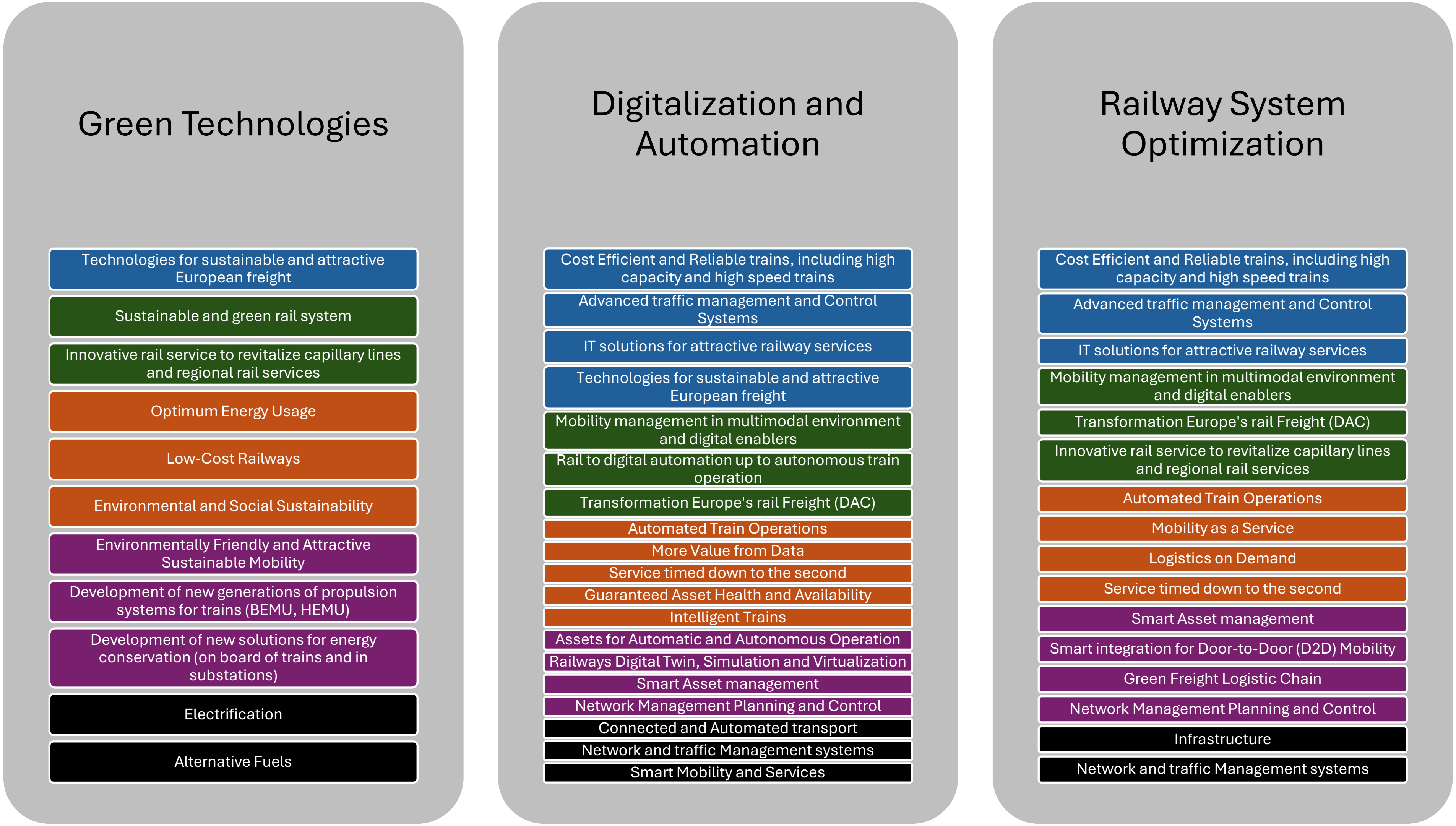

Figure 38: Research Themes - Map 1 (Green Technologies, Digitalization and Automation, and Railway Systems Optimization)

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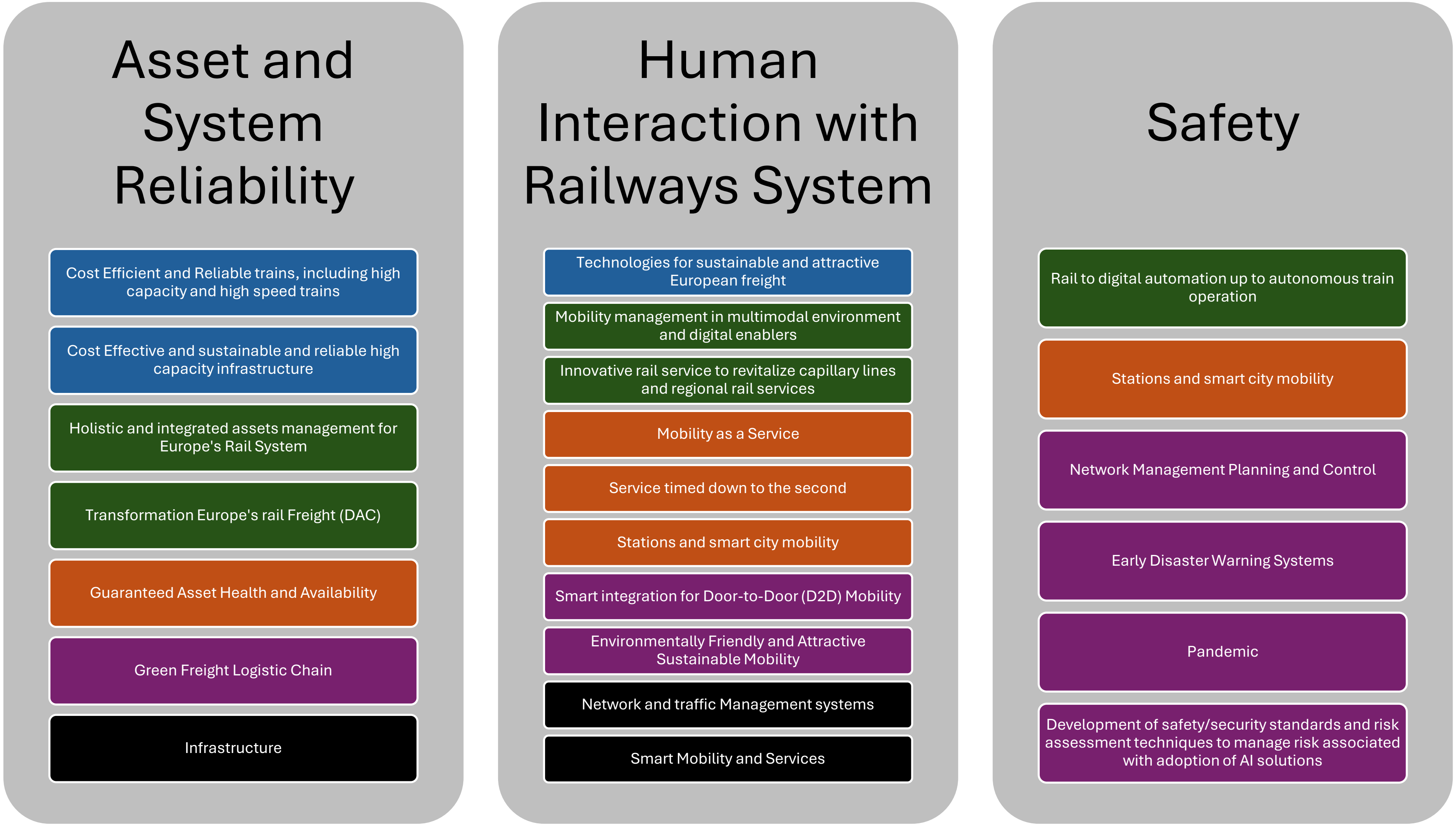

Figure 39: Research Themes - Map 2 (Asset and System Reliability, Human Interaction with Railways System, and Safety)

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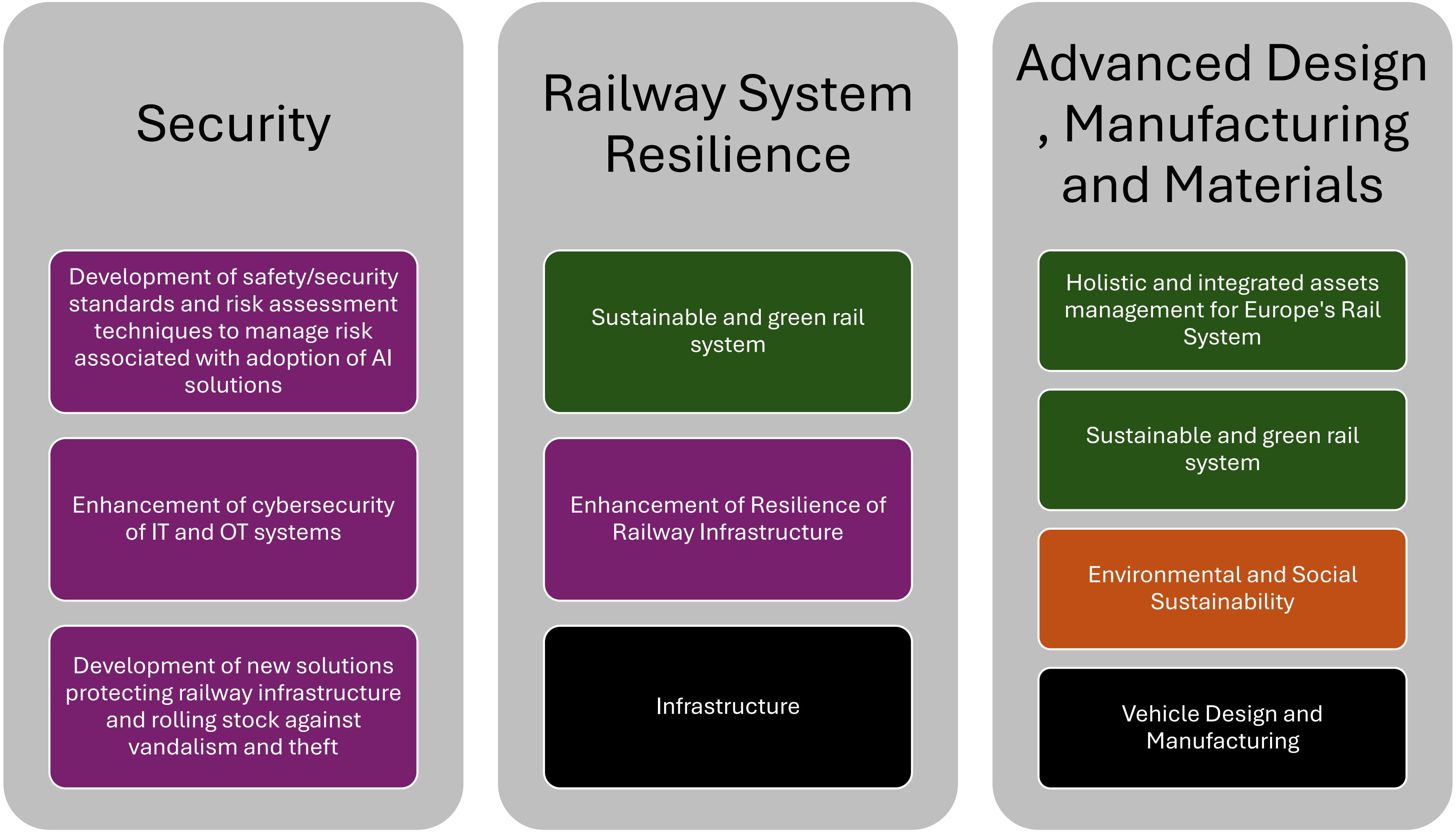

Figure 40: Research Theme - Map 3 (Security, Railway System Resilience, and Advanced Design, Manufacturing and Materials)

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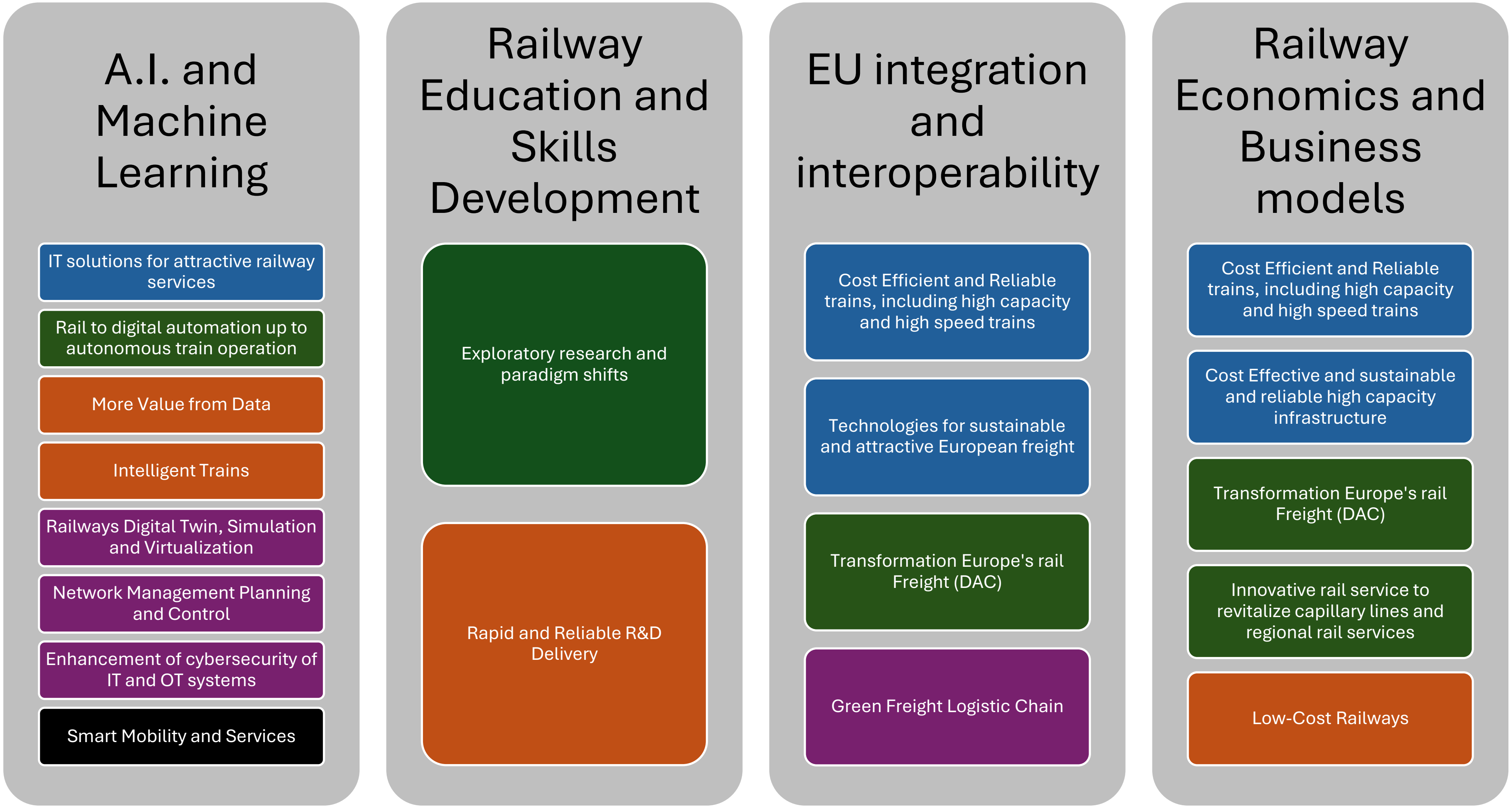

Figure 41: Research Themes - Map 4 (AI and Machine Learning, Railway Education and Skills Development, EU integration and interoperability, and Railway Economics and Business Models)

8.2 Research Gaps

From the academic perspective there are ongoing systemic gaps in railway research that limits the competitiveness and leadership of the European sector. Despite the increased research in digitization, automation, and green technologies, there are still significant gaps in the research and innovation has not yet fully addressed all the research themes and challenges faced by the railway sector. From these sections the following gaps in the railway research sector have emerged:

(1) Fundamental Research Gaps in European Railway sector,

(2) Lack of Multidisciplinary Research Opportunities,

(3) Need for Research Prioritization in Emerging Technologies,

(4) Integration and testing of Advanced Digital Enablers,

(5) Railways as a critical security component in European transport and logistics,

(6) Benchmarking of railway research to global players.

8.2.1 Fundamental Research Gaps in European Railway sector

As indicated in section 2, most of the European rail research funded by EU initiatives have focused on projects with increasing TRL. While the increase of TRL has benefited the railway sector as outcomes trended toward advanced development and solution deployment, there is a notable lack of balance in these projects towards fundamental research. As noted in the ERJU, only one flagship area, FP7, is devoted to fundamental, exploratory research with focus towards lower TRL projects.

The lack of dedicated funding towards lower level TRL, fundamental research projects pose a significant risk to the competitiveness of the railway sector as fundamental research is strongly linked to scientific and industrial leadership in critical fields. From this report, the brainstorming of the UIC 12 capabilities specifically notes that areas like wheel-rail contact efficiency, innovative materials and manufacturing, and advanced predictive maintenance should be further explored which are currently not covered in any of the EU projects. Likewise in the Section 6.3.2 it was noted fundamental research is marked as a possible research area of interest, despite some topics having lower research priority. This indicates that regardless of the research priority, there is a consensus from European Rail researchers for the need to maintain fundamental research across all fields.

The reduction of fundamental research has long term implications, particularly the competitiveness of the European railway sector on a global scale. The Mercator Institute for China Studies (MERICS) has noted that due to the vertical integration of the Chinese rail sector including universities, research institutions, and national laboratories the number of patents by the Chinese Rail Company (CRRC) has increased from 88 in 2006 to over 1800 in 2019 [17] and have taken a significant market share of the global railway industry. While Europe still maintains a strong advantages in rail transport, the China 2.0: Status and Foresight of EU-China Trade report by the EU commission [18], shows that the sector ranking for the rail transportation equipment are at parity, indicating a risk of falling behind if fundamental research levels are not maintained and expanded accordingly (Figure 42).

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Figure 5.2: Sector Fitness rankings (higher is better)

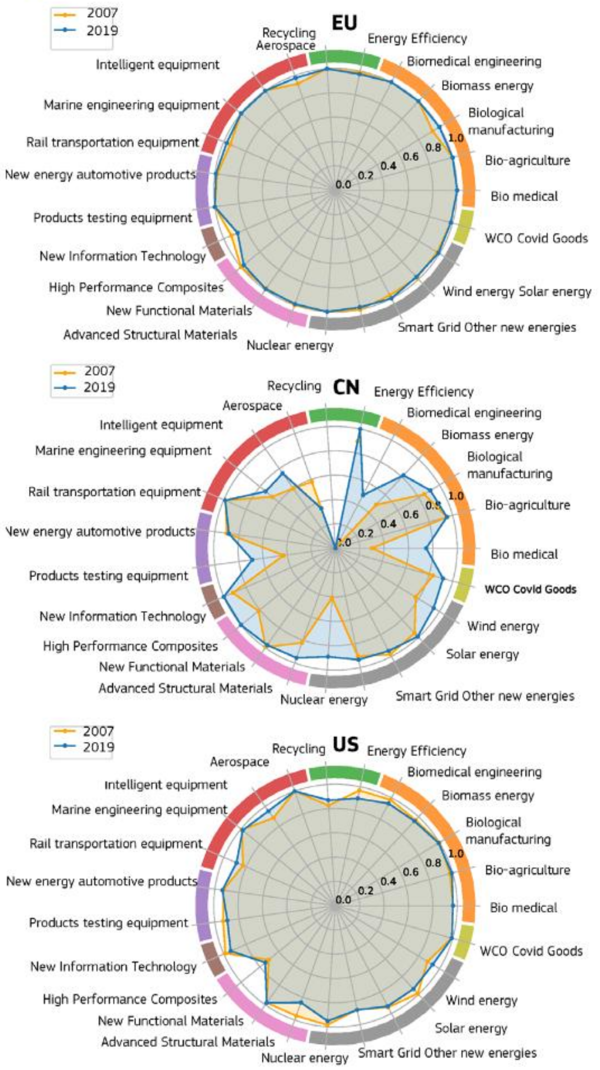

Figure 42: Sector Fitness comparison of EU, China, and US [18]

The expansion of fundamental research can be accomplished by the creation of larger and longer funding opportunities for rail researchers. Larger rail research with larger amounts of fundings is critical in fundamental research where the TRL is low and often requires extensive efforts before moving to higher TRL. It is suggested that there should be a focus on the development of fundamental research centers and academic research consortiums which can leverage expertise to develop the fundamental research needs. Longer funding opportunities are also necessary to see fundamental research projects to fruition. Unlike applied research projects with higher TRL, longer research funding opportunities allow for the sustainable development of novel solutions for future challenges in the railway sector.

8.2.2 Lack of Multidisciplinary Research Opportunities

Currently, there is an inadequate focus on multidisciplinary cross-sector railway research, in particular fields of digitization, advanced materials and design, AI and Green technologies. Despite the research activities in these fields, it is noted that there are limited collaborations between the railway sector and adjacent sectors, including lightweight vehicle design (similar to road and maritime transport), telecommunications (related to digitization and advanced 6G networking), advanced manufacturing (related to additive manufacturing and Industry 4.0), and green technologies (new energy sources, battery technology, and carbon reduction technologies). The co-development of these technologies is critical in the long-term innovation leadership of the railway sector and developing Europe, first research areas where total solutions are developed with Europe.

For successful multidisciplinary research, there is a need for systematic reviews of research gaps in the railway sector and to align these gaps to the research goals of adjacent and relevant research sectors. The alignment of common research goals ensures more efficient resource allocation within Europe where research domain experts can effectively contribute to the railway sector. This can accelerate the progression in the railway sector while improving the research outcomes.

The concept of multidisciplinary research is also highly relevant in studying the social, political, geographical, and economic implications of the railway system. As a sustainable transportation mode with a low carbon footprint, the railway sector is an attractive means to meet the EU sustainability goals. However, there are limited studies which show the quantifies the overall impact and benefits of the railway system. A significant risk occurs when the railway sector is shown to be unattractive and can lead to long-term shifts in behaviour patterns away from the railway sector.

8.2.3 Need for Research Prioritization in Emerging Technologies

Europe has been research leaders in sustainability, digitization, and interoperability, reflecting the broader goals of developing a sustainable and integrated European network. As these research areas mature and the outcomes are slowly realized, there is a need for the development of research objectives in emerging technologies. For the successful development of these new research needs there should be close collaboration between the academic research leaders and the railway sector to develop common plans for the future of the railway sector. While the UIC 12 Capabilities and the UIC Future Research Fields provide a framework for research goals to be effectively expressed, there is a need for continuous collaboration between the academic partners and the railway community to update the research goals.

As outlined in section 8.1.1, the current research topic descriptors are commonly linked to a small set of research themes which correspond to areas where Europe is the research leader. There is a risk that overinvestment into successful research thematic areas leading can result in inadvertent neglect of emerging research areas. As outlined in the UIC 12 Capabilities assessment, some emerging research areas where there is research focus, however low research activity includes high speed technologies like Hyperloop and Maglev. Likewise, the UIC Future research Fields assessment shows that topics like Pandemic, Safety, and Cybersecurity have high priority, however limited number of defined research objectives in these fields.

To address this gap, periodic discussion and evaluation of research needs in Europe, with significant contribution from the academic community, it is recommended to ensure a sustainable and long-term research direction for the European rail research community.

8.2.4 Integration and testing of Advanced Digital Enablers

Advanced digital enablers including AI, Machine Learning and big data are topical and highly relevant tools in the development of an increasingly efficient, autonomous, and digital European rail network. As outlined in Section 7, the RAILS projects has provide an assessment of the potential and limitations of Artificial Intelligence (AI) in railways and recommendations for next-generation railways and the integration of AI in and contributing to the definition of roadmaps for future research. As this space evolves and becomes increasingly competitive and, with global competitors, there is a need for the European railway to take leadership, with regards to governance, safety, security, training and testing.

One aspect of focus is the treatment of data from the railway system and the data security in the rail sector. As the rail system integrates more advanced digital tools are used for both maintenance, condition monitoring, and safety critical applications, understanding how to manage the data and the treatment of data as an *asset* needs to be considered. In the European context establishing guidelines on how to share the data becomes increasingly important. Survey responses from Section 4 indicate that as AI tools develop, there is a current need to develop physical testing and open *sandbox* testing environments for these digital enablers. For critical applications in safety there is a pertinent need to develop realistic test sites and conditions that most accurately mimic the intended application. This will close the development to implementation loop and provide opportunities for researchers, especially small to medium players, to develop these tools and digital enablers.

8.2.5 Railways as a critical security component in European transport and logistics

With the changing security climate, there is an immediate need to strengthen the European railway network as a critical part of European transport and logistics. To improve the security of the railway system, long-term research is needed to understand the vulnerabilities in the system and develop innovative methods to mitigate these vulnerabilities and to build long-term security planes for the railway system. In these cases, it is particularly pertinent to explore all aspects of the railway sector, including infrastructure, and operational contexts. Infrastructure needs to secure the signalling system, electrical system (catenary), and switching and crossing infrastructure from physical and digital intrusion. For operational contexts, exploring methods for enhanced operational redundancy and developing self-healing timetables in case of disruption are pertinent to ensure the security of the system. As the rate of digitization and the use of digital tools increases, there is added need to explore cybersecurity for the railway system and the best methods to detect, suppress, and prevent potential cyberattacks.

Fundamental research in both railway systems and railway economics includes securing the supply chain of critical components in the railway sector. Understanding the bottlenecks in the railway supply chain and prioritizing critical components from onshoring can ensure that the European rail network is secure against physical and digital threats.

8.2.6 Benchmarking of the railway research to global players

As the rate of research increases in the railway sector, there is a need to systematically and periodically assess the academic research themes. In the ERRAC group there are often calls for proposals when pertinent European calls for funding are needed. However, developing a systematic method to gather research descriptors and themes from various European research partners can provide insights on the research priorities, areas, and field. From the academic community, the assessment of rail research based on publication-based metrics can be used to assess research trends and the impact of these research activities. As these activities are already a widespread practice at academic institutions, normally at the regional and national levels, there is a need to provide complementing activities at the European wide levels to assess the productivity of European rail research. In Section 9, there is further discussion on proposed benchmarking and collaboration activities between the administrative bodies and the academic community.

The segmentation of the European railway sector, compared to other regions, also poses long-term challenges to academic research and development. Currently rail research can be supported across multiple levels. However, due to the patchwork of European research across different research forums, this makes the alignment of research and the collaboration of research difficult. This is most relevant to large scale fundamental research which often requires knowledge and expertise from many domains across multiple nations and regions. The failure to provide clear long term research support and clear collaboration guidelines may lead to the falling behind of European rail researchers in these critical research themes. Thus, there is a need for more forums for academic exchange, in collaboration with ERRAC to provide opportunities for future collaboration between academic partners in the railway sector.

8.3 Research Prioritization – Technological Enablers

The progression of railway research should be complemented with technological enablers that will help accelerate the progression in the given fields. Technological enablers include tools, systems, or innovations that drive or facilitate progress in specific fields by enabling new capabilities, improving efficiencies, and overcoming existing challenges. These enablers include hardware, software, and processes and analytical methods that play a help meet the research need or objective.

In the UIC 12 Capabilities a list of complimentary technological enablers was presented to support the progression of the research themes. To understand the relevance of these technological enablers to the current research themes, a mapping of the technological enablers was to the research themes were performed and presented in Table 18, Table 13 and Table 20.

Table 18: Mapping research themes to UIC Technological Enablers - 1

Topic	Enablers (UIC – The 12 capabilities)
Green technologies	2.2, 3.3, 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7,5.8, 7.10, 11.1, 11.2, 11.4, 11.5
Digitalization and Automation	1.1, 2.1, 2.2, 2.3, 2.6, 2.13, 2.14, 2.17, 3.6, 3.7, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.10, 6.1, 6.2, 6.3, 6.13, 9.2, 9.9
Railway System Optimization	2.1, 2.2, 2.3, 2.13, 3.4, 3.6, 4.2, 4.3, 6.3, 7.9, 8.1
Asset and System Reliability	1.4, 2.1, 3.1, 2.2, 2.3, 3.1, 3.2, 4.1, 4.2, 4,3, 4.4, 4.9, 6.2

Table 19: Mapping research themes to UIC Technological enablers - 2

Topic	Enablers (UIC – The 12 capabilities)
Human Interaction with Railway System	1.3, 1.6, 12.4, 12.6, 12.7, 12.8, 12.9, 12.11, 12.12, 12.13
Safety	1.2, 2.1, 2.15, 4.1, 4.2,
Security	1.2, 2.1, 2.13, 2.14, 2.15, 2.16, 2.17, 3.2, 4.1, 4.2, 4.3, 4.4, 4.5, 7.6,
Railway System Resilience	2.1, 2.2, 2.3, 2.6, 3.1, 3.2, 4.1, 4.2, 4.3, 4.4, 4.5, 8.1, 9.2

Table 20: Mapping research themes to UIC Technological enablers - 3

Topic	Enablers (UIC – The 12 capabilities)
Advanced Design, Manufacturing and Materials	4.2, 5.6, 5.7, 7.9, 11.3, 11.4
A.I. and Machine Learning	3.4, 3.6, 3.7, 4.1, 4.2, 4.3,
Railway Education and Skills Development	12.4, 12.6, 12.7, 12.8, 12.9, 12.11, 12.12, 12.13
EU integration and interoperability	1.5, 2.15, 2.16, 2.17, 4.1, 4.2, 4.4, 7.7,
Railway Economics and Business Models	5.5, 6.2, 7.5, 12.10

The list of the enabler is below.

Enablers (according to the UIC – The 12 Capabilities)

1. **Digital and Automated Train Operations**
    - 1.1. Breakthrough approach to implement, use and scale digital and automated train operation.
        - 1.1.1. Modularity as a frame compatibility, easy/remoted upgrade, and investment protection
        - 1.1.2. New skills, affordable responsibilities, and positive role for railway workers
    - 1.2. Next generation technological platforms as a safe, secured, and configurable backbone for:
        - 1.2.1. Low latency and guaranteed communication supporting rail operation timed at the second,
        - 1.2.2. Digital and collaborative register giving everywhere a timely access to trusted data.
        - 1.2.3. Centralised and decentralised computing power supporting multivendor applications.
    - 1.3. New algorithm and (human) machine interfaces supporting enhanced operation.
        - 1.3.1. From fixed (virtual) blocks to full moving blocks: create new itineraries and optimise real-time decisions for a lean network capacity usage.
        - 1.3.2. Automated and remoted train operation: make best use of rail resources, minimise externalities, help a human to concentrate on tasks, adding value to rail transport customers.
    - 1.4. Advanced sensing within the railway system for an enhanced supervision of asset conditions:
        - 1.4.1. Enhanced navigation and positioning technologies
        - 1.4.2. Localisation of all trains, workers, and obstacles, all-time in any place of the rail system land
        - 1.4.3. Manage rolling stock and infrastructure health (available performance e.g. adhesion, diagnostic, e.g. predictive maintenance for high reliability, self-healing)
    - 1.5. Innovative operational solutions: explore concepts to do more with less.
        - 1.5.1. Virtual coupling: open possibilities for frugal control loop in the railway system
        - 1.5.2. Automatic protection system to adapt to any specific implementation case.
        - 1.5.3. Support mixed traffic and best use of legacy devices with residual lifespan.
        - 1.5.4. Intelligent and connecting digital infrastructure.
        - 1.5.5. Automation, sensing, and robotics applications
        - 1.5.6. Computing continuum – EDGE computing, cloud computing, data analytics, processing power
        - 1.5.7. Space technologies as the basis for "omnipresent" and increasingly faster

connectivity
- 1.5.8. FRMCS
- 1.5.9. TMS/TCMS

1.6. Human factor influence
- 1.6.1. Human role in the autonomous system
- 1.6.2. Analysis of the human system in interaction with the machine, fatigue detection, stress
- 1.6.3. Improvement of the Human/Machine interface (HMI)
- 1.6.4. Human /man-machine teaming. Model-based Human system integration/human in the loop.

2. Mobility as a service

- 2.1. Navigation and positioning
- 2.2. Intelligent and connecting digital infrastructure.
- 2.3. Automation and robotics applications
- 2.4. Digital AI-based travel assistant Computing continuum
- 2.5. MaaS
- 2.6. Federated Data Spaces -> various European initiatives to be connected for the rail mode.
- 2.7. Blockchain technology
- 2.8. Account-based, multichannel ticketing and booking,
- 2.9. Biometrics enabling digital payments.
- 2.10. Self-service technologies
- 2.11. Innovative payment systems
- 2.12. Optimisation platforms and applications
- 2.13. Extended reality (including Virtual and Augmented Reality and Metaverse technologies)
- 2.14. Space technologies as the basis for "omnipresent" and increasingly faster connectivity
- 2.15. Data exchanges, especially with customers
- 2.16. Interoperable data flows for customers
- 2.17. Information Technology Services (ITS)

3. Smart Logistics

- 3.1. Predictive maintenance and harmonised railway diagnostics help to increase efficiency, improve planning, and reduce the costs of rolling stock.
- 3.2. Telematics technologies allow to monitor the location of vehicles and manage them online.
- 3.3. Electrification and batteries/hydrogen power supply help to reduce CO_2 emissions.
- 3.4. Artificial Intelligence supports logistics optimization, efficiency, and link with "last mile" which promote "door-to-door" shipment. Increased speed to reduce time of transportation.
- 3.5. Longer trains and heavier loads to increase total cargo per course.
- 3.6. IoT and M2M technologies to increase efficiency and to reduce time for reaction, better cooperation with Train Management Systems.
- 3.7. Big data to help optimise information flow, cargo and rolling stock management - reduction of costs and time.
- 3.8. DAC (Digital Automatic Coupling) - faster coupling and logistic with use of digital technology and automation.
- 3.9. Hyperloop, magnet traction systems and autonomous.
- 3.10. Smart terminal
- 3.11. Automation of terminals and marshalling yards
- 3.12. Automated driving

4. More value from Data

- 4.1. Data Space and Federated Data Space

4.2. IoT
4.3. Artificial Intelligence and entrusted AI (EAI)
4.4. Conceptual Data Model (CDM) to be applied for interoperability/data translation.
4.5. Cloud Computing
4.6. EDGE computing, where AI is processed onboard.
4.7. Connectivity
4.8. Blockchain technology to support specific use cases.
4.9. Advanced & harmonised railway diagnostics (use case of data use both for vehicle and infrastructure)
4.10. Quantum technology

5. **Optimum energy use:**
5.1. Hybrid and renewable energy technologies (BEV (Battery Electric Vehicle) and Biofuels (HVO (Hydrotreated Vegetable Oil))
5.2. Hydrogen and/or fuel cells
5.3. Energy harvesting, Battery technology
5.4. Alternative Energy sources and alternative fuels technological solutions for vehicle propulsion
5.5. Carbon footprint measurement technologies and applications,
5.6. Advanced innovative materials (e.g. smart, recycled, renewable, self-regenerating, lighter), metal alloys and biomaterials.
5.7. Studies of potential replacement of materials in terms of CO2 footprint
5.8. Energy Capture, Storage and Transmission

6. **Service timed to the second.**
6.1. Automated dynamic timetables
6.2. BIM
6.3. Digital Twins and simulation
6.4. Sectoral / Railways Metaverse
6.5. Edge computing
6.6. Federated Data model/space
6.7. IoT
6.8. Big Data
6.9. entrusted AI
6.10. Cloud computing
6.11. Real-time two-way communication and data exchange
6.12. Real-time positioning
6.13. Natural Language Processing (NLP)
6.14. Space technologies as the basis for "omnipresent" and increasingly faster connectivity

7. **Lower-cost railways**
7.1. New models of mobility (e.g. DRT, shared-mobility, multimodality)
7.2. Automation and autonomation
7.3. Transport accessibility.
7.4. Cost optimisation
7.5. Stakeholders' engagement
7.6. Vulnerable users' needs
7.7. Regional development
7.8. Asset Lifecycle Management
7.9. Intensive use of composites and lightweight materials
7.10. New sources of energy

8. **Guaranteed asset health and availability / intelligent asset management**
8.1. Computer Vision
8.2. Drones and robots (also in swarms)
8.3. AI and ML (Machine learning)
8.4. Digital Twin

8.5. Federated Data Spaces
8.6. BIM
8.7. Virtual environment
8.8. Optimisation platforms and applications
8.9. (Harmonised) Railway Diagnostics: Data Models and exchange of information
8.10. Additive manufacturing

9. Intelligent trains / intelligent system

9.1. AI and advanced communication technologies
9.2. 5G and newer communication infrastructure at transportation corridors to allow IoT and M2M communication to trains.
9.3. IoT and M2M technologies for exchange of data within and outside the train.
9.4. Engagement of AI and algorithms for train schedule, planning, and management like CCC or TCS,
9.5. Proper positioning of cargo waggons with use of GPS, RFID, and other technologies, such as space technologies.
9.6. Integration of variable transport modes and their management systems to allow data exchange and "last mile" planning.
9.7. DAC (Digital Automatic Coupling) - faster coupling and logistic with use of digital technology and automation.
9.8. Development of advance processing solutions in Smart Trains via edge computing
9.9. Fostering V2V (vehicle-to-vehicle) communications in support of centralized management in addition to V2X (vehicle-to-everything)

10. Stations and smart city mobility

10.1. Digital twin technologies
10.2. Delivery of up-to-date data for services, connections, trains disruptions and other transport means
10.3. Implementation of coherent rail and public transport timetables (rail-city/city-rail)
10.4. Integration of data between rail and last mile providers
10.5. CCTV systems and passenger flow technologies
10.6. BMS systems at each train station for the purpose of management
10.7. Digital display areas for consolidated information system and marketing purposes

11. Environmental and social sustainability

11.1. Alternative Energy sources and alternative fuels technological solutions for vehicle propulsion
11.2. Carbon footprint measurement technologies and applications,
11.3. Advanced innovative materials (e.g. smart, recycled, renewable, self-regenerating, lighter), metal alloys and biomaterials.
11.4. Zero carbon or decarbonised materials.
11.5. Geostrategic availability of the raw materials and the associated concerned assets
11.6. Energy Capture, Storage and Transmission.
11.7. Energy Harvesting.
11.8. Interiors rolling stock modularity to ease permanent adaptation.
11.9. Ease of connection to soft emissions level transport modes and micromobility.
11.10. Development of more sustainable ESS (Energy Storage Systems) / Batteries.

12. Rapid and reliable R&D delivery

12.1. Enhanced testing, trialling, and validation facilities; piloting in real environment (such as test labs/test rigs/ test beds).
12.2. Demand-driven & output-oriented research: RU/IM as consumer of research; focused work on use cases.
12.3. Revised understanding of risks and requirements for proving innovative technologies and solutions.
12.4. Consideration of human factors and socio-economic scope, involving training to obtain the development of a matching skills agenda correctly and timely coordinated.
12.5. Incentivisation of developing innovative solutions to drive operational improvements,

cost reduction, etc.

12.6. Enabling collaboration between industry, academia, and other relevant actors

12.7. Strategic coordination of R&D/innovation and technology roadmaps.

12.8. Use of integration methodologies, including integration engineering to develop and support architecture framework as tool for fruitful collaboration, simple implementation, and qualified innovation.

12.9. Resolution of interoperability issues slowing down the introduction of technology and innovative processes

12.10. Provision of corresponding funding for innovation and deployment, important as railway market is composed by public entities.

12.11. Deployment strategies and groups

12.12. Reduction of complexity and bureaucracy (red tape)

12.13. Configuration of the related governance and its bodies in the rail system according to the vision and mission required.

The analysis shows that many of the technological enablers from the UIC 12 capabilities can be mapped to the Research Themes, however, the number of enablers is unevenly distributed. Green technologies, Digitalization and Automation, Railway System optimization, Asset and System Reliability and Security have the greatest number of enablers mapped to the research themes. The large and diverse number of mapped enablers to these themes indicates a wide variety of tools and opportunities have been identified that can help progress research in these fields.

In contrast, Safety, Advanced Design, Manufacturing and Materials, AI and Machine Learning, and Railway Economics and Business Models have the least number of enablers mapped to these themes. The small number of mapped technological enablers suggests that there is likely a mismatch between the objectives of the UIC 12 Capabilities and the current railway research themes. In particular, the topics that have a small number of mappings have been identified in Section 8.1 where these themes have a similarly small number of mapped research descriptors. The small number of mappings to these fields indicates that despite the importance of these fields, there has been limited analysis on defining specific enablers that can help advance these research fields. This provides an opportunity for the research community to further analyze and develop a set of enablers for these low-activity research themes.

9 Future Activities Defining joint activities of ERRAC, ERJU and academic community considering the building of a joint network more open and receptive to scientific and technological innovations.

The European Rail Research Advisory Council (ERRAC) in its 2020 Manifesto highlighted 4 key challenges:

I. *System technical performance,*

II. *Sustainability,*

III. *Multimodality and Personalized service,*

IV. *Inclusivity.*

Following consultation amongst its members providing a research outlook for each of these 4 challenges reinforced by the ongoing outcomes of Europe's Rail Joint Undertaking (EU-Rail), 3 key strategic priorities to focus beyond the current Research Framework Programme have been defined:

I. New knowledge,

II. Innovation,

III. Solutions.

9.1 ERRAC activity

ERRAC as the European Technology Platform for the railway sector, emphasizes both the vital importance of rail research/ innovation and consolidation the efforts of academic community and rail industry. The bringing altogether stakeholders, train operators, infrastructure managers, rail vehicle builders and other rail industrial suppliers, academics and scientific experts and many involved in rail research is the straightest way to reach the ambitious goals in implementation of railway innovations. In a single strong voice, it articulates to the European institutions the needs of the sector for research and innovation (Rail 2030 Vision, 2017). ERRAC structure, which is contained by various committees and groups, is presented in Figure 43**.**

The researchers of EU universities and institutes are actively involved in ERRAC Steering committees and working groups (Figure 43). The Permanent Advisory Groups (PAG) ensure promotes harmonization between the proposed objectives and the work carried out by ERRAC, with strategies or programs planned at national level or within universities or research centers (institutes). For example, the Steering Committee includes a vice-President from the academic community, ensuring that academic perspectives are integrated into strategic decisions.

ERRAC Working group 2 *Project group* initiates and supports R&I cooperation of ERRAC stakeholders, fostering communication and collaboration between all ERRAC stakeholders, coordinating initiatives and helping to leverage investment. WG2 follows-up of the various projects/events. ERRAC is asked to provide a contribution at conferences such as *Transport Research Arena* (TRA) and International Trade Fair for Transport Technology *InnoTrans*. The

Transport *Research Arena* (TRA) conference is a major event that showcases the latest advancements in transport research, including railway innovations.

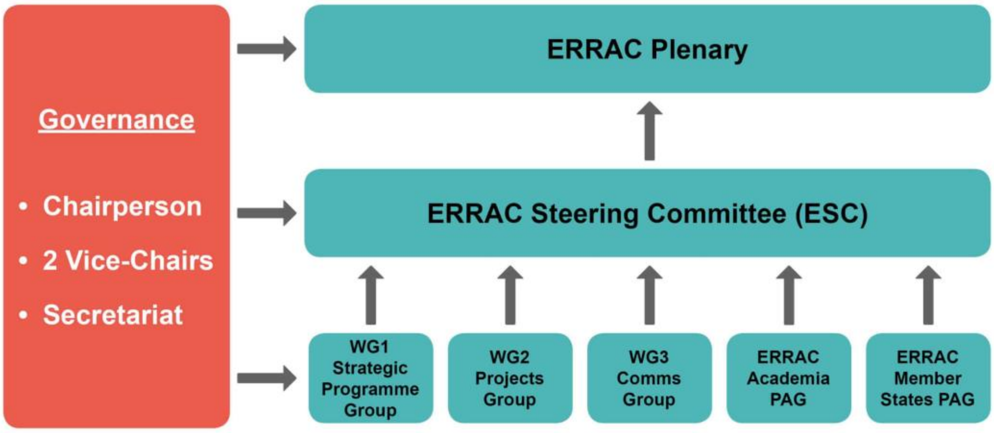

Figure 43: ERRAC structure

WG2 initiates and fosters new collaboration relationships with the other Europe Technology Platforms (e.g. ERTRAC, ALICE, WATERBORNE, ACARE), national research clusters and economic sectors for non-rail specific R&I activities.

ERRAC is a partner with EU universities and research institutions on various projects, such as the Shift2Rail Joint Undertaking and its successor, Europe's Rail. These projects focus on advancing railway technologies and innovations.

ERRAC facilitates knowledge exchange and networking opportunities between academic and rail industry professionals. This includes organizing conferences, workshops, and seminars where researchers present their findings and collaborate on innovative ideas.

ERRAC supports educational initiatives such as the Academics4Rail project, which funds PhD positions in critical railway research areas. It helps bridge the gap between academic research and practical applications in the railway sector. These collaborations ensure that cutting-edge research is effectively translated into real-world railway innovations. This initiative supports PhD positions in critical railway research areas, such as aerodynamics, electromagnetic compatibility, and digital communications. It aims to bridge the gap between academic research and practical applications in the railway sector. This project and research areas are designed to ensure that the European railway sector remains at the forefront of innovation and sustainability.

9.2 ERRAC document Rail 2050 Vision

This strategic document outlines the long-term research and innovation priorities for the railway sector. It emphasizes the need for a fully integrated, digitalized, and sustainable rail system by 2050.

The RAIL 2050 VISION document represents the vision of the rail sector for the needs of the future railway system at the heart of mobility provision for Europe. The document sets out the significant role that rail already plays in delivering economic and societal benefits in Europe and that it can contribute much more, taking advantage of technical developments. For this to happen RAIL 2050 VISION sets out that research and innovation (and other supporting elements, including appropriate regulatory structures) are vital and that end-user and public support for research, development and innovation in the railway of the future is necessary.

https://errac.org/publications/rail-2050-vision-document/

The distribution of rail industry innovations is supported by technical and scientific research in EU railways. The development of related technologies includes the evolution of current developments:

1. the digitalization is the instrumentation of assets, processes and personnel with powerful Information and Communications Technology (ICT) capabilities, able to sense, detect, process, receive, transmit and analyses digital information across secure, reliable and ubiquitous networks, making them all participants of a global *internet of things*.
2. distributed cognitive computing endowing machines to become aware of and understand their surroundings, to recognize patterns, to generate insights from large amounts of distributed data, and to learn.
3. robotics machines to perform goal-oriented tasks autonomously.
4. distributed immutable shared ledgers is “blockchain” technology, allowing the secure recording of transactions without centralized control or coordination.
5. new “intelligent” materials with self-healing properties and the ability to shape themselves in response to external stimuli.

One of the requirements for delivery is the integration of experts from other scientific disciplines and from academia, bringing valuable knowledge from other sectors.

Rail 2030 Research and Innovation Priorities is an action-oriented document supports the delivery of the Rail 2050 Vision by identifying specific research areas and projects to be pursued in the coming years. Key areas include automation, digitalization, and the development of new materials and technologies for rail vehicles

https://errac.org/wp-content/uploads/2019/09/ERRAC_2030.pdf

Full version RAIL 2030VISION is at https://errac.org/

9.3 The ERRAC, ERJU and scientific community seminars

The joint undertakings Shift2Rail and Europe's Rail enhance the competitiveness and sustainability of the European railway sector. They focus on developing innovative technologies and solutions for railway systems, including advanced train control, energy-efficient propulsion, and improved passenger services.

ERRAC and ERJU often participate, presenting their collaborative projects and research findings. ERRAC and the European Rail Joint Undertaking (ERJU) collaborate on various seminars and scientific events to foster innovation and knowledge exchange in the railway sector. One notable initiative is the Academics4Rail project, which aims to build a stable scientific community that can share and exchange knowledge with ERRAC and ERJU.

ERRAC organizes plenary meetings, such as the one held on the 4th of December 2024, in Paris. These meetings brought together key stakeholders, including academics, to discuss research priorities and collaborative projects. Specialized workshops and seminars were on specific research areas, such as aerodynamics, electromagnetic compatibility, and digital communications. They provided a platform for researchers to present their work and closely collaborate with rail industry experts.

ERRAC and ERJU research seminars covered a wide range of topics in railway research.

1. The research in **Aerodynamics of Freight Train** area focused on improving the aerodynamic efficiency of freight trains to reduce energy consumption and increase speed.

2. This topic **Electromagnetic Compatibility** addressed the challenges of ensuring that railway systems and components do not interfere with each other or with external systems, which is crucial for safety and reliability.

3. The innovative approach **Additive Manufacturing in Wheel Reprofiling** uses 3D printing technologies to create and maintain train wheels, potentially reducing costs and improving performance.

4. The research on **Digital Communications for Virtual Coupling** aims to enhance communication systems to enable virtual coupling of trains, which can improve operational flexibility and efficiency.

5. The area **Prognostics and Health Management for Railway Asset Maintenance** focuses on developing predictive maintenance strategies to monitor the health of railway assets and prevent failures.

6. The research in field **Driving Assistance Systems** aims to develop advanced driver assistance systems to enhance safety and efficiency in train operations.

These seminars and events are crucial for consolidation railway research and ensuring that innovative solutions are effectively implemented in the rail industry.

The ERRAC, ERJU and EU scientific community seminars are held also on several key aspects to advance railway research and innovation:

Research Collaboration. These seminars bring together researchers, industry experts, and policymakers to foster collaboration and share the latest findings in railway technology and innovation.

Technological Advancements. Discussions often include cutting-edge technologies such as digitalization, automation, and sustainable energy solutions for railways.

Policy and Regulation. The seminars also address the impact of European policies and regulations on railway research and development, ensuring that innovations align with broader EU goals.

Funding and Investment. Insights into funding opportunities and investment strategies for railway research projects are shared, helping participants understand how to secure financial support for their initiatives.

Case Studies and Best Practices. Presentations of successful case studies and best practices from various railway projects across Europe provide practical insights and lessons learned.

9.4 Description of Proposed and developed Virtual Intercourse Pool (Cluster)

To enable the discussion and collaboration between ERRAC, ERJU and the academic community, proposed virtual intercourse pools have been proposed by the railway academic community. The purpose of these clusters is to provide clear linkages between the academic community and ERRAC with the goals for more systematic input from academia. The proposed cluster is shown in Figure 44.

EU railway R&D&I information flowchart

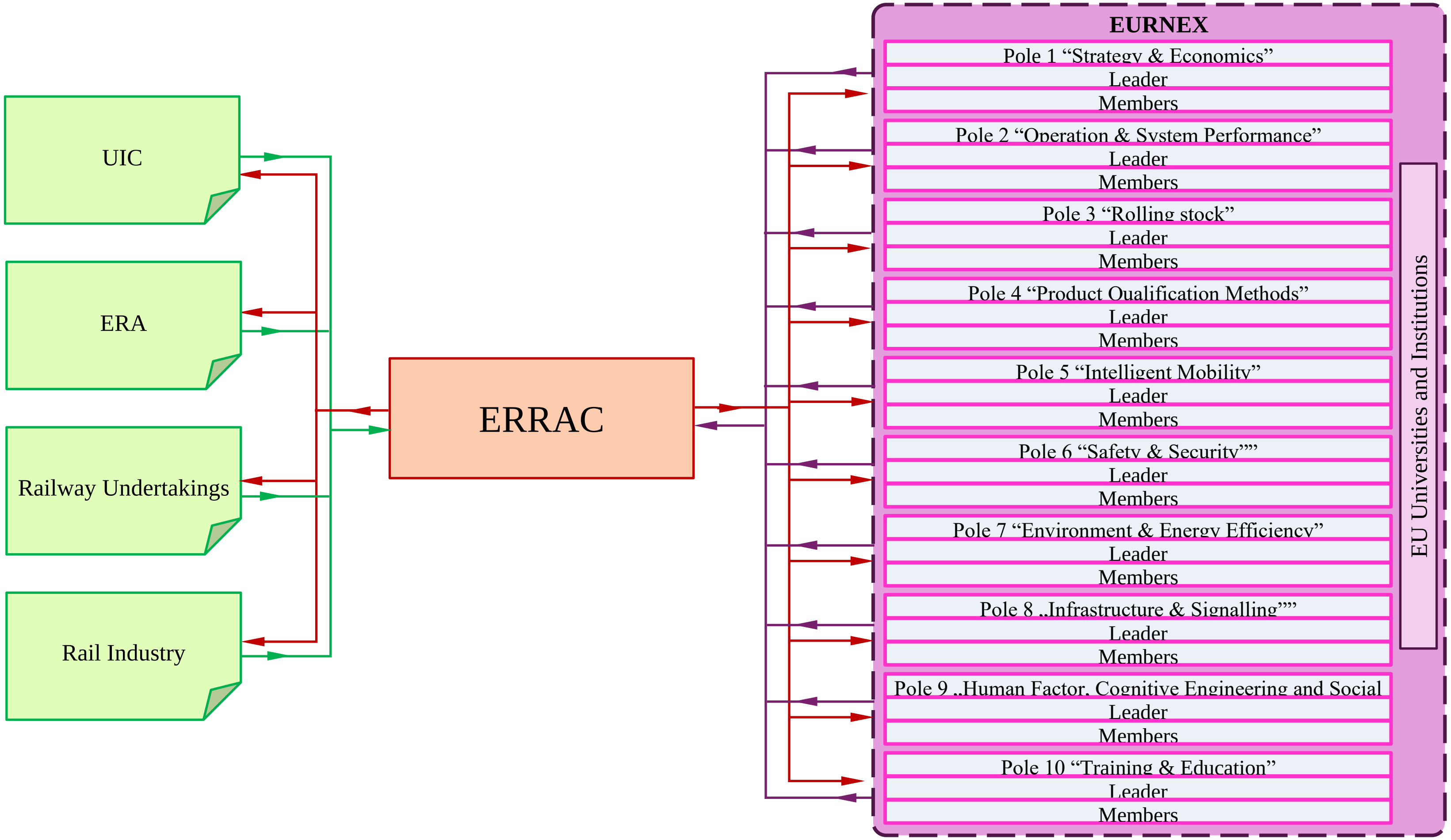

Figure 44: Virtual intercourse POOL (CLUSTER) of railway R&D&I information flows

10 Description of the EU Railway Research and Innovation Coordination Development

For interactive coordination of EU railway research and innovation between ERRAC, ERJU and EURNEX , it is proposed to create a virtual Cluster to manage (control) the R&D&I and decision-making information flows.

Closer and more interactive cooperation between the European academic community – universities and research institutes – in the field of research and innovation with railway undertakings and the railway industry should be coordinated in “on-line” through the ERRAC Academia Permanent Advisory Group (see Figure 44).

ERRAC would coordinate information flows in the three areas generated by:

1. Academic/ scientific representatives.
2. Railway companies (operators, undertakings).
3. Rail industry stakeholders.

An association EURNEX, in turn, completed 10 poles on the following railway research topics:

- Pole 1 “Strategy & Economics” ;
- Pole 2 “Operation & System Performance” ;
- Pole 3 “Rolling stock” ;
- Pole 4 “Product Qualification Methods” ;
- Pole 5 “Intelligent Mobility” ;
- Pole 6 “Safety & Security” ;
- Pole 7 “Environment & Energy Efficiency” ;
- Pole 8 “Infrastructure & Signaling” ;
- Pole 9 “Human Factor, Cognitive Engineering and Social Science” ;
- Pole 10 “Training & Education”.

ERRAC activities considered the R&D&I would be carried out through the newly created official interactive website "Railway Research and Innovation Cluster”. The information on it would be interactively updated and supplemented every 6 months by authorized persons.

An access to the CLUSTER content management and updating sites should be available to ERRAC members, EURNEX Pole leaders, designated ERJU and Rail industry representatives (individuals).

Actual operational ERRAC decision-makings and recommendations on EU railway research and innovation should be adopted and solutions should be made at ERRAC periodic meetings.

11 Conclusions

European railways research plays a pivotal role in advancing transportation infrastructure, promoting sustainability, and reinforcing Europe's global leadership in railway innovation. As rail transport increasingly contributes to Europe's decarbonization objectives and digital transformation agenda, it becomes imperative for academic research initiatives to align with the broader priorities of the railway sector. This position paper aims to identify critical gaps in current research activities, synthesizing insights from the UIC 12 Capabilities assessment and academic surveys on future research areas. It further delineates strategic actions designed to address these gaps, thereby fostering sustained development, innovation, and competitiveness within the European railway industry.

The following conclusions are achieved.

a. **Identification of Critical Research Areas Identified.** Key research priorities include automation, energy efficiency, digital twin technology, AI in railway safety, and cybersecurity. These fields require sustained investment and cross-sector collaboration to realize their potential.

b. **Need for Greater Industry-Academic Integration.** While academia plays a vital role in railway research, closer integration with industry stakeholders is needed to translate research into deployable solutions. Enhanced collaboration mechanisms can help bridge this gap with a focus on data sharing and open *sandboxes* for testing developed tools.

c. **Sustainability as a Core Priority.** Environmental sustainability remains at the forefront of European railway research, with significant emphasis on energy conservation, emissions reduction, and circular economy principles. Future research should continue to build on the strategic European research advantage and emphasize eco-friendly solutions.

d. **Emerging Research Challenges.** Areas such as multimodal transport integration, resilience of railway infrastructure, and AI-driven decision support systems require further exploration and increased research support. Addressing these challenges will be critical to the future competitiveness of the European railway sector, with the changing social, security, and industrial drivers in these fields.

e. **Strong Alignment with European Goals.** The current research landscape, including Shift2Rail and Europe's Rail Joint Undertaking, demonstrates significant alignment with European railway innovation priorities and the priorities outlined by the EU Strategic Transport Research and Innovation Agenda. The transition from S2R to ERJU has reinforced a targeted approach toward the development of innovation pillars that showed the continuation of new projects. With the maturation of these innovation pillars, there is a need for renewed discussion on innovation pillars, with a focus on fundamental research. (Low urgency, high impact, high feasibility)

f. **Systematic Approach to Research Gaps.** The identification and prioritization of research gaps highlight the importance of structured research planning. The adoption of systematic roadmaps, such as those developed in the RAILS project, ensures research efforts remain focused and impactful. Further analyses into other emerging research themes, including Advanced Design, manufacturing, and materials, railway system resilience, railway education and skills development, and railway economics and business models should be considered to ensure research alignment with the railway sector.

g. **Framework for Future Collaboration.** The establishment of the Academics4Rail initiative and its integration with ERRAC and ERJU represents a positive step toward unifying European railway research efforts and providing input from the academic research community. Ongoing dialogue between stakeholders will be essential for fostering a cohesive research ecosystem. Periodic and systematic discussion forums have been proposed to improve the integration of the academic research community with the railway sector.

These recommendations and conclusions provide a structured pathway for advancing European railway research, ensuring alignment with long-term transport and sustainability goals.

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