ERRAC
The European Rail
Research Advisory Council

2025

FUTURE TRACKS

Vision and Goals for Rail Transport Research & Innovation in a Changing Europe

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Autor: ERRAC 2025

Contents

Abbreviations

ACEA	European Automobile Manufacturers' Association
AI	Artificial Intelligence
ASTP	Absolute Safe Train Positioning
ATO	Automated Train Operation
CAPEX	Capital Expenditures
CCS	Control-Command and Signalling
CER	Community of European Railway and Infrastructure Companies
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CMMS	Computerized Maintenance Management System
CT	Combined Transport
DAC	Digital Automatic Coupling
ERA	European Union Agency for Railways
ERTMS	European Rail Traffic Management System
ESA	European Space Agency
EU	European Union
EU-Rail	Europe's Rail Joint Undertaking
EUSPA	European Union Agency for the Space Program
FDFTO	Full Digital Freight Train Operations
FRMCS	Future Railway Mobile Communication System
GDS	Global Distribution System
GHG	Greenhouse Gas
GoA	Grade of Automation
GVA	Gross Value Added
HE	Horizon Europe
HVAC	Heating, Ventilation, and Air Conditioning
IATA	International Air Transport Association
IT	Information Technology
JU	Joint Undertaking
LEO	Low Earth Orbit
MaaS	Mobility as a Service
Mt CO_2e	Million tons of CO_2 equivalent
OPEX	Operational Expenditures
PSO	Public Service Obligation
R&D	Research and Development
R&I	Research and Innovation
RFC	Rail Freight Corridors
RRIA	Rail Research and Innovation Agenda
SERA	Single European Railway Area
SIL	Safety Integrity Level
SSMS	Sustainable and Smart Mobility Strategy
SWL	Single Wagon Load

TEN-T	Trans-European Transport Network
TMS	Traffic Management System
TRL	Technology Readiness Level
UIC	International Union of Railways
UNIFE	The European Rail Supply Industry Association
VR/AR/XR	Virtual Reality / Augmented Reality / Extended Reality

1.

1 Railway in Europe

Europe faces a shifting landscape marked by heightened geopolitical tensions, supply chain vulnerabilities, and the imperative for climate action. The Draghi Report (2024)[1] underscores that the EU competitiveness is threatened by fragmented markets, insufficient investment, and persistent regulatory barriers, particularly in transport. Labor market transformations, driven by automation and digitalisation, are altering workforce requirements, necessitating upskilling and reskilling to match new technological demands. The development of new technologies is also necessary to tackle the labour gap. As Europe advances toward climate neutrality and strategic autonomy, as the most efficient, resilient, and future-ready mode, rail is key for the European mobility of persons and goods. It is not only key to reducing emissions, but also essential for economic strength, energy security, and geopolitical stability.

Unmatched energy efficiency and climate performance: Rail produces just 25 kg of CO_2 per Euro of economic output - 24 times less than road transport (600 kg/€), and far below maritime (255 kg/€) and aviation (243 kg/€)[2]. At the European level (EU27), in 2022, the rail mode was representing 0,3% of the total of Greenhouse gas emissions from transport with a continuous decrease since 1990 for a 7,2% market share for the passenger transport and 16,6% for the freight transport. This isn't just about emissions - rail also consumes far less energy overall. Thanks to its physical efficiency (steel wheels on steel rails), trains require 3 to 5 times less energy per ton-km or passenger-km than road or air, and such efficiency rises-up much more in case of metro. Most of the European rail network is already electrified, providing the best energy efficiency for the mobility. Moreover, land consumption caused by rail is low compared to other modes of transport. This is a real advantage as it increases the quality of life, particularly in large and dense urban areas.

Stable employment, high-tech leadership, and export potential: Rail creates 1,09 % of EU jobs (road 3,42 %, air 0,44 %, maritime 0,33%)[3], with an employment multiplier like the one of automotive sector but much more stable and less volatile - each direct job

[1] https://commission.europa.eu/topics/eu-competitiveness/draghi-report_en
[2] Calculation based on market value data from ACEA, IATA, UNIFE, CER, UIC, EMSA and Eurostat on GHG production in Mt CO2e/year
[3] Direct, indirect and induced jobs. Source: Land transport jobs: Key figures on European transport 2024 edition (Eurostat), rail transport jobs: Eighth monitoring report on the development of the rail market under Article 15(4) of Directive 2012/34/EU of the European Parliament and of the Council. Indirect and induced jobs multiplicator: Source1 Trends, challenges and opportunities in the EU transport labour market, Ecorys, requested by the TRAN Committee, EU Parlament 2024. Source2 Employment in Sustainable Transport, Ekosgen UK, 2010

supports further employment in services and industry. It offers stable, long-term workplaces in infrastructure, manufacturing, operations, and innovation.

Europe is also a global leader in rail technologies, engineering and services, exporting high-speed systems, digital signalling, and rolling stock, the capacity to manage the engineering. Demonstrating its commitment to next-generation technology, the European rail supply industry reinvests 3.6% of its annual revenue to R&I activities. With an annual global market growth of 3% and an expected value of 240 billion Euro by 2029[4], the European rail supply industry is a global leader in the design, manufacturing and maintenance of railway systems and products, corresponding to over 650,000 jobs in Europe. In addition, European industry is also world leader in metro automation (Unattended Train Operation) ensuring unique performances in terms of scalability, adaptation and resilience of urban transport services. The sector is a cornerstone of EU industrial competitiveness and sovereignty, driving high-tech development and green innovation/clean-tech, but not in a consumer-oriented market. Market launch depends primarily on socio-political factors.

- *Compared to other modes of transport, railway jobs enjoy a certain degree of stability, resistant to crisis and market fluctuations.*
- *Investing in rail strengthens a competitive strategic industrial base with global reach and resilience against economic shocks.*

Strategic infrastructure for emergencies and defence: Rail is more than just a means of transport - it is a critical infrastructure. In times of crisis - be it pandemics, natural disasters, or other emergencies - rail ensures the reliable transport of people and vital goods across regions and borders.

- *It also plays a key role as strategic logistics factor, enabling the rapid deployment of heavy equipment and personnel, reinforcing Europe's strategic and defence capabilities.*
- *In large urban areas, urban rail systems are the main tool to make cities liveable and attractive.*

Rail at the service of the socioeconomic growth, the freedom of movement and the right to travel: Throughout all European countries, rail is the mobility backbone for both goods and people, acting as an essential mobility service for socioeconomic advance and well-being of European cities and citizens, as well as a tool for building liveable, democratic and people-centred region and cities. Urban rail systems, including metros,

[4] World Rail Market Study, forecast 2024 to 2029 - https://www.unife.org/news-resources/wrms/

trams, and suburban trains, highly contribute to enable over 25 billion passenger journeys annually. Urban and regional rail allow to connect citizens with workplaces, schools and healthcare institutions, their families and their social life, easing the tourism all over Europe. It is at service of every person being mobile all over Europe even relevant for low-income families, elderly, and less mobile people. It reduces congestion in cities, which costs the EU some €270 billion a year, avoiding in urban areas greater inequality, reduced productivity and greater environmental and economic stresses. In cities, a metro line can support 40.000 passengers per hour when the equivalent road in terms of width supports a traffic of 700 cars per hour which means serving around 900 people by car (1,3 average number of people/car) at a speed of less than 15 km/h.

1.1 Six Key Challenges

Rail is at a cornerstone of Europe's green transport future - yet despite its environmental, economic and social benefits, it remains underutilised. In 2022, rail accounts for just 7-8% (stagnating) of passenger transport output and a modest 18% (declining stagnating) of freight in the EU, dwarfed by roads (75-80%) and undercut by aviation, especially low-cost companies[5]. Europe's rail strength comes from nationally rooted systems working together under a common EU vision, fostering innovation, accountability, and local adaptability.

This model has turned Europe into a global rail leader - pioneering high-speed technology, fostering competitive industry giants, engineering companies and transport operators, and setting standards for seamless cross-border travel. While exact investment figures vary, the EU and its member states invest big amounts annually into rail, support smart modernization and infrastructure expansion to keep rail competitive and performing towards the other modes.

Challenges like fragmented rail systems and freight inefficiencies persist - but Europe is addressing them through the TEN-T network and the Single European Rail Area (SERA), which aim to delete the barriers for the rail operations all over Europe. Meanwhile without rail, urban areas would experience greater inequality, reduced productivity and greater environmental and economic stresses.

The European rail supply industry is a global leader in the design, manufacturing and maintenance of railway systems and products. Maintaining its positive trade balance through the development of innovative solutions will not only support Europe´s rail industry on a global level, make the European railway system stronger but also address climate chang and ensure economic growth. Because of this, hurdles are opportunities

[5] Eurostat 2024, detailed datasets, transport, railways, railway transport measurement. Values in passenger-km and tkm

for Europe to pioneer a uniquely collaborative, green, and people-centred rail renaissance, proving that sustainability and progress can go hand in hand.

- **Fragmented rail systems & lack of standardisation:** despite tangible progress, differences in signalling systems, electrification, track gauges, and rail slot allocation due to the history, the long-life cycle of the assets and the associated evolution of the national regulations still pose challenges for seamless cross-border rail operations. Operational rules also vary, affecting overall efficiency and in particular of train drivers. Harmonisation activities which started in Europe's Rail must still be completed, implemented and validated in cooperation with the European Union Agency for Railways.
- **High System Costs:** The European railway system is facing high costs due to fragmented national networks, increased costs of a fragmented digitalisation, causing inefficiencies and rail systems duplication. Variations in technical standards and associated certification processes necessitate costly modifications not only to ensure cross-border operations. Additionally, elevated asset require investment in modernizing infrastructure and implementing technologies like ERTMS further escalates costs. Regulatory complexities and lengthy approval processes for projects also contribute to higher operational and development expenses. Simplification and harmonisation of operations, processes and products is cornerstone to reduce costs.
- **Low competitive rail freight operations and lack of competitive pricing & flexibility:** Freight trains have suffered for many dozens of years of a long list of hurdles even with the total opening of competition at the European level, an increase flexibility of the trucks (decrease of oil prices, definition of European regulations, low level of the road charges, etc.), with the decrease of the heavy industry, insufficient digitalisation, lack of offers and service flexibility, limited last-mile connectivity and long waiting time at the borders. They all together make rail freight less appealing to customers and less competitive to road transport. A large-scale deployment of the Digital Automatic Coupler (DAC), the development of new digital services on top of it, consolidation, integration and advanced data analytics and automation of freight operations would significantly increase the efficiency of rail freight operations and making them attractive again.
- **Underinvestment in maintenance, regeneration & modernisation:** aging infrastructure is an issue for many rail networks, leading to delays, speed restrictions, and loss of reliability. Some governments often prioritise roads and aviation over rail upgrades. New maintenance and retrofitting solutions, using

Digital Twins or AI for instance, could mitigate low investment by cost-efficient alternatives.

- **Urban congestion & last-mile connectivity issues and regional/rural services;** In many European cities, weak links between rail and other local transport modes make trains less convenient for the last mile. This is especially true in regional and rural areas, contributing to transport poverty and limiting access for underserved communities. It deems necessary to create multimodality and specific last mile solutions to fight transport poverty and feed regional and rural rail lines, ensuring capillarity.
- **Lack of seamless ticketing & integration:** Unlike aviation with the Global Distribution Systems (GDS), the rail ticketing services are fragmented, mainly governed by fragmented markets, operators and national rules/regulations, they are managed by public authorities under the Public Service Obligation or open to competition. Given the lack of a common framework for booking systems, making cross modes and cross-border travel planning can be easily cumbersome. Digitalisation and cybersecurity and harmonisation are the required tools, together with regulation if needed given the sector initiatives for cross-country ticketing, to overcome this challenge.

1.2 EU Objectives vs. Investment: Bridging the Gap

While the European Union has placed rail at the core of its decarbonisation and sustainable mobility agenda, a closer look at funding patterns reveals a persistent imbalance between ambition and allocation. Despite rail's proven environmental, economic, and social benefits, investment in rail research remains disproportionately low compared to other transport modes.

To achieve Europe's long-term mobility goals especially towards an shift in modal split, budgets must, support not only the construction of tracks but also the innovation that powers them.

It is time to put brains to the muscles of rail: aligning investments with the EU's strategic objectives to unlock the full potential of Europe's most sustainable mode of transport.

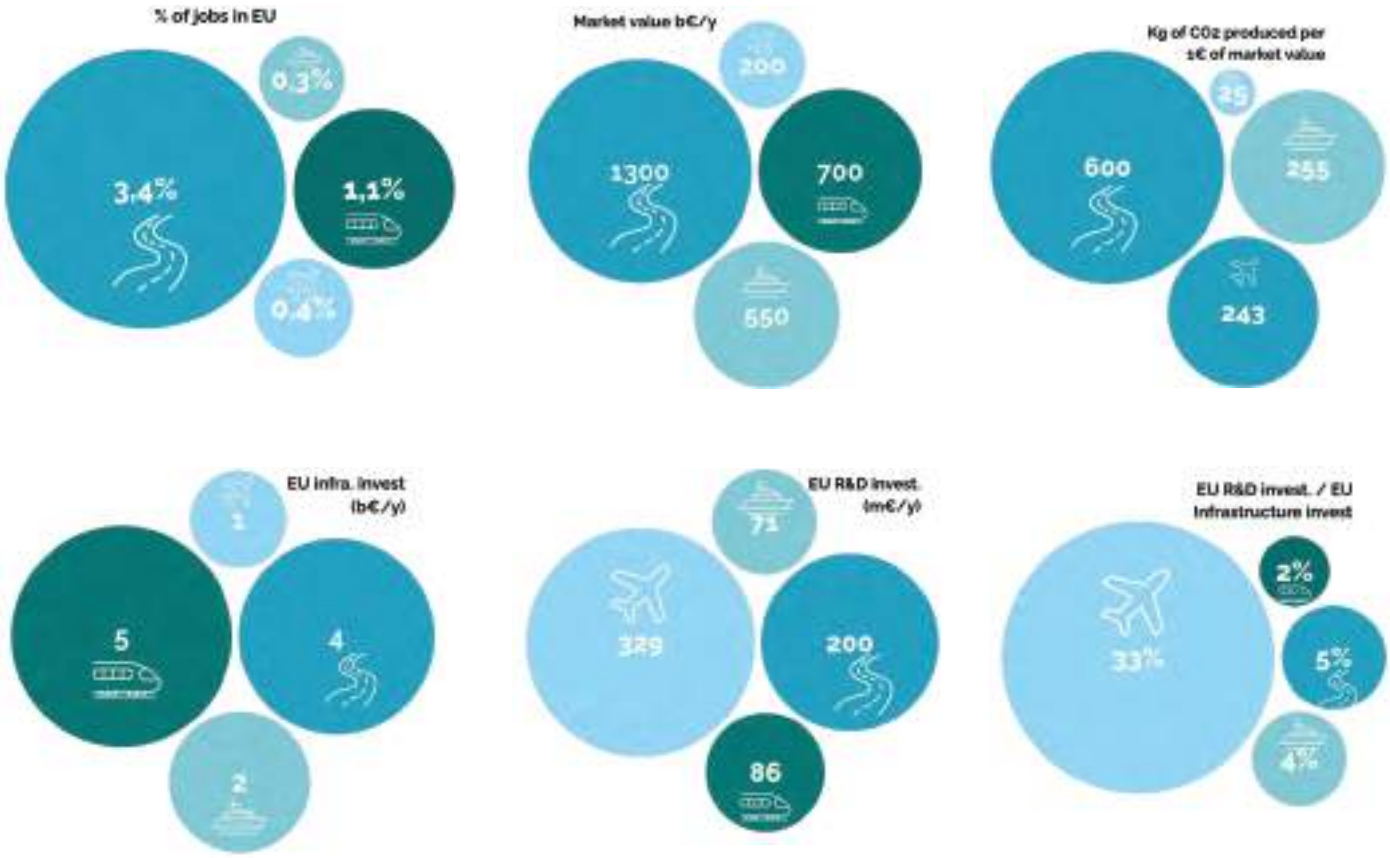

Figure 1. Comparison of EU Transport Modes: Market Value, Employment, CO_2 Efficiency and Investment Patterns. Source and data: EURNEX www.eurnex.org/wp-content/uploads/2025/10/image.png

This section aligns closely with the recent Oxford Economics study for CER, “The Economic Footprint of Railway Transport in Europe” (2025), which confirms and reinforces the trends illustrated above. The study shows that rail now contributes €247 billion to EU GDP and supports over 3.1 million jobs, equivalent to 1.6% of total EU employment, marking an increase in both economic value and employment since previous assessments. These results demonstrate that rail is not only the most climate-efficient mode of transport, but also a powerful driver of industrial competitiveness, innovation, and regional cohesion. Yet, as the investment comparison highlights, the sector still receives disproportionately low levels of R&I funding.

Closing this gap is vital for Europe to fully realise rail’s potential, fostering sustainable growth, advancing the Green Deal, and aligning financial priorities with the EU’s long-term climate and mobility objectives.

2 The European Context

2.1 European Union Goals supporting Rail

The European Green Deal aims to achieve a 90% reduction in transport-related greenhouse gas emissions by 2050[6]. The European Commission's "Sustainable and Smart Mobility Strategy (SSMS) – putting European transport on track for the future" of December 2020 sets concrete objectives and milestones towards the digitalisation and greening of the transport sector and rail. Achieving Europe's climate neutrality targets by 2050, including a targeted 90% reduction in European transport GHG emissions, is only possible by attracting more passengers and freight to the rail mode which therefore needs to increase its efficiency, attractiveness, accessibility and competitiveness. The targets are ambitious for the rail mode, i.e. traffic on high-speed rail to double by 2030 and triple by 2050, rail freight traffic to increase by 50% by 2030 and double by 2050, rail and waterborne-based intermodal transport to compete on an equal footing with road-only transport in the EU by 2030.

A coordinated European approach to R&I , like through Shift2Rail and Europe's Rail, has proven to be vital to overcome the historic and obstructive fragmentation in the rail system and to deliver harmonised European-wide technical and operational solutions making the European rail system more agile, innovative, reliable, resilient, capacity-performant and achieve a Single European Railway Area (SERA)[7] and the objectives set out in the SSMS.

The Letta Report on the Future of the Single Market (2024)[8] rightly points to key objectives that need to be achieved in the future to ensure that the Single Market serves as a catalyst for seamless and sustainable transportation in the EU.

> ***"The completion of the European transport network, with a special focus on railways, must be accelerated if the Single Market is to regain dynamism and strategic depth"*** **Letta Report (2024)**

The Draghi Report (2024) warns that Europe's competitiveness is at risk due to fragmented markets, underinvestment, and dependence on foreign suppliers. It calls for Europe to re-industrialise and to invest more in sectors like rail. Rail infrastructure and supply chains are now seen as essential, not only for the environment, but also for keeping Europe strong and secure. In addition, the report supports the development of a

[6] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[7] https://www.consilium.europa.eu/en/policies/rail-transport-policy/
[8] https://single-market-economy.ec.europa.eu/news/enrico-lettas-report-future-single-market-2024-04-10_en

high-speed rail network connecting all EU capitals and major cities, which would enhance rail attractiveness and contribute to decarbonisation. Indeed, the Starline blueprint, published by the think tank 21st Europe, envisions a transformative high-speed rail network connecting major European cities by 2040. It claims to reduce emissions by up to 95% and cut short-haul flights by 80%[9].

> ***"Strengthening strategic infrastructures such as rail is vital to enhance Europe's competitiveness and autonomy in a more contested global environment."*** **Draghi Report (2024)**

Various political initiatives at European level (e.g. the March 2025 EU transport minister meeting[10], The Targeted Consultation on Military Mobility establishing a new regulatory framework[11]), are currently emphasising the need for dual-use technologies. Railway, which is predestined for the rapid transport of goods and people, has a special role to play here. This shows how rail is no longer just about transport - it's about resilience and sovereignty

To be sovereign and more independent from external supply chains, we need to support our own rail supply industry. Europe has a strong rail industry with many capable companies, large and small. But they need support to stay competitive. The ERRAC Rail Research and Innovation Agenda (RRIA, 2024)[12] and UNIFE's industry priorities for 2024–2029[13] both stress the need for investment, innovation, and better coordination.

Rail is not just about tracks and trains - it's also about people. As rail systems become more digital and more automated, people working in rail sector need new skills. At the same time, the sector is facing a shortage of skilled workers, especially in areas like IT, engineering, and operations. The World Economic Forum and the RRIA both point to a big gap between current skills and what is needed for the future. If we do not invest in training and attract new talent, the sector will fall behind.

2.2 The Need for European Rail R&I

A well-functioning rail system is strategically important for the EU citizens, the economy as well as for security of the EU and its Member States. Rail is central to decarbonise the transport sector, being the most environmentally friendly transport mode in Europe

[9] https://21st-europe.com/blueprints/starline
[10] https://polish-presidency.consilium.europa.eu/en/events/informal-meeting-of-transport-ministers-17-183/
[11] https://defence-industry-space.ec.europa.eu/consultations/targeted-consultation-military-mobility-package_en
[12] https://errac.org/publications/rail-research-and-innovation-agenda-rria/
[13] https://www.unife.org/wp-content/uploads/2024/03/UNIFE_Priorities_2024-2029.pdf

today. This role must be further strengthened and expanded by upgrading and extending the necessary infrastructure and retrofitting rolling stock as well as by supporting innovative solutions to current and future challenges, taking in account the significant investment's needs rail is facing to maintain a coherent and performing European rail system.

Given today's challenges, it is particularly important to further strengthen the European railway system as an essential part of services in the general interest and to take the necessary steps in the field of research and innovation to this end. All types of rail services (high speed, freight, regional, urban, and suburban trains, metros, tramways) must be a reliable element of the European transport network, running even in situation of crisis. To achieve this, a focused, fast, use-case and business-case approach is needed. Only this allows us to achieve a true Single European Railway Area (SERA) with a well-running and customer-oriented rail transport that contributes to reach the objectives of the SSMS and lays the foundation of a competitive Europe.

Following the RRIA published in September 2024, further research is needed for **System Optimisation**, **Lowering Costs** strengthening **Sustainability**, improving **Multimodality and Intermodality** as well as **Inclusive and Personalised Services** in the sense of comprehensive "Mobility as a Service" solutions. This means to increase the capacity of existing infrastructure, improve traffic management systems, lower costs, simplify the system and improve interfaces with other transport modes as well as become more reliable and resilient against climate change, armed conflicts, and cyberattacks. Decarbonisation can also be fostered with advances in asset management, deepening on asset monitoring and hence, planning and execution of works using "cutting-edge" technology, techniques and processes, which could, amongst other targets adequately support Regulatory Asset Based (RAB) models for investment in (high speed) railway infrastructure, suggested for its development by the Draghi Report. Likewise, increased research activities are necessary to achieve total decarbonisation of rail as well as set up a circular economy to further strengthen the railway system as the most environmentally friendly and sustainable means of transport. This will lead to a system in which productivity, capacity quality and attractiveness will be significantly increased.

2.3 Success of Past European Rail R&I

The European rail sector has made significant progress in recent years, driven by ambitious research and innovation programmes of Shift2Rail and the ongoing Europe's Rail Joint Undertaking "EU-Rail". These initiatives have laid the foundations for greater interoperability, digitalisation, and efficiency across the sector, supporting the competitiveness of the European rail industry. Stakeholders from both the European rail

supply industry and rail operating community have together invested, collaborated and benefitted from the first two European rail Joint Undertakings (JU). The success of Shift2Rail and EU-Rail in contributing to EU policy and addressing its common objectives outlined below validate the significance of such public-private collaboration for the future rail system and have demonstrated that collaboration across the value chain is not only possible but essential.

R&I remain essential levers for the railway sector to safeguard and further develop the system. The previous programs have shown that it is not sufficient to just look at rail research innovation, but also to consider the full lifecycle, including the future concept for operation and the functional system architecture. Shift2Rail and the EU-Rail fostered a cross-industry collaboration unlike anything that had come previously. Success stories include:

- **Traffic Management System:** Further developments for TMS were made to develop a more dynamic strategic planning for the network and a dynamic and optimised network traffic management at European level including European cross-border scheduling and optimisation, contributing to ERTMS, enabling automatic management of cross-border rail traffic and attempting to connect rail and aviation Information System.
- **Automated Train Operations:** Success stories of the past programmes included the test of up to GoA4 train tests, automated shunting and stabling, remote train operations also for tramway systems, train positioning development (incl. joint actions with other EU-body as EUSPA and ESA), preliminary tests of virtual coupling, development of the moving block concepts, tests of the new European telecommunications standard FRMCS – all technologies which allow to increase the capacity and efficiency on existing infrastructure.
- **Rail Freight:** For the freight sector, huge steps were made with the development and testing of the Digital Automatic Coupling (DAC) under operational conditions. European harmonised, scalable, upgradable DAC systems were developed to support digital-enabled operational procedures and digital yard automation, and management solutions were developed and tested. In addition, solutions to digitalise freight transport such as standardized European railway checkpoints easing cross-border traffic, harmonized maintenance data exchange, and multi-country driver licensing new wagon concepts to make freight more competitive were developed.
- **Resilience, sustainability & maintenance:** to increase resilience and improve the system maintenance, a common European asset management framework using digital technologies and data analytics to minimize lifecycle costs and extend the service life of rail assets was developed, wayside monitoring

technologies were improved, additive manufacturing was successfully applied to railway technologies and field test campaigns for robotic platforms were carried out. To improve the sustainable footprint of the railway sector, a 200km demonstrator testing for a battery electric multiunit was carried out. Silicon Carbide developments are now a reality and part of the portfolio of the rail traction industry. Moreover, technologies to improve air quality in passenger cars through innovative HVAC systems, solutions for airless trains and SIL 4 braking systems are notable success stories.

- **Regional Railway:** For regional railway lines, cost-efficient, energy self-sufficient wayside solutions as well as digital solutions to help reducing the number of necessary wayside devices and the associated concepts of simplified operations were developed. This will ensure the long-term economic sustainability of regional railways by lowering CAPEX and OPEX.

In addition to the challenges the sector is facing, i.e. to introduce research and development results already achieved or the integration of new technologies in a system that serves the general public and is not anchored in a traditional consumer market, and to make the associated resources available, the continuation of R&I activities is crucial to increase the technology readiness level (TRL) and maturity of the innovative European solutions initiated and developed within these programs and to ensure the next development steps to bring innovations and their benefits to the market more quickly through targeted upfront testing and implementation across the entire EU rail network. In this context, the Pre-Deployment Group of Europe's Rail, initially focusing on the Future Railway Mobile Communication System (FRMCS), provides the necessary framework to accelerate the time-to-market of such innovations. Furthermore, both Shift2Rail and Europe's Rail have proven to be essential instruments in strengthening cooperation among rail stakeholders at the European level. They have fostered the creation of enduring networks of expertise and collaboration, successfully integrated universities and start-ups into these ecosystems, and laid the groundwork for the harmonisation of the European railway system, supported by key enablers such as the System Pillar.

3 Areas of Attention Requiring Joint Innovation

Despite the important advances achieved, several challenges remain and still limit the sector's ability to reach its full potential. At the same time, there is a growing cultural shift across Europe: an increasing alignment and willingness among stakeholders to break traditional silos, embrace joint innovation, and drive simplification forward. The momentum is there to take stronger and more decisive steps toward a fully competitive, agile, attractive and sustainable European rail system.

The primary R&I areas are therefore:

- **Increase of Rail Capacity and Boost Agility:** Use of innovative solutions and digitalisation to increase capacity as a supplement to conventional expansion methods. Develop a system that can react dynamically to disruptions and implement shorter innovation cycles through enhanced modularity and simplified certification processes. Accelerating the validation and authorisation of innovations and encouraging faster deployment of new technologies.
- **Sustainable and Resilient Rail Transport:** Ensure safety and security of critical infrastructure in all areas and expand capacity to improve resilience and continuous availability of the system, also addressing the shortage of skilled workers in the railway sector. Increasing the resilience of the railway system, in particular to be able to adequately manage critical disturbances. In addition, define measures to further improve energy efficiency and energy supply, the use of sustainable materials to further reduce the system's ecological footprint, and massive investments in sustainable competitiveness.
- **Address Customer's Needs for Freight Transport as well as for Passenger Transport, especially Urban and Regional**: Improve quality and attractiveness of rail transport for freight and passengers by further development of multimodal and intermodal integration in all dimensions, better door-to-door service solutions so that customers and their needs are at the heart of all activities by inclusive and personalised services.
- **Drive Simplification by Ensuring a Standardised and Harmonised Approach:** innovation plays a crucial role in standardising and harmonising the European railway system. This will lead to cost reductions, lower barriers to new entrants to make railway more efficient, providing the suppliers/manufacturers a competitive advantage by shorter technology innovation life cycles. The known challenges underline that a lack of a European approach towards a system simplification would significantly undermine a) the EU industrial leadership and competitiveness, b) the European ability to respond to passengers' and businesses' needs and c) the achievement of a Single European Railway Area. Based on the European and national challenges.

Figure 2. Vision of achievable goals from a new R&I programme

3.1 Increased Rail Capacity and Boosting Agility

3.1.1 Motivation & Objectives

The creation of a comprehensive pan-European high-speed rail network and the establishing of a truly integrated Trans-European Network of Transport (acc. to TEN-T Regulation (EU) 2024/1679)[14] seamlessly connecting all EU capitals and major urban centres (among the 431 “urban nodes” identified by the Regulation) represent a unique opportunity to revolutionise European rail transport and advance EU integration. By ambitiously connecting the continent's most important cities, this project stands to

[14] https://eur-lex.europa.eu/eli/reg/2024/1679/oj/eng

significantly elevate rail's role in long- and medium-distance transport, aiming to capture more than 50% of the market share. This initiative is not merely an advancement in transportation infrastructure; it represents a critical step toward forging a more connected, accessible, and unified Europe. Its realisation will serve as a cornerstone in the EU's journey towards enhanced connectivity, economic growth, and environmental sustainability, underscoring its profound importance for the future of the European Union. In addition to these challenges, increased efforts are also needed for covering all parts of cities, suburbs and rural areas, providing better opportunities to commute between cities as “core” and the suburbs and the wider (rural) environment, increased capacities and affordable services to all citizens including the elderly and persons with reduced mobility. To be able to cope with the ever-increasing demands and the expected higher transport performance in passenger and freight transport, it is necessary to further increase the adaptability, agility and rapid response capacity to changes in the railway system.

3.1.2 Needed Technical Enablers

To achieve this objective, research and innovation are necessary in the following areas, among others:

- Modular & Scalable Technology Development: Develop plug-and-play modules/components for different fleet sizes and use cases
- Higher automation up to autonomous operation for railways (GoA 3/4), e.g., in the field of Safe-AI, Sensor Systems and Absolute Safe Train Positioning (ASTP), Virtual Coupling and Unmanned Operation, and thus higher route utilisation. Role of humans and the interface with the automated systems.
- Safe-AI-Driven Decision Support: Use Safe-AI to optimise traffic flow, train path allocation, and logistics planning
- High speed vehicle components including aerodynamic and engine improvements for less energy consumption
- Safe Communication Network for Rail, e.g., in the fields of FRMCS, 6G, European Satellite System (LEO satellites)
- Predictive Maintenance Technologies: Innovate maintenance strategies through AI and big data to shift from reactive to predictive maintenance, reducing downtime and lifecycle costs for both rolling stock and infrastructure.
- Integration of Construction Innovation: Leverage new construction methods (e.g., modular bridge building, 3D printing, robotized track laying) to speed up the building and renewal of infrastructure while minimising disruptions

- Digital Twins and Virtual Certification: Establish a pan-European approach to digital twins and virtual testing environments to speed up certification processes and reduce physical testing requirements
- Digital twins to support increased decision processes by the integration of modelling and simulation.

3.2 Sustainable and Resilient Rail Transport

3.2.1 Motivation & Objectives

Given today's challenges, it is particularly important to maintain and enhance the SERA and non-SERA European railway system as an essential part of services in the general interest and to take the necessary steps in the field of research and innovation to this end. Rail in all its kinds (High speed, Freight, Long Distance and Regional Trains, Metros and Tramways) must be a reliable component of the European transport network, usable even in crisis situations. Increasing the resilience of the railway system requires research into the impacts of climate change, health crises, dangerous interventions in critical infrastructure, cyberattacks, military conflicts, and tackle the skills and labour gap, as well as research into general railway operations to cope with increased loads on the railway network and enable faster decisions to deploy alternative solutions. Likewise, increased research activities are necessary to achieve total decarbonisation of rail transport to further strengthen railway's position within the European transport system.

By enhancing the availability of trains and tracks through improved maintenance, we can significantly increase the reliability of the promised mobility service, reduce the inconvenient disruptions caused by maintenance closures, ensuring safer and more gratifying travel experiences for all passengers *and freight services*. Continuous monitoring allows to identify potential issues before they escalate, thereby decreasing the requirement for human intervention in challenging or hazardous situations. Enhancement and improvement of the human skills of rail working staff to decrease risks coming from the actions involving human factor shall help for the overall abovementioned objectives, especially contributing for an increased resilience of the rail system. In summary, resources *are optimized*, *downsize educed* to take informed maintenance decisions that prioritize both urgency and cost-effectiveness.

3.2.2 Needed technical enablers

To achieve this objective, research and innovation are necessary in the following areas, among others:

Sustainability

- Decarbonisation strategies for hard-to-electrify rail areas by research in Alternative Propulsion, Smart Power Management and saving Traction Energy
- Energy recovery from operational processes, e.g., safe electric brake, use of waste heat in metro tunnels
- Circular Economy in rail manufacturing, construction, operation, maintenance and service
- Usage of sustainable materials for railway applications, e.g., wood or composite with green fibres, etc.
- Environmentally friendly Vegetation Management, Biodiversity Management along railway corridors and Smart Environmental Monitoring Systems for railways
- Construction of lighter and more energy-efficient vehicles based on new safety technology (active vs. passive safety) and adaptation of the corresponding standards
- Reduction of negative externalities such as noise and air pollution, and vibrations through innovative mitigation technologies and regulatory harmonisation

Resilience

- Determination and evaluation of military requirements regarding dual-use and derivation of necessary research projects
- Cyber Security and Shielded Systems, e.g., common frameworks and solutions for cybersecurity, protecting both digital and physical assets across the rail system
- Quantum Computing for Train Planning and Operation Systems for provision of the better optimised solution in real time in case of disturbance
- Using Extended (Virtual and Augmented) Reality to tackle the skills and labour gap through virtual assistance systems to support operations and maintenance, e.g., as smart helmets and/or glasses
- Wearable Technology for Maintenance Crews, e.g., suits equipped with sensors monitoring the health and safety of maintenance workers in real-time (e.g., detecting fatigue, location, and vital signs).
- Drones for Track and Infrastructure Inspection: Drones equipped with high-resolution cameras, LiDAR, and thermal sensors to inspect tracks, overhead wires, bridges, tunnels, and other infrastructure components.
- Robotic and Autonomous Track Inspection and Maintenance, e.g., for track alignment, ballast cleaning, and rail welding.

- Standardised Modular Infrastructure Components, e.g., track systems, signalling equipment, which can be produced and deployed rapidly with minimal customisation
- Data-Driven Maintenance Management Systems (CMMS) using big data and analytics to streamline the scheduling of infrastructure maintenance tasks, track inventory, and manage work orders.
- Safe-AI-assisted Predictive Maintenance and Real-Time Monitoring for continuous monitoring e.g., vibrations, temperature, pressure, and wear
- Research, investigations and development due to Climate Resilience of Rail Infrastructure, e.g., better predictive capabilities, design principles to increase the resilience of the systems to withstand extreme weather conditions, analyse the different types of hazards faced for decision, in line with climate adaptation goals outlined in broader EU resilience strategies, collaborate on designing rail systems that can withstand extreme weather conditions, in line with climate adaptation goals outlined in broader EU resilience strategies
- Planning rules for reaction to (multiple) local and massive disruptions and definition of the associated strategy for decision-oriented investments
- Innovative rail vehicles for disaster relief and medical care
- Build European-wide train monitoring detector station and data networks

Alongside technical enablers, information on the economic parameters needed to optimise cost, sustainability, and resilience objectives is lacking. Understanding the

trade-offs and even win-wins between these would greatly strengthen research impact and implementation.

3.3 Addressing Customer's Needs for Freight Transport

3.3.1 Motivation & Objectives

European freight transport is an important economic sector and at the same time a key element in our collective effort to take on climate change, since rail is nine times less CO2-emitting than road[15]. Clean and decarbonised logistics chains are vital for enhancing Europe's competitiveness, strategic autonomy, security, and defence. In addition to intermodal freight transport, single wagon loads (SWL) and combined transport (CT) are crucial for efficient and sustainable freight transport throughout Europe. To increase rail freight by 50% by 2030 further research and innovation is necessary that aims at increasing rail freight's competitiveness, flexibility, performance, reliability, and profitability. Furthermore, we need the full integration of rail freight transport with other transport modes which then leads to an improved multimodal and intermodal logistics chain and will ensure environmentally friendly and sustainable door-to-door logistics services.

3.3.2 Needed Technical Enablers

To achieve this objective, research and innovation are necessary in the following areas, among others:

- Full Digital Freight Train Operations (FDFTO)
- Dynamic Scheduling and Capacity Management for cargo services
- Green City Logistics Concepts and Joint Transport of People and Goods, including modular hubs / micro-hubs
- Fully Automated Yard Management / Freight Hubs
- creating Open Digital Ecosystems for rail freight innovation and improving Rail freight with Personalised, Real-Time Solutions
- Developing new freight wagon models by adapting existing freight wagons including tank wagons to safely transport new commodities and power supply
- Freight vehicle components and overall design development including aerodynamic, weight and load bearing improvements for less energy consumption advancing in performance and efficiency of operations, if possible, allowing maximum compatibility and capacity between high-speed and freight traffic operations in the TEN-T lines and Rail Freight Corridors (RFC)

[15] https://www.eea.europa.eu/en/analysis/maps-and-charts/term27-specific-co2-emissions-per-passenger-km-and-per-mode-of-transport-in-europe

3.4 Addressing User Needs for Urban and Regional Passenger Transport

3.4.1 Motivation & Objectives

Achieving a modal shift for local and daily mobility must be a European priority. In fact, the fastest and most cost-efficient way to reduce CO_2 and pollutant emissions in people's daily mobility is to accelerate the shift towards mass transit, multi-modal and intermodal mobility. Smart public transport, like Mobility as a Service (MaaS), and increased digitalisation accelerating the deployment of Intelligent Transportation Systems solutions can improve and complement high-capacity urban rail transport to make mobility more sustainable, efficient and inclusive, and benefit all citizens by putting public transport at their core. In addition, Customer Experience is becoming a relevant element of differentiation for transportation modes. That means, user needs will be satisfied by ensuring a customer-centric design beyond efficiency and functionality and laying the foundation for tools and measures for customer experience management, using service as a key differentiator.

3.4.2 Needed Technical Enablers

To achieve this objective, research and innovation are necessary in the following areas, among others:

- Artificial Intelligence used to deliver more flexible passenger services and information
- Artificial Intelligence and emerging tools used to optimise urban transport operations, incl. improved data management for enhanced network performance and streamlined flow management
- New services and flexible capacity models, based on demand-responsive and Service-Oriented Rail approaches, e.g., intermodal passenger transport systems, smaller vehicle configurations
- Deployment of small rail vehicles controlled by AI supported swarm intelligence
- Urban Regeneration driven by the deployment of Multimodal and Intermodal Mobility Hubs
- Enhancing Passenger Experience though digital solutions and cooperative systems that support intermodality, provision of personalised services and real-time travel information, and improved safety and security on board, on platforms and at train-platform interfaces
- Flexible, adaptable, comfortable, accessible and inclusive design of rail vehicles
- Solutions for improved journey quality by mitigating negative externalities (e.g., noises, vibration, etc.)

3.5 Horizontal Enablers – Harmonised and Standardised Approach

3.5.1 Motivation & Objectives

Simplification and lowering barriers to the European Single Market are essential enablers to safeguard the future of the EU as an economic powerhouse. A key contribution to this is the simplification of regulations and the acceleration of administrative procedures, moving towards flexible, risk-based approvals. Virtual certification methods, common standards, and modular solutions should become the norm, also common processes, lowering requirements due to the introduction of new technologies (e.g. crash). This will drastically shorten lead times and lower barriers for new entrants. To achieve this, in addition to transferring research results into potential new standardisation projects, research is also necessary to fundamentally revise or reduce existing regulations and standards.

In addition to modernising the regulatory governance framework and removing intra-European barriers, tasks also include preventing the emergence of new barriers, as well as activities to reduce regulations, proposals for revising standards and adapting them to the latest state of the art (e.g., crash safety compared to active vs. passive safety technologies), as well as cross-sectoral approaches (e.g., fire protection in passenger transport).

3.5.2 Needed Technical Enablers

For reduced lead time/authorisation

- Harmonisation of operational rules as fundament for highly efficient CCS systems (for moving block, virtual coupling deployment models), also for cross-border operations
- Research on the effects of active safety elements on reduced passive vehicle safety, including comparative safety simulations and validation of the resulting dominant models
- Digitisation of the authorisation process (functional approach; system-based model engineering)
- Modular authorisation for safety-related technologies, reusable certification blocks and harmonised criteria for subsystems
- Approval of new technologies before delivery based on e.g. early virtual validation and certification environments, digital twins, AI and predictive compliance metrics
- Modularity and standardisation of interfaces, universal interface protocols, model libraries and semantic interoperability standards

- Re-integrating learnings from deployment of architecture and technology in the EU-RAIL system pillar
- Harmonize operational practices and specifications across borders, using e.g. best-practice harmonisation tools, joint training simulators, corridor alignment pilots…
- Prepare infrastructure managers and railway undertakings for synchronized system rollouts
- Align industrial roadmaps of manufacturers, reducing fragmentation in the rail supply market
- Test and validate specifications and standards for integrated technologies in real conditions via cross-border pilot corridors via pre-deployment activities

4 Requirements for a New Joint EU Rail R&I Initiative

To realise this vision, joint innovation efforts are necessary across the entire rail value chain: including operators (both infrastructure managers and train operators), suppliers, construction companies, Small and Medium-sized Enterprises, wagon keepers and maintenance providers – and in case of urban rail local competent public authorities for sustainable mobility. Equally important is the involvement of Research Institutions and Universities as well as open cooperation with other sectors to avoid the development of singular solutions. By maximising the use of modular, standard components and integrating technologies from other industries (such as automotive, aerospace, and electronics), the rail sector can benefit from economies of scale, reduce costs, and increase the speed of innovation.

The core objective of future European research and innovation in rail transport is joint action to further strengthen the sector's competitiveness and increase the resilience and sustainability of the rail system. Following the Draghi Report's recommendation, this means high-impact research and innovation projects and the promotion of horizontal competitiveness factors, as well as the optimisation and simplification of systems and regulations, and the removal of internal market and intra-community barriers to ensure competitive markets and investment in future-oriented solutions with incentives for industrial deployment. The continued promotion of research and innovation, covering all TRL, will strengthen European industry and the academic research and innovation ecosystem in rail transport and increase global competitiveness through effective research and innovation, as described in the Heitor Report[16]. To simplify programs with agile funding, streamlined processes, and reduced administrative burden can help to achieve the R&I goals more effectively and efficiently.

Future European Research and Innovation should also allow clear inclusion of urban rail research topics and clear mechanisms to include urban rail stakeholders with their capabilities and peculiarities. This is particularly important as local operational urban rail scenarios do not match with the today programmes administrative costs, designed for more pan-European scenarios. The approach taken so far to structure European rail research and innovation has been crucial to overcome the divergence and lack of continuity in rail research and innovation. This has been achieved by developing a long-term strategy in close cooperation with all stakeholders (industry, operators, academia, and regulators). A coordinated EU-level approach is essential for aligning new technology deployment across varying national and local systems, shape future standards and regulations to speed-up R&I to market, requiring long-term investment and collaboration

[16] https://op.europa.eu/en/publication-detail/-/publication/2f9fc221-86bb-11ef-a67d-01aa75ed71a1/language-en

among stakeholders within a comprehensive framework. To achieve this, the following principles should be considered:

- **Mission-driven innovation:** Focused on climate neutrality, resilience, and digital leadership. Unite stakeholders behind common missions aligned with EU strategic priorities.
- **Standardisation, harmonisation, interoperability & migration:** standardisation and harmonisation must be considered from the very beginning and will also allow for the simplification and harmonisation of operational processes and the overall system. To ensure the migration of new technologies and scalability, a technology-neutral approach and interoperability of the technologies used should be aimed for. This requires a strong involvement of the railways together with industry and European approval authorities in development processes to ensure faster migration paths for existing systems toward digital, sustainable targets. Therefore, tight links with ERA and CEN/CENELEC to embed research outcomes into standards and authorisation processes are needed.
- **Innovation funnel:** Supporting projects across all TRL, ensuring seamless pipeline from research to deployment, to enable future-oriented research and preliminary developments as well as shorter-term implementation-oriented development projects. Combine funding for high-risk research (low TRL) and deployment support (high TRL).
- **Focused, large-scale implementation projects with agile governance:** projects with a single objective and maximum use of existing technologies reduce complexity and enable rapid piloting and implementation of demand-oriented solutions. Projects should have sufficient size to ensure implementation. Flexible, efficient decision-making bodies involving industry, operators, infrastructure managers, and regulators are of utmost importance.
- **Pre-deployment under operational conditions:** to ensure a fast market uptake, all projects need to strive for demonstrators/pilots under real operational conditions, the migration having been carefully considered and taken into account in the technologies development Pre-deployment pilots under real conditions will accelerate adoption and de-risk innovation. This requires strong support from authorities and regulators and new methods of approval.
- **Active collaboration with other sectors:** in line with the "EU Competitiveness Compass"[17] call to re-orient the innovation pipeline with a new focus on increasing R&D spending and coordinating it on high-impact projects, the rail sector will align its future priorities with the Sustainable Transport Investment Plan (including a plan for an ambitious European high-speed rail network), as well as

[17] https://commission.europa.eu/topics/eu-competitiveness/competitiveness-compass_en

increase research in the field of *"digitalisation and diffusion of advanced technologies, such as AI, quantum computing, robotics."* This also means pursuing and expanding cross-sectoral and cross-disciplinary research activities.

- **Attracting new skills:** investing into innovation helps making the rail sector more attractive. Investment in innovation and brings fresh academic talent into the sector, can attract new talent by showcasing the industry's commitment to cutting-edge technologies and the adoption of digital tools in rail operations, such as predictive maintenance and smart infrastructure, can create demand for software engineers, data analysts, and cybersecurity experts. This will help the sector to reduce the lack of manpower.

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