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High Level Paper Annex - Flagship Initiatives

CONTENTS

1. INTRODUCTION

This Annex details strategic areas of R&I and pre-deployment to simplify the rail system and its operations, while enhancing its fundamental capabilities in alignment with the core objectives of making European railways more agile, resilient, and competitive. Those areas are grouped in four flagship initiatives, which needs to be complemented by other policy actions beyond the field of R&I and pre-deployment to reach the intended objectives.

- The first flagship initiative - **the European Simplified and Integrated Railway System (ESIRS)** – is an initiative for increased Europe's railway competitiveness and lowering European rail system costs through automation, cutting-edge technology and harmonized operations. This based on simplification/standardisation and improvement of Command-Control and Signalling Systems, Capacity and Traffic Management Systems, digital infrastructure information systems, systems for digital operational communications and unified data management solutions and related processes, aiming at optimum system cost-effectiveness and efficiency. This initiative directly addresses upgradability and scalability through secure modular systems and simplified certification and to harmonised approaches or adaptors solutions towards legacy systems, resilience by design and through harmonized cybersecurity frameworks, and competitiveness through cost reduction and industrial leadership.

- The second flagship initiative **- the Next-Generation Rail Freight Operations with European Digital solutions** – is an initiative for transforming Europe's rail freight operations and making rail freight transportation more competitive. For this purpose, a comprehensive plan is needed to favour a competitive European rail freight through automated processes, digital coupling with advanced communication systems technologies, and intelligent capacity management. Transition pathways are developed jointly, to identify the actions needed to achieve the twin greening and digital transitions for logistics with rail with proper solutions' cost effectiveness and efficiency. This initiative enhances competitiveness of rail freight accelerating modal shift, supports quick adaptability to demand through dynamic freight planning, and strengthens resilience through multimodal integration and strategic logistics capabilities.

- The third flagship initiative - **Resilient Railway (Re²Rail)** – is an initiative addressing the fundamental challenge of maintaining reliable, secure rail operations under increasingly complex and unpredictable disruption scenarios. Climate change (floods, heavy storms or landslides), cybersecurity threats, geopolitical tensions, and system interdependencies create vulnerability patterns that demand integrated resilience strategies built into the core architecture of European railway systems while enabling seamless civilian-military interoperability and logistics (dual-use) when required. This initiative addresses the entire system with a focus in the area of automation, digitalization and control command (on-board and trackside), but as well design and maintenance of infrastructures and rolling stock in order to create a system which is resilient and recoverable. This flagship directly delivers resilience through climate adaptation and cybersecurity, supports agility through adaptive systems, and enhances competitiveness through dual-use infrastructure optimization.

- The fourth flagship initiative - **Innovative EU High-Speed Rail Corridors** – is an initiative unifying the innovation, deployment, and operation of next-generation high-speed systems within a harmonised European architecture. It ensures unmatched interoperability across borders. The initiative will pioneer harmonised pre-deployment corridors serving as early implementation pilots for pan-European high-speed expansion. These corridors will validate new rolling stock and infrastructure technologies, including ETCS L2-only operations, predictive maintenance, and EU traffic management under real conditions, ensuring safe, reliable, and cost-effective scaling. This flagship directly delivers competitiveness through cost reduction, energy efficiency, and industrial technological sovereignty; enhances service quality through reliability improvements and multimodal integration; and strengthens resilience through climate-adaptive infrastructure, cybersecurity, territorial inclusion, and strategic autonomy in critical high-speed technologies.

These first four flagship initiatives are focussed on areas involving an EU system thinking that necessitate activities of European pre-deployment and associated research to ensure a long-lasting positive impact. There are further activities that should also be considered under the work of a future partnership:

- **Horizontal Research and Innovation at lower TRLs**: There are a number of important areas of work where further research and innovation is required to improve future railway systems, but which may not lead to full pre-deployment activities within the identified time frame, still providing a valuable input to the works of the Flagship Initiatives. The focus would be on a limited set of areas related to the four flagships initiatives and on fostering new ideas. These are captured in a dedicated chapter.

- **System and deployment integration**: the production and validation of harmonised specifications and standards with the sector, and the coordination of the outputs of the Flagship Initiatives towards the European regulatory harmonisation and standardisation framework is an essential consideration within the overall programme. Additionally, the broader deployment considerations, including the coordination of European and national deployment programmes resulting from the pre-deployment activities is also necessary within the programme.

These flagship initiatives and additional horizontal activities described in chapter 4 share the same mission and focus together, they form a cohesive living roadmap for the future of European rail that extends the scope beyond SERA to include complete rail market coverage, including urban rail systems and multimodal transport integration, as urban nodes are included in the revised TEN-T guidelines aligned with the EC Communication on EU Urban Mobility Framework. They represent a holistic effort to ensure that through coordinated investments onto legacy systems, the European Single Rail Area will be delivered capitalising on the strength of the European Single Market. They will bring innovation, sustainability, and security—delivering long-term environmental, economic, and social benefits for Europe and beyond.

2. THE IMPORTANCE OF AN INTEGRATED APPROACH: FROM RESEARCH AND INNOVATION TO PRE-DEPLOYMENT

The challenges to achieve successful European deployments are large and can only be done at European level with a strong coordination instrument, in a PPP setup with an EU-wide geographical and stakeholders representation supported by a joint governance.

This is particularly the case where a framework for harmonisation and joint development on design and implementation concepts such as modularity and adoption of open standards are needed.

The development of such systems will build on the work of Europe's Rail Joint Undertaking – both in terms of solutions, but also the approach to not only focus on research and development, but also consider the necessary specifications and standards to be developed, and the overall considerations for a successful deployment.

A complete and coordinated process from research and innovation to pre-deployment across the EU, taking into account for economic reasons existing proven productive systems as basis, is critical for the successful implementation of new system related approaches on the European rail network. This represents a fundamental change in how the rail sector collaborates and helps shift to demand driven innovation.

Such an approach is necessary to:

- Harmonise operational practices, specifications/rules, and processes across borders.
    - New harmonised rules need to be tested and validated in real world (commercial) operations
    - New harmonised professional requirements for staff who will operate and maintain the new systems
- Develop improved design principles.
    - Standardised interfaces between rolling stock and infrastructure components ensure interoperability while allowing for platforms and solutions standardisation, creating economies of scale for European manufacturers. These simplified designs, that may also make use of (the latest) generic components/solutions from other sectors, reduce complexity in vehicle-infrastructure interactions, allowing for more efficient certification

processes, including by use of virtual simulations, and faster market entry for innovative solutions. It will also facilitate interchangeability and avoid “technical borders.”

- Validate innovative EU system solutions based on harmonised specifications and standards for integrated technologies in real conditions via cross-border pilot corridors.
  - Technical solutions put forward must be adequately tested and validated to finalise the overall specifications. Pre-deployment activities are crucial to this.
  - Validate system robustness, safety and interoperability across a range of operational and national contexts, including differing and extreme weather conditions.
  - Demonstrate the economical commercial viability of EU wide system solutions across diverse business cases for individual stakeholders and for the European economy.
- Involve and prepare rail stakeholders (including infrastructure managers and railway undertakings) for system rollouts from the beginning. Pace of delivery and rollout is the a challenge for rail and with the stakeholders involvement there is an opportunity to make the rail system more agile and effective:
  - Technical development is crucial, but the preparation and training involved in implementing new systems and processes is also vital, and pre-deployment activities support this essential element, including a just/proper workforce preparation and adaptation into the new systems
  - Moreover, it helps to measure the gap between existing situation and expected one leading to reliable business cases
  - The involvement of infrastructure managers and railway undertakings in specification and pre-deployment activities, will accelerate the take up for future market implementation of innovative solutions developed by the rail supply industry.
- Improve and accelerate authorisation and certification processes
  - The commercial operations of pioneer trains and infrastructures, complemented whenever possible by tests on virtual environment, can support the preparatory work for a streamlined certification in view of smoother European authorisation, including for massive retrofitting, particularly important when safety critical components are software based, and new versions will be downloaded frequently. Those tests should be based on fully harmonised testing specifications, tools and procedures.
- Support the synchronisation across the introduction of different programmes
  - Pre-deployment activities can support a more integrated approach to transition than country by country programme specific implementation, addressing in a comprehensive manner the funding challenges, coordination complexity across actors from different geographical (weather and rail network conditions, and operations) realities, and the industrial capacity and logistic/expertise flow within Europe.
  - Railways face many ongoing and upcoming transition programmes – ETCS, FRMCS, DAC, vehicle digitalisation; approaching and prioritising them in a non-individual and non-local manner for pre-deployment activities would result in both economies of scale and optimum time-to market possible implementation.
- Address potential market, technical, regulatory and policy barriers, while securing buy-in from all relevant actors.
  - Engage infrastructure managers, vehicle keepers, terminal operators, maintenance companies, rail operators, and suppliers.
  - Build confidence and ownership across the sector to support smooth transition into future system European wide deployment.
  - Use pre-deployment activities to identify and resolve potential technical and operational risks early, reducing delays and cost overruns.

- Trial in pre-deployment activities new business cases and addressing potential new policies approaches
- Improve visibility of market needs for significant technical improvements to the rail system, reducing fragmentation and increasing competitiveness in the rail supply market.

- Maximise short-term to long-term investment benefits
    - Limited commercial tests may result in new findings and can, therefore, help improve the business case for the roll-out of new technologies.
    - Coordinated planning ensures future-proofing, cost efficiency, and an assessment of the trade-off between flexibility and cost.
- Reduce time-to-market
    - Bringing the required maturity to the technical solutions, including faster (pre-) deployment
    - Showing the real benefits in a real environment demonstrating the business case to decision-makers

To ensure an efficient transition from Research and Innovation (R&I) to pre-deployment and in reasonable time to a recovery of pre-investments, Flagship Initiatives must be implemented. These initiatives will create a structured link between R&I activities that have reached higher Technology Readiness Levels (TRL) and pre-deployment actions that bring innovation closer to the market. Pre-deployment will be further supported by complementary R&I and harmonisation activities to ensure robustness, interoperability, and stakeholder alignment. Additional horizontal R&I activities will focus on R&I topics complementing at lower TRL the four flagship initiatives or fostering new ideas, laying the groundwork for future innovation, facilitating international cooperation and enabling the launch of subsequent pre-deployment activities.

The R&I activities will include:

- **Deep Tech**: Harnessing AI for dynamic capacity and traffic optimisation, predictive vehicle diagnostics, and real-time train composition detection. Leveraging edge computing and IoT for real-time diagnostics and predictive maintenance. Developing decentralised IT infrastructures, including data space technologies and data ecosystems, to ensure European digital sovereignty. Advancing automation in yards and logistics hubs, transforming overall operational efficiency.
- **Clean Tech**: Deploying energy-efficient traffic management and traffic control systems and advanced energy management solutions to facilitate modal shift and reduce greenhouse gas emissions. This includes appropriate infrastructure description, energy-optimised driving strategies, smart energy metering across freight trains, and innovative operational practices that improve efficiency and sustainability.
- **Secure Tech**: Delivering resilient, modular cyber-secure solutions to protect digital operations and ensure safety across a fully connected rail ecosystem. Ensuring long term sustainability of critical Infrastructures and the secure and harmonised use of AI, attracting and developing talent and skills for secure tech innovative solutions.

3. MISSION ORIENTED OBJECTIVES

To deliver the simplification mission for the future European railway system, several key objectives described in the table below must be met.

The impacts of the four Flagship initiatives described in chapter 4 will support these key objectives[1]. The R&I activities coupled with pre-deployment work of the Flagship initiatives will enable the Flagship Initiatives

[1] Baseline 2025 state of the art

to demonstrate their achievement through coordinated implementation that creates synergistic effects exceeding individual target achievements.

Key objectives

Key objectives	2035 Pre-deployment Target	2038 Mission Achievement	Measurement Methodology
Operational Complexity Reduction	25% reduction across 5 TEN-T corridors	30% reduction in operational procedures and interfaces	Interface mapping, procedure analysis, operator feedback
Cross-border Interoperability	Seamless operation on 5 corridors	90% of cross-border services fully interoperable	Service continuity metrics, border crossing analysis
System Cost Optimization	20% cost reduction validated on pilot networks	30-40% total system cost savings demonstrated	Total cost of ownership analysis across lifecycle
Technology Readiness	All flagship technologies at TRL 7-8	Complete technology portfolio at TRL 8-9 with industrial deployment capacity	Independent technology assessment, market readiness evaluation
Industrial Capacity	European supply chain ready for scaled deployment	Leadership of European suppliers in the global rail technology market, with new export opportunities.	Market share analysis, export performance tracking
Migration Capability	Validated adapter solutions covering 60% of legacy interfaces	Proven migration pathways for all critical systems	Migration success rates, timeline adherence, cost performance

Expected impacts of the Flagship initiatives

Flagship initiative 1 (ESIRS)

The impacts of Flagship Initiative 1 represent a step and major change toward a simpler, cheaper, and more predictable European railway, combining service quality, cost-effectiveness, system optimisation, and resilience. By moving from bespoke national practices to harmonised operational rules—paired with a simplified ETCS Level 2-only trackside, a harmonised ATO/TMS interface, and an EU-wide data/semantics backbone—services become more consistent, and costs can be reduced.

Pre-deployment of a full ETCS L2 trackside, including all signalling trackside assets, with harmonised rules and automated configuration/diagnostics targets measurable savings of ~20% through process automation, fewer physical assets, and streamlined delivery. Migration is de-risked via adapter solutions to new modular equipment covering ~60% of legacy interfaces to keep networks running during transition, while authorisation is accelerated by heavy reuse and automation of proofs. Using cyber resilient general-purpose hardware further reduces lifecycle and change costs, replacing one-off engineering with repeatable, scalable builds across Member States.

System optimisation shifts from national silos to European and multi network corridor-level, data-driven operations. Improved digital infrastructure information and capacity and traffic management algorithms are demonstrated across multiple networks; traffic management systems and digital infrastructure information systems are linked with automatic train operations (ATO) for tighter traffic management, improved punctuality, and in-operation energy monitoring; and dynamic and automated capacity allocation becomes feasible through shared digital platforms, unified digital infrastructure information and harmonised traffic rules supported by digital operational communications. A common rail ontology (managed at EU level) plus a federated rail data space provides consistent semantics and secure, real-time exchange, enabling automatic compliance of harmonised rules and reliable multimodal integration. Validated simulation tools and integration with other transport modes round out a repeatable optimisation toolchain.

Digitalization, automation, and intelligent public transport solutions enhance and complement high-capacity urban rail systems by providing greater flexibility, agility, sustainability, and efficiency. They also support urban regeneration through adaptable and easily deployable cost-efficient solutions, ultimately benefiting all citizens.

Finally, resilience and security are strengthened by simplifying architectures and reducing the attack surface inherent in bespoke systems, embedding cybersecurity and long-life software maintenance into the baseline. Future radio pre-deployment ensures robust, sabotage-resistant communications (including coexistence with future systems like IRIS² and the preparation to the use of next generation mobile communication systems), while federated data-space pilots include governance, sovereignty levels, and cross-border stress-tests. Harmonised degraded-mode rules and standardised automation processes support safe recovery, and an interoperable European market—grounded in open specifications rather than technology lock-ins—bolsters strategic autonomy and supply-chain robustness over the long term.

It will facilitate a harmonised European deployment of digital capacity and traffic management systems, digital infrastructure information systems, and systems for digital operational communications, by providing pre deployment activities at European and multi network corridor-level.

The European Simplified and Integrated Railway System (ESIRS) aims to create a unified, inclusive, and multimodal European rail network that genuinely serves all citizens. It focuses on user-centric platforms, seamlessly connecting rail with other transport modes for easier, integrated journeys. ESIRS is committed to harmonized accessibility requirements, guaranteeing consistent and inclusive travel experiences across borders for all passengers. Its simplified approach will make secondary lines economically viable, connecting remote communities and ensuring comprehensive European coverage with interfaces for all abilities. Advanced algorithms will enable dynamic rescheduling, seamless transfers, and first/last mile integration, while sophisticated data processing will optimize schedules and passenger flows in real-time. This transforms journey planning into personalized mobility guidance, supporting intelligent traffic management and evolving rail into a complete, citizen-focused mobility ecosystem by 2038.

Flagship initiative 2 (Next-Generation Rail Freight)

The impacts of the Flagship Initiative 2 represent a transformative shift for European rail freight, combining service quality, cost-effectiveness, system optimisation, and resilience. A coherent EU-level deployment roadmap for freight will prevent fragmentation, secure stakeholder confidence, and enable automation in yards and digital freight trains. Pre-deployment activities in the Flagship Initiative 2 target to accelerate transhipment by up to 50%, improve cargo visibility, and increase line capacity by 5%. Cost-effective measures include large-scale retrofitting that provides an industrial boost, and improved terminal and asset utilisation that lowers logistics and lifecycle costs, while also opening export opportunities and strengthening European technological leadership.

System optimisation will stimulate European industrial capacity in strategic rail technologies, reduce physical strain in coupling operations to address workforce challenges, ensure interoperable digital systems across borders, and make yard operations more energy efficient.

Resilience and security will be enhanced by reinforcing rail’s role in achieving Green Deal and TEN-T targets, enabling modal shift from road to rail, reducing CO_2 emissions, road congestion and energy consumption, improving safety with fewer accidents and less manual strain, and strengthening Europe’s strategic autonomy by reducing reliance on non-EU suppliers while consolidating leadership in sustainable rail technology.

Flagship initiative 3 (Resilient Railway)

Investing in resilience, digitalisation, and cybersecurity across the European rail network enhances service quality, reduces costs, and ensures continuity under disruption. Automated inspections and improved surveillance reduce delays and human error by up to 50%, boosting passenger and freight reliability. Early integration of secure, automated systems cuts long-term costs by 20–30% and avoids expensive retrofits. Digital traffic management and real-time asset monitoring which includes highly reliable predictions enable 15–20% increased terminal throughput and faster recovery from disruptions—limiting the need for major infrastructure upgrades. Upgrades and new design for rolling stock and infrastructure as well as harmonisation measures would allow creating a resilient system, ensuring 99% system availability during cyber incidents, 85% network capacity during extreme weather events, and dual-use capability on strategic corridors supporting 96-hour EU-wide military deployment.

The resilient systems create the foundation for enhanced services by ensuring reliable operations under all conditions, supporting both passenger experience and business continuity through comprehensive climate adaptation and security measures that enable the holistic network development required by the strategic framework.

Flagship Initiative 4 (Innovative EU High-Speed Rail Corridors)

The impacts of Flagship Initiative 4 represent a transformational advancement for European high-speed mobility, combining service quality, cost-effectiveness, system optimisation, resilience, and territorial cohesion. This initiative will be further specified based on the recently published Commission communication: Connecting Europe through High-Speed Rail[2], which provides a comprehensive policy direction and deployment priorities for European high-speed rail development.

Pre-deployment of harmonised high-speed corridors targets cost reductions through lifecycle optimization via predictive maintenance, simplified ETCS Level 2-only infrastructure, and standardised European designs. System optimisation delivers increased capacity through AI-driven traffic management, reduced travel times between major EU major cities, and improved integration with conventional networks and multimodal services. Resilience and improved security are strengthened through rolling stock and infrastructure innovations and with territorial accessibility across all EU regions, and European technological sovereignty addressing the EU supply ecosystem while supporting dual-use strategic mobility objectives.

Horizontal R&I activities

Horizontal R&I activities provide the essential research foundation that enables the advanced capabilities and future evolution of the first four flagship initiatives while addressing fundamental challenges in railway digitalization and automation that require longer development timelines. These horizontal activities focus on breakthrough technologies at lower Technology Readiness Levels (TRL 1-4) that will become critical enablers for the next generation of railway systems beyond 2038.

It also provides a framework for more disruptive or fast-paced R&I into marketable solution for pre-deployments, leveraging on the knowledge of the partnership and in particular of its Members who can provide the nurturing framework of data and processes for trialling and scale-up.

4. FLAGSHIP INITIATIVES

4.1 Flagship Initiative 1: European Simplified and Integrated Railway System (ESIRS)

The cost and complexity of improving European railway systems has entered a critical phase.

Costs for deployment and maintenance are high and deployment remains slow and complex.

The current path is economically unsustainable and is not a temporary market fluctuation.

To be cheaper and simpler, implementations must move from complex hybrid systems based on legacy systems, to systems based on harmonised operational rules, favouring smooth migration, technological evolutions without gaps, and based on standardised interfaces eased by smooth authorization processes.

In the past, long-lived non digital systems—often lasting 50 to 80 years—could be developed nationally with an acceptable level of risk, even on an individual installation basis. These relatively simple systems could be optimized case by case, configured specifically, and then operated at reasonable cost over extended periods. Precisely because of their longevity, this initial situational optimization process made

[2] https://transport.ec.europa.eu/document/download/774e79c9-1ece-4514-8f16-a2b98049c82e_en?filename=COM_2025_903_HSR.pdf

sense and became part of the engineering culture. With their low degree of automation, such installations were relatively isolated, had few dependencies, and therefore rarely required changes, which were also simpler and less knowledge dependent.

Modern digitalised systems, by contrast, are fundamentally different. Highly digitalized systems can be cost-effective - if designed in a whole system approach and used in the right way, necessarily considering the migration and the technological evolutions.

Once designed and used in the right way, such digitalisation will lead to more efficient railway operations, addressing also the challenges posed by a shortage of skilled labour, which is necessary for the future of European rail. This triggers a condition for designing digitalisation: future operational use shall always be part of the design phase – for improved and more efficient operations.

Digital systems are shorter lived, and subject to more frequent change. Managing the obsolescence and the software maintenance of such technologies has become correspondingly more complex (for example linked to associated cybersecurity considerations), particularly due to the exceptionally long-life cycles expected in the rail sector (over 30 years). Experience shows that current introduction of highly digitalized national systems can be extremely expensive. Some railways experience that there seems to be high costs for software development and changes, in large part due to insufficient harmonisation.

And this leads directly to the core issue: this high level of technological maintenance and support cannot be sustained for every country's individualized digital solutions, and every company's bespoke solution to such individualised solutions, especially considering the speed of the digital technologies' evolution. Those who seek to digitalize and automate are, by necessity, compelled to harmonize.

The European Simplified and Integrated Railway System (ESIRS) initiative aims to simplify and harmonise rail operations across Europe. In addition, it also ensures a smooth transition to these new technologies and seeks to support the decommissioning of legacy systems.

The goal is to create a unified, inclusive European rail network that genuinely serves all citizens. It prioritizes user-centric platforms, seamlessly integrating rail with other transport modes for easier, more connected journeys and rail-freight based supply chains. Harmonized accessibility guarantees consistent, inclusive travel experiences and transport reliability across borders for everyone.

ESIRS's simplified approach makes secondary lines economically viable, connecting remote communities and ensuring comprehensive European coverage for all users, regardless of ability or technical literacy. Advanced systems will provide dynamic rescheduling, seamless transfers, and personalized mobility guidance, integrating real-time journey and transport planning with essential accessibility information.

By 2038, the ESIRS initiative aims to deliver solutions to support a fully integrated, simplified, secure and digitally native European rail system, smoothly managing the migration from legacy systems and the technological evolutions that operates under a common set of rules and technologies across the continent. If the migrations are based on modular and upgradable equipment, and are economically sustainable, this will not only increase the efficiency of rail transport but also enable a competitive and efficient European market for rail solutions and products, also acting as a springboard for a competitive global European rail supply industry.

All elements for a successful deployment and decommissioning must be considered to enable success

- R&I to deliver solutions in cooperation with universities and research centres, as well as closer cooperation with other sectors, especially the IT sector.
- development of tested, validated, and open standards and specifications to guide product development, and which do not require the use of a specific technology
- adapt and adopt, whenever possible, technologies and solutions from other sectors, being relevant to mainline railway but specially to urban segment due to its coexistence with other modes of transport
- including a major contribution of railway operators in order to aim at a correct introduction of digitalization while maintaining the triple relation of products / operational rules / human beings
- a focus on decentralized systems (federated data spaces) supported by a common ontology (under an EU governance) to implement trust and sovereignty for the rail data and service ecosystems.

- Support to the development of migration solutions, as in reality we must prepare for adaptations over a long period, and are accompanied not only by technology change, but also updated national processes. The deployment of the new solutions will not happen in a coordinated timeframe across EU MS: the migration strategy must take account of those permanent (or at least long-term) differences, the need for transitions, interfaces, and national political priorities.

Building upon the foundation established by Europe's Rail Joint Undertaking, ESIRS takes a decisive step toward creating a truly unified, intelligent, and efficient rail system spanning the continent.

The expected transformative impact extends far beyond technological advancement. By drastically simplifying the system architecture, and deployment/update process, ESIRS promises to reduce both capital and operational expenditures across the European rail system enabling the system competitiveness of densely operated as well as low density lines.

Pre-deployment coordinated activities across EU and associated R&I

Pre-Deployment is essential because the transformation that ESIRS envisions cannot be implemented through isolated national initiatives, and require testing and validation, including validation in real time operations, in particular at European and multi-network corridor level. The Europe's Rail High Level Deployment Group demonstrated the need of such coordinated approach at the sector and European level.

Areas of pre-deployment and associated research and innovation coordinated activities for ESIRS:

1) **Full trackside CCS system solutions for ETCS only operations based on harmonised operational rules**

a. Context

The slow rollout of ETCS, including all signalling trackside assets, is highly significant for cost reduction in rail. Lowering costs depends on simplifying, harmonizing, and automating installations and processes, which requires aligned operational requirements. ETCS Level 2 offers strong potential here due to its simple architecture and modern, automation-friendly technologies. Yet, current ETCS systems are often complex hybrids weighed down by legacy elements, making cost savings harder and slower to achieve.

Infrastructure managers spend hundreds of millions annually on CCS trackside systems, yet cost optimisation remains slow due to bespoke orders overstretching development capacity. A well-designed demonstration through pre-deployment can break this cycle, integrating existing solutions to accelerate harmonisation and deliver robust, cost-optimal processes.

In order to address the challenges of increasing costs and complexity it is essential for pre-deployment activities on a full trackside CCS to fully test, validate and demonstrate the operational and costs benefits of such a harmonised approach.

Above all, trust among railway operators and suppliers in the feasibility of a cost-efficient solution must be established—only then can meaningful change occur.

b. Objective

By 2034, following pre-deployment activities,

- there will be a fully demonstrated at [TRL 8] in [4] cross border situations real-world, end-to-end CCS trackside (with ETCS Level 2) implementation using simplified and harmonised specifications and processes, integrating cost optimisation, and demonstrating measurable savings [20%] from process automation, reduction in physical assets, interoperation between components from different suppliers and streamlined project delivery.
- to facilitate migration, adapter solutions covering [60%] of legacy system interfaces will have been developed, enabling seamless migration without service disruption on operational networks. These

interfaces will allow at least the connection of systems between two sections from different suppliers to seamlessly interconnect.

c. Pre-deployment activities

Pre-deployment activity 1: CCS trackside system ETCS L2 based installation

- In service trackside systems in operation in cross border areas, interconnecting systems from different suppliers
- Test and validate
  - Harmonised operational rules and L2 engineering rules together, including degraded mode
  - Key interface specifications, for example, the interfaces between CCS trackside and TMS
  - Automate the exchange of infrastructure configuration management and diagnostics
- Develop any necessary product adaptations, and safety case preparation for a cost-efficient installation
- Revision of processes and associated training/upskilling for staff, with focus on cultural aspects, in at least 10 Member States, ensuring geographical balance
- Demonstration of the use of general-purpose hardware systems to deploy CCS applications and digitalized object controllers for Trackside assets which will demand a bigger number of serial communication channels and connections.
- Defined pre-deployment across at least 4 Member States, including cross border operations by 2035.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL

- Within the EU-RAIL System Pillar, the steps towards a European CCS system based on harmonised operational rules is underway. This process goes significantly beyond harmonisation based on current ETCS specifications (for example including signalling rules and degraded modes).
- The development of the System Concept and associated specifications for the Traffic Control System in the System Pillar, as well as the associated work in the Transversal Control Command and Signalling, Trackside Asset Control System S, and Computing Environment domains
- Demonstration activities in the Flagship Area 2 (for example on moving block and hybrid train detection)

e. R&I and harmonisation activities:

R&I and associated harmonisation activities efforts will play a crucial role in enabling pre-deployment activities and preparing for industrial ramp-up. Key focus areas include:

Migration/Adapters

- consideration of overall migration and integration solutions including for the target architecture. This can include the development of technical solutions, for example, adapters, and the consideration of implementation of new operational rules operating alongside existing operational rules. Where possible, backward compatibility with legacy systems during the transition period should be ensured.

Authorisation and certification

- New approaches for lighter, faster, and economically sustainable authorisation and certification processes should be developed and implemented. Consideration of radical processes to streamline authorisation including efficient (re)verification techniques for safe functions and integration of software-centred components, enabling heavy reuse and automation of proofs
- One approach for European authorisation and certification, including for massive retrofitting of vehicles could be: Grouping similar vehicle types into clusters or transferring more responsibility to the EVU; both can potentially develop significant time and cost synergies. In general European coordination would be needed to achieve massive retrofitting or upgrading of vehicles across borders

2) Automated operations (up to GoA 3/4) and modular onboard (including full Advanced Safe Train Positioning)

a. Context

The development of the higher levels of automation is an important component to future operational efficiency, resilience and flexibility, and reduction in the overall cost base of the European railway.

GoA3 (Conditional Automation) and GoA4 (Unattended Train Operation) require very high assurance: of safety, reliability, cyber-security, and system integration.

Automation on both the heavy rail network, and in urban light rail are major opportunities for the rail sector.

Accompanying higher grades of automation is the necessity to further develop the onboard unit, including to accommodate more precise localisation approaches, with a modular approach allowing interoperability and large scale cost reduction benefit.

b. Objective

By 2036, following pre-deployment activities,

- There will be ATO GoA3/4 in operation in [4] cross border areas using harmonised specifications and processes, as well as relying on equipment from different suppliers
- There will be a fully tested and validated modular on-board system including full Advance Safe Train Positioning and perception systems
- There will be automated light rail in operation in [6] urban areas based on the partnership specifications and solutions.

c. Pre-deployment activities

Pre-deployment activity 1: ATO GoA 3/4

- ATO GoA 3/4 systems in operation in cross border areas including depots and shunting yards
- Test and validate
    - Harmonised operational rules
    - Mature ATO specifications
- Develop any necessary product adaptations, and safety case preparation for a cost-efficient installation

- Revision of processes and associated training/upskilling for staff, with focus on cultural aspects, in at least 5 Member States, ensuring geographical balance
- Defined pre-deployment across at least 4 Member States, including cross border operations by 2035.

Pre-deployment activity 2: future CCS onboard

- modular on-board system including full Advance Safe Train Positioning, piloted on high speed and conventional network
- Test and validate
    - Mature specifications
- Develop any necessary product adaptations, and safety case preparation for a cost-efficient installation
- [defined area of use] Defined pre-deployment across at least 8 Member States, ensuring geographical balance by 2035.

Pre-deployment activity 3: Urban light rail automation

- Automated light rail in operation – fully automated line and operations, and automated depots - in urban areas,
- Test and validate
    - Fully connected (V2X) and automated operations in service
    - Perception systems
    - Human factors, including passenger acceptance, and recovery from incidents
    - Digital onboard train protection system (cooperative awareness), with no infrastructure components, also applicable to regional low-density lines
- [Defined pre-deployment across at least 6 urban areas, ensuring geographical balance by 2035.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL

- the demonstration activities on ATO GoA3/4 in Flagship Area 2
- the development of the on-board architecture within the System Pillar, and demonstration activities for full ASTP in Flagship Area 2

e. R&I and harmonisation activities:

R&I and associated harmonisation activities efforts will play a crucial role in enabling pre-deployment activities and preparing for industrial ramp-up. Key focus areas include:

Operational rules for ATO GoA 3/4

- The finalisation of complete harmonised operational rules, but also shunting, stabling, and fall-back situations for ATO GoA 3/4 operations.

- Comprehensive protection and monitor of lines (including level crossing) based on distributed sensor networks

Specifications for ATO GoA 3/4

- The finalisation of mature specifications for the technical solution for ATO GoA 3/4.

Specifications for modular onboard

- The finalisation of mature specifications to enable testing and validation of the future on board architecture including full ASTP

Urban light rail automation

These activities build upon the findings and results of EU-RAIL's Flagship Area 2 (FA2) on urban light rail.

- Further development of sensors and certification activities
- V2X between trains and road users in complex scenarios
- New automated depot operations (washing, inspection…) and tailored depot design benefiting from automated vehicles
- Safe streamlined train protection system based on onboard technologies (cooperative awareness), also applicable to other segments and scenarios (e.g. low-density lines, degraded modes)

Autonomous train operations

- Study data-centric signalling approaches that rely on train-to-train and train-to-satellite communication towards virtual coupling models, reducing dependency on trackside infrastructure, through a proof of concept
- validation and testing of the system on regional (low-density) lines enabling its approval and further network expansion

3) Future rail radio communications

a. Context

By 2030 the process for the deployment of the FRMCS 1st Edition specification set should be in place. There will though be important elements of work outstanding to develop, test and validate new features, or to enhance the functionality of new use cases to e.g. improve reliability or support further applications (e.g. ATO GoA 3/4).

The development of any further elements on communication needs to go hand in hand with other deployment activities in order to minimise costly interventions on the system.

The deployment chain from requirement engineering, development, testing, deployment, operation and monitoring should be a central aspect, especially with respect to vehicle authorization

b. Objective

By 2033, following pre-deployment activities

- There will be a tested and validated product available for the future radio system in Europe based on an extended use case set compared to the Edition 1

c. Pre-deployment activities

Pre-deployment activity 1: FRMCS Edition 2

- Broad pre-deployment campaign for the FRMCS Edition 2
- Test and validate
    - Mature specifications for FRMCS edition 2
- Defined pre-deployment across at least 8 Member States, including cross border operations and ensuring geographical balance by 2035.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL including the FA2 MORANE 2 project, which is testing and validating the FRMCS 1st Edition specifications.

e. R&I and harmonisation activities:

R&I and associated harmonisation activities efforts will play a crucial role in enabling pre-deployment activities and preparing for industrial ramp-up. Key focus areas include:

Satellite Navigation for Safety-Critical Applications

- Validate GNSS-based positioning (EGNOS/Galileo) for ETCS former L3 and ATO.
- Ensure anti-spoofing/jamming resilience and integrity.
- Launch cross-border pilots for satellite-based localisation.

Low-Orbit Satellite Communication (LoSat)

- Consider LoSat as primary system for ERTMS, with radio as backup.
- Reduce reliance on ground infrastructure and cut deployment costs.
- Enable resilient, secure, interoperable communication.
- Pilot satellite-first corridors.

Compatibility

- Ensure compatibility and coexistence with future communication systems (e.g., IRIS², local systems based on Wi-Fi evolution) for secure, sabotage resistant data exchange

Mainstreaming

- Reduce the railway specific aspects of FRMCS, to facilitate the future migration to next mobile telecommunication solutions (6G, 7G, etc.)

4) Future rail traffic and capacity management

a. Context

In the early 2030s, the implementation of the capacity regulation will be proceeding. To meet the growing demands for sustainable and efficient transport, cross-border train paths and capacity allocation necessitate shared digital platforms and agreed-upon traffic rules. A European-wide capacity management approach of federated state of the art national systems must evolve from disparate national frameworks to integrated, network-based models, ensuring that path requests, allocation, and scheduling processes are standardized and interoperable. This evolution is not just about operational efficiency; it's about delivering significant value for society and people by fostering greener mobility, reducing road congestion, supporting economic growth, and enhancing the overall quality of life across Europe.

Crucially, dynamic and flexible capacity allocation will empower rail to respond in near real-time to demand fluctuations, disruptions, and rerouting needs. This enhanced responsiveness will not only optimize freight logistics but also significantly improve accessibility for passengers, making rail travel more reliable, convenient, and attractive for a wider range of users, including those with specific mobility needs. The continuous development of higher levels of capability and the seamless integration of still required national systems with selected central supporting tools to a European Traffic and Capacity management approach will be paramount to extracting maximum efficiency from networks, ultimately creating a more resilient, user-centric, and environmentally friendly railway system.

b. Objective

By 2035, following pre-deployment activities will establish a highly efficient, responsive, and integrated European rail network by leveraging advanced digital solutions and harmonized operational frameworks, thereby optimizing capacity utilization, enhancing operational performance, and fostering seamless multimodal logistics and as well connections into the urban and aviation system where appropriate.

- Implement and demonstrate advanced planning and regulation algorithms to significantly enhance network management efficiency and adaptability. This will lead to more predictable and resilient rail services, ensuring smoother journeys for passengers, more reliable delivery of goods, and reduced societal disruptions across Europe.
- Integrate Traffic Management Systems (TMS) with Automatic Train Operations (ATO) to optimize energy consumption, improve punctuality, and maximize network capacity. This crucial system enhancement will result in a more reliable, environmentally friendly, and comfortable travel experience for all passengers, contributing to cleaner air and more efficient operations.
- Deploy and validate interoperable digital platforms and data exchange standards to foster seamless information flow and integrate multimodal transport. This will empower individuals and businesses with real-time routing, tracking, and booking information, making rail travel and freight logistics more transparent, accessible, and convenient for everyone, thereby enhancing the overall efficiency and trustworthiness of the European transport system.

c. Pre-deployment activities

Pre-deployment activity 1: Digital systems supporting existing EU framework

- Pre deployment and validation of digital systems compliant with existing and planned regulatory requirements supporting the development of other activities.

Pre-deployment activity 2: Implementation of improved planning and regulation algorithms

- In service demonstration of improved planning and traffic regulation algorithms across countries, including for cross border and freight operations (Real-time conflict detection and resolution, Dynamic re-routing, Optimized train sequencing, Predictive delay management.), designed to enhance network management efficiency and adaptability.
- Pre-deployment activities for implementing improved planning and regulation algorithms in railway capacity management involve rigorous testing in demonstrators. Different methods are evaluated and combined to address national, international, and corridor-specific requirements. These activities ensure compatibility and effectiveness across diverse operational contexts. By simulating

real-world scenarios, stakeholders can identify optimal algorithm combinations. This approach supports robust, scalable solutions for enhanced railway capacity planning.

- To validate the effect in non-commercial demonstrations, operational evidence is gathered within a controlled, limited scope. This approach ensures compliance with European procurement regulations while still enabling meaningful assessment. Although the pre-deployment activities are restricted in scale, targeted tests can demonstrate measurable improvements. By focusing on representative scenarios, stakeholders can reliably evaluate the algorithms' impact without breaching regulatory constraints.
- Possible areas for a pre-deployment could include national railway networks or specific corridors in countries where advanced traffic management and planning systems are already operational. This could include parts of the European Transport Corridors, as these areas offer established infrastructure and operational complexity, making them suitable for testing and validating improved planning and regulation algorithms in a pre-deployment context.
- Defined pre-deployment across at least 4 Member States including cross border operations by 2035.

Pre-deployment activity 3: linking TMS to ATO for optimised operations

- Application in commercial environment of harmonised ontology for TMS and ATO
- In service demonstration of TMS linking to ATO to improve energy consumption monitoring, punctuality and impact on capacity
- Comprehensive Validation, Safety Assurance, and Performance Optimization: Conduct thorough safety analyses, develop a robust safety case, and utilize advanced simulation (including Hardware-in-the-Loop testing) to rigorously validate integrated functionalities and fine-tune performance optimization algorithms for energy efficiency, capacity, and dynamic conflict resolution under all operational scenarios.
- Ensure Operational Readiness and Human-System Collaboration: Develop specialized training programs for operators and validate intuitive Human-Machine Interface (HMI) designs to ensure effective monitoring, supervision, and intervention within the integrated TMS-ATO environment, preparing personnel for efficient and safe system management.

Pre-deployment activity 4: Digital platforms and data interoperability

- Deploy and test digital platforms that enable the aggregation of complex multimodal services for rail-based supply chains, real-time routing, tracking, and ETA predictions, based on data standards developed under an EU governance (ESOs or ERA). Implement and validate interoperable data exchange standards and interfaces between railway undertakings, infrastructure managers, terminal operators, and first/last mile transport providers.
- Adapt and deploy integrated, intelligent digital platforms from the works of EU-Rail that provide seamless, personalized, and accessible end-to-end journey solutions for all passengers and freight customers, from first mile to last, across borders and modes, ensuring proactive communication and simplified travel experiences.
- Pilot deployment on [5] selected TEN-T corridors with high cross-border traffic and strong intermodal interfaces (e.g. Rhine–Alpine, North Sea–Baltic, Scandinavian–Mediterranean) ensuring geographical balance. Strategic nodes: major intermodal terminals and to validate cross-border and multimodal data exchange.

Pre-deployment activity 5: Digital operational communications

- Adapt and integrate automated and operational telematics data exchange opened protocols between infrastructure managers and railway undertakings (TCMS/TMS) based on modular products for driver advisory systems (DAS) that work with harmonised ETCS and are scalable to ATO GoA2 operation over ETCS

- Integration of multilingual requirements, including for automated language tools, fit for operation in normal and degraded mode
- Pre deployment for testing and validation in operation along [5] pilot cross-border corridors

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL in FA1 and the harmonised interface between ATO and TMS from the System Pillar.

e. R&I and harmonisation activities:

R&I and associated harmonisation activities efforts will play a crucial role in enabling pre-deployment activities and preparing for industrial ramp-up. Key focus areas include:

Linking TMS to ATO for optimised operations

- Application of unified digital infrastructure information with a granularity and reliability fit for ATO and traffic control
- Establish Secure and Standardized Interoperability: Develop and agree upon harmonized data model and interface for the enhanced seamless, real-time information exchange between TMS and ATO systems, while rigorously conducting cybersecurity threat modelling and resilience testing to ensure the integrity and security of the interconnected architecture.

Integration with other modes

- Intelligent traffic and capacity management system that allows integration with other transport modes, in particular combined transport for freight (road, maritime and inland waterways) and multimodal hubs including airports for passengers, to anticipate congestion, manage incidents, enhance passenger information and improve the daily mobility of residents. Integration with urban system where relevant.
- Develop where relevant, interoperable data exchange standards and interfaces between railway undertakings, infrastructure managers, terminal operators, and first/last mile transport providers.

Simulation tools

- European validated simulation tools in terms of predictability and accuracy of the simulations compared with a real operation scenario, enabling the models to reflect continuously enhanced models of influencing factors (weather, state of equipment from digital twins, human flows on the stations, etc.).
- Development of capabilities to set out working timetable fit for intermodal (rail/road) transport services integrating buffer times and milestones in multi-modal freight terminals for the departure/arrival and decision making on the availability of such services.
- Artificial Intelligence & Quantum Computing: Enabling dynamic planning, predictive capacity management, and adaptive routing across the multimodal network.

Autonomy

- Improved Traffic and Capacity management through improved feedback from operations and real time decision support system for train dispatchers, preparing for Autonomous traffic managements systems.
- validation and testing of sensor setups for ATO/RTO: during development (e.g. sensor model in detailed simulation of rail environments) and for ATO/RTO system approval (e.g. scenario-based HiL-testing)

5) The Common Rail Ontology and Federated Rail Data Space

a. Context

The move to much more data-centric processes is central to ESIRS.

The development of a shared rail ontology, monitored and manged at European level by the European Union Agency for Railways, is a foundational infrastructure for a digital railway. It supports seamless cross-border operations, regulatory alignment, better data quality, and greater agility for innovation. Therefore, it is crucial that there is focussed well-resourced work at European level to develop semantic interoperability across European rail systems and to define standardized, machine- & human-readable vocabulary of rail-related concepts and relationships.

In addition to the development of the ontology, there is also the need to create federated, decentralized data ecosystems to enforce innovation while following EU values – a federated rail data space.

b. Objective

By 2036, following pre-deployment activities

- In order to facilitate the uptake of TSI, the common rail ontology will cover all of the subsystems across the TSIs (TAP/TAF, CCS, OPE, INF, ENE, LOC+PAS, SRT, PRM, NOI), supporting fully interoperable European rail operations.
- The European register of infrastructure (RINF) will be the single European source of digital infrastructure information populated by infrastructure managers and a reliable source of data for operational systems
- The European federated rail data space will be part of the common European mobility data space and in commercial operation, providing a real-time and user-friendly digital platform.

c. Pre-deployment activities

Pre-deployment activity 1: Extension of the ERA ontology

- ERA ontology extended to all subsystems across TSIs
- Test and validate the shared set of definitions, and the data use by IMs and RUs, relevant to all systems to be defined at European level
- Pilot products using the common ontology
  - Trackside CCS products involving data preparation, configuration, and coherence and completeness checks

Pre-deployment activity 2: Pilot Operations of the European federated rail data space

- Testing of the interlinking layer with common European mobility data space (EMDS)

- [5] cross-border pilot corridors with federated data nodes
- To test interoperability, real-time data exchange, and resilience (including stress tests to validate robustness against physical threats)
- [5] pilot cross-border corridors

Pre-deployment activity 3: Enhancing digital infrastructure information to support operational use

- Enhancement of the granularity of RINF model to support ATO
- Integration of a digital route book in the driver cabin
- [5] cross-border pilot corridors

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL

- the development of extension for the ERA ontology, for example through the System Pillar CCS/TMS Data Model.
- the development of the Rail Data Space integrating the interlinking layer of common European mobility data space (EMDS), which will move into a first operative mode by 2028

e. R&I and harmonisation activities:

R&I efforts will play a crucial role in enabling pre-deployment activities and preparing for industrial ramp-up. Key focus areas include:

Common rail ontology: Automatic compliance

- Exploit expression of harmonized operational rules in human- & machine-readable format in semantic open standard as SHACL to facilitate automatic compliance.

Federated rail data space: Architectures

- Further research into federated SW architectures (with enabling services) for railway application and advanced railway service
- Interlinking layer of common European mobility data space (EMDS)
- Decentralized IT infrastructures for digital EU sovereignty by data space technology and data ecosystem enabling.
- QC integration and applicability study in the context of federated rail SW architectures.
- Research into extensions of federated data space architecture as digital railway enabler for secure and trusted data and service exchanges with new approaches such as code-to-data and potential QC algorithms.
- Leverage the Data Space APP Store component to provide a set of common services and applications to support the above points (ex. Compliance).
- Extension of federated architectures with sovereignty levels, Federated IT infrastructure for data sovereignty.

Federated rail data space: Governance

- development of Data Governance Frameworks (define access levels, roles, and responsibilities for data sharing across stakeholders, ensuring compliance with EU regulations)
- Extension of federated architectures with sovereignty levels, Federated IT infrastructure for data sovereignty.
- Full integration in the overall common European mobility data space (EMDS)

Federated rail data space: Complex data processing

- Evaluation of potential of quantum computing to accelerate complex data processing and encryption tasks for rail in federated architectures.

Impacts

Service Quality enhancement

- Cross-border services become more predictable and reliable by replacing bespoke national practices with harmonised operational rules and simplified ETCS L2-only trackside—tested end-to-end in real operations—so operators and dispatchers work from the same rulebook and engineering rules, including degraded modes.
- Higher grades of automation (ATO GoA3/4) plus a modular onboard with Advanced Safe Train Positioning raise punctuality and regularity, while standardised processes and safety cases make automated operations service-ready on both mainline and urban networks.
- Linking TMS with ATO enables tighter regulation in real time (better adherence to plan, smoother recovery), with improved energy monitoring and more stable ETAs for customers.
- Federated, EU-wide data exchange (rail data space) and a common ERA-led rail ontology give stakeholders consistent, machine-readable semantics and near real-time visibility across borders, supporting accurate journey information and dependable handovers between actors.
- FRMCS (Edition 2) validation across multiple countries improves communications robustness for operational messaging and ATO use cases, reducing service disruption from comms bottlenecks.
- Flexible and adaptable urban rail services, enhancing network performance and streamlining the flow management.
- Digital platforms provide passengers and shippers/forwarders with seamless, personalized, and accessible end-to-end journey or transport solutions, including real-time routing, booking, and highly accurate ETA predictions across borders and modes. These increases the attractiveness of rail-based journeys/supply chains and proactive communication and transparency significantly improve the travel experience and the trust in using rail.

Cost effective solutions

- Moving from hybrid, legacy-laden designs to harmonised operational rules with simplified ETCS L2 architectures cuts bespoke engineering, lowers software change effort, and enables reuse—addressing today’s spiralling, unsustainable cost base.
- Pre-deployment of a full trackside CCS (ETCS L2) with standardised interfaces and automated configuration/diagnostics targets measurable savings (around 20%) from process automation, fewer physical assets, and streamlined delivery.
- Migration is supported through tested technical solutions such as adaptors.
- Modular, upgradable equipment and adapter solutions de-risk migration by keeping legacy interfaces running during transition, avoiding costly cutovers and service downtime.

- General-purpose hardware and digitalised object controllers reduce lifetime costs and supplier lock-in, while a re-engineered authorisation approach (heavy reuse, automated proofs) shortens deployment cycles and curbs expenditure.
- A unified market for solutions—fostered by common specifications, open standards and shared rules—strengthens Europe's supply industry and scales volumes, lowering unit costs for both dense and low-density lines.
- An onboard urban light rail protection system, independent of infrastructure, which together with autonomous operations, enables the efficient and cost-effective deployment of new lines or the upgrade of existing ones.

System Optimisation

- Corridor-based capacity and traffic management (shared digital platforms, harmonised traffic rules) shift planning from national silos to European-level optimisation, supporting dynamic allocation and faster, cleaner recovery from disruptions.
- Common technical interfaces ensure the ability to seamlessly and safely interconnect equipment from differing suppliers, in both national and cross-border contexts.
- In-service demonstrations of improved planning/regulation algorithms, and the TMS–ATO link, unlock higher throughput and smoother operations with data-driven, repeatable processes rather than one-off local practices.
- ATO GoA3/4 and ASTP drive repeatable running times and stable headways, while a mature onboard architecture provides a consistent integration point for future capabilities.
- The ERA common ontology, extended across all subsystems and TSIs, underpins semantic interoperability; coupled with a federated rail data space interlinked with common European Mobility Data Spaces (EMDS), it enables scalable, trust-preserving integration of planning, operations, maintenance and logistics services.
- FRMCS development aligned with other deployments minimises costly re-touch of systems and ensures communications keep pace with automation and capacity management advances.
- Establishing a unified, secure rail data space with standardized models and APIs creates a single source of truth, enabling seamless, real-time information exchange across all stakeholders and modes. This foundational layer supports data-driven decision-making for optimal network management.
- Integrated digital platforms leverage this unified data to optimize routing, tracking, and scheduling for both freight and passenger services, facilitating efficient multimodal logistics chains and unlocking the full potential of rail as a central component of integrated European transport networks.

Resilience and improved security

- Simplified, harmonised architectures reduce operational fragility and the attack surface inherent in bespoke, aging hybrids; cybersecurity and long-life software maintenance are treated as first-class design and migration concerns.
- FRMCS Edition 2 validation, with compatibility and coexistence (e.g., IRIS², Wi-Fi evolution), strengthens secure, sabotage-resistant data exchange for safety-critical operations.
- The federated rail data space includes governance frameworks (roles, access levels, EU-compliant sharing) and stress-tested cross-border pilots to harden operations against physical and cyber threats.
- Harmonised degraded-mode rules, modular onboard fallbacks, and standardised processes for automated operations raise reliability under disruption and speed safe service restoration.
- More affordable standardised and modular equipment facilitates repairs in any locations and reduces the costs of implementing key systems redundancies.

- By consolidating demand on interoperable, European solutions, ESIRS supports a robust supply chain and long-term maintainability, enhancing Europe's ability to sustain critical rail services under shock.
- Automation and infrastructure independence make urban rail systems even more resilient to external events, whether accidental, climate-related, or intentional.
- Real-time data visibility and standardized interfaces allow for quicker detection of disruptions and more agile responses across the network and different transport modes. This foundational digital layer enhances the overall resilience of the rail system by enabling faster recovery and more adaptive operations.

4.2 Flagship Initiative 2: The Next-Generation Rail Freight Operations with European Digital solutions

Europe stands at a pivotal moment where decarbonization, digitalization, competitiveness and geopolitical challenges intersect. As supply chains become more complex, climate imperatives more pressing, and global competition more intense, the European Union must reinforce the European systems that underpin its economic sovereignty, sustainability and strategic autonomy. Rail freight plays a central role in this transformation.

Transport accounts for 29% of all greenhouse gas emissions[3] in the EU, with rail producing only 0.4% of Europe's total transport emissions[4], highlighting the significant environmental benefits of modal shift to rail. Therefore, each percentage point increase in rail's modal share is estimated to reduce transport-related CO_2 emissions by approximately 3 million tons annually. However, rail currently accounts for a small share of freight transport (11.9%[5] in Tonne-Kilometres) in Europe, despite its clear environmental advantages and capabilities beyond EU borders. Decades of underinvestment, fragmentation of rail freight market with a high-cost pressure, a lack of coordination across stakeholders, a lack of level playing field between different transport modes and outdated technologies have limited rail's competitiveness against road transport. At the same time, the sector faces mounting pressure to modernize, decarbonize, and support strategic logistics, including military mobility and crisis response capabilities. To unlock its full potential, the rail freight system must be developed as an integrated, automated, and digitalized logistics ecosystem—capable of seamless cross-border and multimodal operations, resilient to disruption, and responsive to both civil and military needs.

This flagship initiative addresses these challenges by setting an ambitious goal: the deployment of a fully integrated, digitalized, automated and interoperable European rail system by 2050, enabling a significant modal shift from road to rail, supporting the development of rail freight, enhancing efficiency and resilience, and reinforcing Europe's industrial and technological leadership.

Central to this transformation is a system approach that brings together infrastructure, rolling stock, digital platforms, and human capital but also allow an efficient combination of existing systems with new assets. This approach combined with the other Flagship Initiatives (addressing key enablers like ETCS, FRMCS) must prioritize the development, integration and deployment of key enabling technologies.

The Next-Generation Rail Freight Operations with European Digital solutions requires seamless integration with multimodal logistics chains and comprehensive digitalization to enhance rail freight's competitiveness against road transport but also reinforce co-modality. To achieve this, rail freight must become significantly more flexible and responsive, with adaptive access points, interchange nodes, and routing capabilities that respond dynamically to real-time demand. This transformation depends on intelligent systems that enable

[3] https://www.eea.europa.eu/en/topics/in-depth/transport-and-mobility?activeTab=fa515f0c-9ab0-493c-b4cd-58a32dfaae0a

[4] https://www.era.europa.eu/system/files/2024-07/20242052_PDF_TR0924239ENN_002.pdf?t=1756872250

[5] https://transport.ec.europa.eu/facts-funding/studies-data/eu-transport-figures-statistical-pocketbook/statistical-pocketbook-2024_en

the integration of diverse service providers into coordinated intermodal offerings, supporting near-full asset utilization while ensuring reliable, efficient and predictable operations that meet the cost, speed, and quality expectations of modern logistics.

Advanced IT tools for Train Planning and Traffic Management in a federated European system must evolve into components for a comprehensive multimodal freight coordination platform. These systems will integrate real-time data from rail, road, maritime, and inland waterway transport modes. AI-driven algorithms will enable dynamic rescheduling and seamless modal transfers while maximizing network utilization through predictive capacity management and flexible routing optimization.

By ensuring trusted access to operational, capacity, and demand-related data, this framework supports transparency, efficiency, and innovation in multimodal freight chains. In parallel, the Telematics Applications for Freight Technical Specifications for Interoperability (TAF TSI) provides the regulatory and technical backbone for harmonized data exchange within the rail sector, defining common standards for information such as train composition, path requests, consignment notes, and real-time operational updates. Together, the federated data space and TAF TSI create the conditions for reliable, AI-driven coordination across transport modes, ensuring that rail freight can integrate seamlessly into digital logistics ecosystems while maintaining interoperability, safety, and compliance at a European scale.

Effective first-mile and last-mile integration, based on efficient railway access to well dimensioned freight yards, is critical to eliminating logistical bottlenecks. By digitally synchronizing various freight transportation modes with rail schedules and cargo flows, connecting ports, distribution centres, and industrial facilities to flexible rail access points throughout the network, real-time optimization—powered by hybridised mathematical optimisation and artificial intelligence —will enable dynamic, predictive logistics management across the entire multimodal network.

Harmonized interoperability standards including Digital Automatic Coupling (DAC), standardized loading and transhipment technologies including the respective interfaces (rules/requirements/IT) between stakeholders/modes, and unified data exchange protocols will enable to achieve seamless cross-border operations while reducing complexity for operators.

Innovative digital platforms will provide state-of-the-art routing, automated documentation, unified booking and tracking, and dynamic pricing capabilities. These tools will level the playing field, ensuring competitive access for small and medium-sized operators while enabling flexible and secure interoperability between different logistics services.

Migration scenarios require careful coordination across multiple operators with standardized protocols ensuring interoperability during transition to automated freight operations that deliver predictable service quality.

Additionally, the new rail digital harmonised system will provide a platform for integration of the entire supply chain, driving the further integration of ports with railways and covering for example the needed development activities to close the existing technical and capabilities gaps.

This comprehensive system approach will transform rail freight into a modern, integrated, and intelligent logistics ecosystem that maximizes efficiency, resilience, and predictability, while laying the groundwork for a truly interoperable European rail freight system by 2038.

It will require not only technological investment but also a skilled and adaptable workforce. The rail freight sector must attract new talents, retrain existing workers, and foster a culture of innovation and digital competence. Developing training programs aligned with the digital and automated future of rail is critical to ensuring a just and inclusive transition.

Pre-deployment coordinated activities across EU and associated R&I

Pre-Deployment is essential because the Next-Generation Rail Freight Operations cannot be implemented through isolated national initiatives due to the inherent cross-border aspect of rail freight. Without pre-deployment activities, the entire vision for rail freight risks fragmentation, inefficiencies, and loss of cross-border interoperability.

Areas of pre-deployment and associated research and innovation coordinated activities for next-generation rail freight operations

1) **The European Automated and Digital Freight Train with Digital Automatic Coupling (DAC) as key enabler**

a. Context

Rail freight still relies heavily on manual processes, fragmented digitalisation, and diverse national practices that limit efficiency and cross-border interoperability. One of the most significant bottlenecks is the manual coupling of freight wagons, a time-consuming and physically demanding task that constrains productivity, puts workers' safety at risk, and weakens rail's competitiveness compared to road transport.

The Digital Automatic Coupler (DAC) has been identified as a game-changing technology to address these challenges. It represents the key enabler for the European Automated and Digital Freight Train, a concept that integrates smart wagons, predictive maintenance, and automated yard operations into a seamless, data-driven ecosystem. Its successful implementation requires a synchronized approach to fleet migration, trackside readiness, and coordinated deployment alongside other key technologies, such as ERTMS. It involves close collaboration among infrastructure managers—including first- and last-mile infrastructure—terminal operators, vehicle keepers, maintenance companies, freight operators, and the wider supply industry across Europe. Additionally, enhancing the competitiveness and capacity of rail freight transport through digitization is only possible if, alongside technical enablers (e.g., Digital Automatic Coupling), a structured network of interfaces is created, particularly for the automated collection and exchange of real-time data. Given the current decline in rail freight market share, quickly implementable and cost-effective digital solutions (such as RFID and video gates) are necessary for train localization and integrity as bridging technologies and future components of a fully automated freight transport system. Planning must consider the financial capacity of the rail freight sector in different regions of the EU and beyond, as well as the time needed for adaptation. A balanced and non-discriminatory European funding and financing framework is essential to support deployment while positively influencing the market share of European rail freight. The initiative also necessitates a central managing structure to maintain the system and serves as a prerequisite for automated yard operations, fully unlocking the benefits of digital freight train operations in European shunting yards.

b. Objective

By 2038, following pre-deployment activities, freight wagons equipped with DAC (full package) will fully operate across 6 major European routes, fully integrated with ERTMS deployment and Traffic Management Systems (TMS) as well as logistic chains, enabling 60% reduction in coupling time and further competitiveness of rail freight while delivering net zero logistics.

c. Pre-deployment activities

Pre-deployment activity 1: Large-scale Field Demonstrations on TEN-T Corridors

- Around 5,000 wagons equipped with DAC operating across six major routes.
- Test interoperability, robustness, and safety of DAC in diverse operational environments (cross-border traffic, different wagon fleets, climatic conditions) including validation of:
    - Derailment prevention systems,
    - Self-diagnosing wagons
    - Dynamic wagon composition
    - Advanced goods condition monitoring
    - Predictive train integrity
    - Automated wagon tracking for real-time visibility and logistics optimization

- Self-propelled freight wagons and their operation in synergy with DAC and virtual coupling, enabling flexible, automated train formations without locomotives.

Routes may for example includes (part of) the corridors Atlantic corridor, North Sea - Rhine - Mediterranean corridor, North Sea–Baltic corridor, Scandinavian–Mediterranean corridor, Baltic Sea – Adriatic Sea corridor, Rhine–Danube corridor, Mediterranean corridor, Western Balkans –Eastern Mediterranean corridor, and Baltic Sea - Black Sea - Aegean Sea corridor (to ensure geographic and operational diversity).

Pre-deployment activity 2: Pilot Operations in Freight Terminals and Yards

- Deployment of DAC-enabled wagons in marshalling yards, first/last mile terminals, and logistics hubs.
- Pilot automated yard operations, integration with terminal management systems, mainline systems and coupling efficiency gains.
- A selection of strategic terminals along the major European routes.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL and other initiatives:

- the technology development, testing, demonstration and standardisation activities carried out in the Europe's Rail Flagship Area 5 and System Pillar Task 4.
- the pre-deployment activities conducted in the European Pioneer DAC train project.
- the work done in the European DAC Delivery Programme

e. R&I and harmonisation activities:

R&I efforts will play a crucial role in enabling pre-deployment activities and preparing for industrial ramp-up. Key focus areas include:

Modular and Scalable Technology Development including adaptors

- Design plug-and-play modules or adaptors to accommodate diverse rolling stock fleets across the EU and ensure compatibility with legacy systems.

Lifecycle and Maintenance Innovation

- Apply AI, IoT, and predictive analytics for lifecycle cost reduction.

Open Standards and Vendor Interchangeability

- Align with ERA and European standardisation bodies to establish harmonised technical specifications.

Structured network of interfaces

- for the automated collection and exchange of real-time data:

- R&I for quickly implementable and cost-effective digital solutions (such as RFID and video gates) for train localization and integrity as bridging technologies and future components of a fully automated freight transport system
- research for novel digital approaches and standards support

2) Yards and logistics hubs

a. Context

Transhipment points—rail yards, terminals, ports, and logistics hubs—are vital for seamless door-to-door freight transport. Yet today, their operations remain manual, fragmented, and labour-intensive, creating delays, higher costs, and safety risks:

- Transhipment points are important in the door-to-door transport process, and therefore, in order to improve the delivery of goods to their final destination.
- Automation and digitisation of transhipment process improving workers safety will bring significant added value to the planning of the entire freight transport process.
- Digital transhipment enables seamless intermodal integration, ensuring smooth coordination and handover between rail, road, maritime, and inland waterway modes through standardised interfaces and real-time data exchange.
- Integration of yards/terminal with their specific offerings and needs in the multimodal supply chain planning and routing is vital for planning and executing reliable transport service offers.

By combining Digital Automatic Coupling (DAC) with digital yard management, automated shunting, and interoperable data platforms, Europe can transform these nodes into faster, safer, and more efficient hubs, boosting rail's role in multimodal logistics and supporting Green Deal and supply chain resilience objectives.

b. Objective

- Reduce average transhipment time by 30–50% by 2036.
- Cut work-related accidents in yards/terminals by 40% by 2036.
- Boost terminal throughput by 20–25% by 2035 without major infrastructure expansion.

c. Pre-deployment activities

Pre-deployment activity 1: Pilot Digital Yard Operations

- Deployment of digital yard management systems in at least 10 strategic freight yards along TEN-T corridors.
- Test automation of wagon sorting, tracking, and scheduling, integrated with DAC and automated shunting systems.
- Selected yards on TEN-T corridors

Pre-deployment activity 2: Intermodal Handover pilots

- Large-scale pilots at intermodal hubs where rail meets road, maritime, and inland waterways to validate and optimize digital processes for container handover, slot booking and administrative operations.
- Test and validate standardised digital interfaces for seamless data exchange.

- Selected intermodal hubs across Europe where rail connects with road, ports, and inland waterways, ensuring diverse geographic, operational, and logistical conditions.

Pre-deployment activity 3: Rail–Port and Rail–Inland Waterway Interface Development

- Integrate and test new solutions and interfaces at key rail–port and rail–inland waterway hubs to improve connectivity, streamline cargo handover, and overcome current operational bottlenecks..
- Integrate digital adaptations, data exchange standards, and infrastructure upgrades. Validate interoperability, process automation, and real-time data exchange for container handover, slot booking, and logistics coordination.
- Major intermodal hubs and corridors where rail connects with ports and inland waterways across Europe, ensuring geographic and operational diversity.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL and other initiatives:

- the technology development, testing, demonstration and standardisation activities carried out in Europe's Rail Flagship Area 5 and in the System Pillar Task 4.
- the digital yard pilots and automation demonstrations undertaken in Shift2Rail projects (e.g. digital yard management systems, automated shunting, wagon tracking).

e. R&I and harmonisation activities:

R&I efforts will play a crucial role in enabling pre-deployment activities and preparing for industrial ramp-up. Key focus areas include:

Interoperable Data Standards

- Develop open APIs and standardised data models for intermodal cargo exchange.

AI Optimisation

- Research advanced simulation and optimisation tools for capacity planning and disruption management.

Human-Machine Interaction

- Explore safe interaction between workers and automated equipment in complex yard environments.

Cybersecurity & Data Governance

- Develop frameworks to ensure secure and competition-neutral data sharing.

Ports and inland waterways integrations

- Development of interoperable data exchange models and harmonisation of operation for interfaces with rail.

- Development of innovative European harmonised solutions (that can be deployed at scale) addressing the physical bottlenecks impeding more freight transport by rail from European ports and inland waterways

Cost-Benefit Analysis Models

- Assess lifecycle benefits of automation (efficiency, safety, emissions reduction) versus investment costs.

3) Electro-Pneumatic Brakes on freight vehicles

a. Context

Conventional pneumatic brakes of freight wagons are an important factor to spark capacity bottlenecks in rail. They slow down braking response times, lengthen headways between trains, and reduce the ability to run freight trains at higher speeds or mixed with passenger services.

Electro-Pneumatic (EP) brakes, already used in passenger rolling stock, allow:

- Much faster and uniform brake application across the whole train.
- Shorter headways and better train path allocation.
- Increased line capacity and safety.
- Compatibility with digital freight technologies (DAC, ERTMS, TMS).

b. Objective

- Increase effective line capacity by 10–15% on upgraded corridors by 2036, by allowing shorter headways.
- Reduce average brake response time.
- Speed & Flexibility: Enable 20–30 km/h higher average operating speeds for freight trains on mixed-traffic lines by 2035.

c. Pre-deployment activities

Pre-deployment activity 1: Pilot corridors demonstrations

- Operate ~1,000 EP-equipped wagons in mixed passenger–freight traffic to validate capacity and braking performance.
- Test reduction in headways, braking response, and operational flexibility under real conditions.
- Where: 3–4 Major European route with high freight traffic.

Pre-deployment activity 2: Fleet retrofitting pilots

- Retrofit a representative sample of freight wagons across different types, operators, and keepers.
- Test technical feasibility, installation workflows, and lifecycle maintenance needs.
- Selected commercial services on major European route or TEN-T corridors.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL:

- the work on EP-brake architectures and monitoring done in the Flagship Area 5

e. R&I and harmonisation activities:

R&I efforts will play a crucial role in enabling pre-deployment activities and preparing for industrial ramp-up. Key focus areas include:

System Integration

- Research compatibility between EP brakes, DAC power supply, and ERTMS.

Optimisation Models

- Quantify network capacity gains with EP brakes in real traffic simulations.

Retrofit Solutions

- Develop modular, cost-efficient retrofit kits for different wagon fleets.

Impacts

Service Quality Enhancement

- Provide a coherent EU-level deployment roadmap that avoids fragmentation and secures stakeholder confidence.
- Enable automated yard operations, unlocking the full benefits of digital freight trains.
- Enhance operational resilience through predictive maintenance and digital decision support.
- Enable seamless intermodal integration through real-time data exchange between rail, road, maritime, and inland waterways.
- Enhance network-wide efficiency by improving visibility of cargo movements and resource availability.
- Up to 50% faster transhipment times, reducing bottlenecks in door-to-door supply chains.
- +10–15% line capacity; shorter stopping distances; improved schedule reliability.

Cost-Effective Solutions

- Establish a balanced and non-discriminatory funding schedule, supporting both large and small operators across Member States.
- Expand workshop capacity and workforce skills for large-scale retrofitting, ensuring a temporary but crucial industrial boost.
- Create export opportunities for European suppliers, reinforcing EU technological leadership.
- Improved terminal and asset utilisation, reducing logistics costs.

- More freight per day without new infrastructure; lower lifecycle costs.

System Optimisation

- Stimulate European industrial capacity in strategic rail technologies, in line with the Draghi report.
- Reduce physical strain in coupling operations, addressing challenges of an aging workforce and making rail more attractive to younger workers.
- Stronger European industrial position in automation and digital logistics technologies.
- Energy-efficient yard operations through digital optimisation.
- Harmonised, interoperable systems across borders.
- Strengthen the role of rail in achieving Green Deal targets by making freight more competitive.
- Contribute directly to net-zero logistics by shifting more freight to rail.

Resilience and Improved Security

- Strengthen EU strategic autonomy by reducing dependence on non-European suppliers in critical infrastructure technologies.
- Increase resilience of European supply chains through more reliable, digitally integrated freight transport.
- Strengthened EU strategic autonomy in logistics and digital platforms.
- Contribution to TEN-T and Green Deal objectives by enhancing multimodality and competitiveness of sustainable freight transport.
- Significant reduction in accidents and improvement of workers' safety by reducing exposure to manual, physically demanding tasks.
- Modal shift incentives from road to rail and waterborne, lowering CO_2 emissions.
- 50% reduction in rear-end collision risk; safer yard operations.
- 5–10% energy savings per train; supports CO_2 reduction and modal shift to rail.
- Strengthens EU leadership in rail technology.

4.3 Flagship Initiative 3: Resilient and Recoverable Railway System

To address emerging threats from among others climate change, cyber-physical attacks (hybrid threats), and the need for dual use of the rail infrastructure to expand the capabilities regarding military mobility, the Re²Rail flagship integrate dual-purpose resilience strategies by increasing the resilience of the railway infrastructure as well as the availability of these assets through reduced maintenance efforts and enabling the rail infrastructure for military mobility.

A future resilient railway operation needs to re-consider the operational value of individual assets in the railway system. It integrates reinforcement of the asset capabilities, climate adaptation, secure protocols, and cyber-physical redundancy to ensure uninterrupted service under extreme stress.

The Resilient and Recoverable Railway System requires comprehensive resilient multimodal integration to create a robust European transport network and service offers, that maintains essential mobility services during climate emergencies, cyber-physical attacks, and military mobility requirements. This vision centres on crisis-adaptive platforms connecting rail with other transport modes through hardened APIs and the resilient Train Planning System (TPS), which evolves to emergency-responsive coordination integrating real-time data from railways and backup transportation modes during disruptions.

A resilient railway system requires coordination across infrastructure managers and operators of any kind with different elements: redundant protocols ensuring system recovery capabilities, while mathematical optimisation, AI and Quantum Computing supported by digital twins will enable complex real-time crisis optimization coordinating backup schedules, emergency capacity, and evacuation flows while maintaining social cohesion through preserved community connectivity. This comprehensive approach transforms the rail system into a crisis-resistant mobility ecosystem that maintains essential connectivity and social resilience during disruptions while delivering a more efficient but also more resilient and recoverable European railway system by 2038.

Military mobility refers to a set of measures and capabilities that enable the swift, smooth and unimpeded cross-border movement of troops, military equipment and materiel in times of peace, crisis and armed conflict. Key areas for the implementation of these measures include transport infrastructure, regulatory, legal and political frameworks, digital tools, and effective coordination within a whole-of-government and whole-of-society approach. It should cover the following areas:

- Addressing military requirements in terms of capacity, automation and control. Integrating military logistic points into the rail network. Incorporating the required loading gauge, train length and weight requirements and addressing special operation requirement of military mobility.
- Considering part of the rail system as a military critical infrastructure that need to be protected.
- Incorporating "military-grade" cyber and electronic protection where needed to avoid accidents or destructions.
- Creating enough resilience in terms of energy and telecommunications to the system, including resilience against small drone attacks.
- Integrating the rail technology with space-based technology, either to replace vulnerable ground-based systems, improve reliability or to reduce costs.
- Designing the next generation secure system that can make use of the latest digital/technical capabilities
- Migration strategies

Harmonized resilience requirements across the European rail network ensure consistent emergency response capabilities across borders during disasters, cyber-attacks, or military operations. Comprehensive accessible emergency procedures include multilingual visual and audio alerts, PRM evacuation routes, cognitive accessibility support during high-stress situations, and simplified emergency interfaces accommodating all users regardless of abilities, ensuring no one is left behind during crises. They also provide the additional benefit of improved maintenance and performance, as well as increased availability of the network in normal times.

Identifying and applying in real networks the requirements for resilient railway operations and the necessary measures and technologies, including those needed to maintain operations and maintenance even in the event of a loss of essential personnel, is part of the work of this Flagship Initiative.

Pre-deployment coordinated activities across EU and associated R&I

Pre-Deployment is essential because the European resilience levels that Re²Rail envisions cannot be achieved through isolated national implementations, and require testing and validation at EU scale and collaboration across authorities from different Countries. The effort that the European Union is currently doing in addressing both military mobility and climate change can be capitalised with such EU wide and ambitious PPP programme among the sector with the public authorities.

Areas of pre-deployment and associated research and innovation coordinated activities for a resilient and recoverable railway across the EU

1) A cyber secured railway network

a. Context

The increasing digitalisation and connectivity of Europe's railway systems—driven by ERTMS, ATO, digital platforms, and IoT-based infrastructure—have significantly expanded the sector's vulnerability to cyber threats. The interconnected nature of rail services demands a harmonised cybersecurity approach across EU Member States.

b. Objective

By 2038, the objective is to achieve a harmonised, resilient, and proactive cybersecurity framework for the European railway network, integrated into both legacy and future digital rail systems, and fully aligned with the EU cybersecurity framework (NIS2 Directive, Cyber Resilience Act, etc.).

c. Pre-deployment activities

- Develop, test, and validate cybersecurity-by-design architectures for rail systems,
- AI-enabled threat detection systems,
- secure communication protocols,
- interoperable incident response mechanisms for rail-specific assets (e.g. signalling, rolling stock, control centres).
- To anticipate evolving cyber threats, avoid fragmented national responses, and ensure secure interoperability across the Single European Railway Area.
- At least 3 cross-border testbeds and living labs in critical rail and urban hubs with high automation levels.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL:

- foundational work through its System Pillar, including the publication of cybersecurity guidelines.
- Demonstration works are expected to take place in the second half of the EU-RAIL programme.

e. R&I and harmonisation activities

Future efforts must focus on:

- Real-time resilience analytics,
- Dynamic risk assessment tools,
- Integration of quantum-safe cryptography, and cyber training for operational staff.
- Collaborative frameworks for sharing threat intelligence across national rail operators are needed.

2) Intelligent Video Gates

a. Context

As rail freight aims to become more competitive, automated and seamless border control of wagons and cargo is essential. Intelligent Video Gates (IVGs) are emerging as a key enabler for digitalising freight operations by allowing the automatic identification, inspection, and tracking of trains and wagons at terminal entry and exit points. Developed under Shift2Rail and further enhanced under EU-RAIL, IVGs leverage AI-powered video analytics to increase transparency, safety, and efficiency in freight terminals.

b. **Objective**

By 2035, the objective is to deploy Intelligent Video Gates widely across European rail freight terminals, enabling near real-time monitoring, automated asset recognition (e.g. wagon number, hazardous materials placards), and seamless integration with digital freight platforms and customs systems.

c. **Pre-deployment activities**

- Design and validate interoperable IVG prototypes.
- establish data-sharing protocols that are secure, GDPR-compliant, and harmonised across operators and Member States.
- To overcome current manual inspection bottlenecks, reduce terminal dwell times, and ensure compatibility across different terminal infrastructures and operators.
- Deployment and testing could focus on major freight corridors and terminals.
- Cross-border pilot sites (at least 3) on TEN-T Core Network Corridors could also be targeted in order to ensure a European coordinated approach.

d. **EU-Rail activities**

This work will build on ongoing work already in EU-RAIL

- On the basis of the work done in Shift2Rail (FR8Rail III project) where IVGs were developed
- The concept was further matured within EU-RAIL (FP5-TRANS4M-R project). Proofs of concept have been successfully tested in operational environments (in Sweden and Germany)

e. **R&I and harmonisation activities**

- Advanced AI algorithms for anomaly detection (e.g. damaged wagons),
- Integration with blockchain-based freight traceability tools, standardised APIs for terminal management systems, and solutions for energy efficiency of IVG systems.
- Socio-technical aspects, such as operator training and change management, must also be addressed.

3) Minimum viable operations

a. **Context**

The ability of Europe's rail system to continue safe and coordinated operations under degraded, emergency, or crisis conditions—such as cyberattacks, natural disasters, or military disruption—depends on a new framework for **Minimum Viable Operations (MVO)**. This includes harmonised rules, technical fallback procedures, resilient planning, secure digital operations, and human-system integration to maintain continuity and safety across all operating scenarios.

b. **Objective**

By 2035, implement and validate a harmonised, cross-border MVO framework across key TEN-T corridors, ensuring rail operations can safely continue under disruption through ERTMS-based fallback profiles, resilient infrastructure planning, cyber-protected operations, and decision support systems linked to live asset data. The final objective is to validate a unified European approach to safe degraded-mode operations that ensures continuity of passenger and freight services under crisis, supports military mobility objectives, enhances resilience to climate and cyber threats, and reduces downtime through predictive and automated systems.

c. Pre-deployment activities

- Implement and test harmonised operational rules for emergency scenarios, including civil defence and military mobility;
- Integrate and adapt MVO profile for ERTMS with reduced but safe operating functions under degraded communications or signalling;
- implement EU-wide planning rules for infrastructure resilience and recovery;
- Run Traffic and Capacity Management Systems (TMS/CMS) with live asset condition data, including power, tunnels, and rolling stock;
- Test cyber-isolation protocols (“locked-up” mode) for critical zones and simulate nomadic cyber threats;
- Validate augmented human-machine interfaces (HMI) under high-stress conditions;
- Validate supply-chains under stress-conditions;
- Validate infrastructure to meet dual-use (civil/military) standards and develop autonomous maintenance capabilities for fallback lines.

R&I activities should be prioritised along high-value TEN-T corridors, especially where cross-border coordination, civil protection relevance, or military interoperability is critical. Pilot implementations should occur at operational control centres (OCCs), intermodal hubs, and fallback lines.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL:

- activities on simulating cross-border scenarios for CMS and TMS in FA1;
- development of ATO solution (up to GoA4) over ETCS in FA2

e. R&I and harmonisation activities

- Field validation of harmonised emergency operational rules, with joint IM–RU–military exercises;
- Finalisation of the ERTMS MVO functional set and procedures for switching between full and degraded modes;
- Full integration of fallback communications and localised train control under cyber-isolated conditions;
- Development of ERA-approved planning handbooks, including recovery timetables and climate stress design criteria;
- Operationalisation of AI-enhanced decision support tools and SOC (Security Operations Centre) integration with CMS platforms;
- Standardisation of dual-use infrastructure design and robotic maintenance capabilities for fallback route readiness.
- Recovery requires rapid assessment of damage and immediate access to replacement materials and components. This implies the need for a resilient and responsive supply chain Therefore efforts

for harmonization of infrastructure and rolling stock key components should be part of the supporting R&I activities;.

- Standardised processes investigation for the failure of centralised control and monitoring units, as well as technologies that allow for provisional decentralised operation and oversight. In particular, provisional redundancies in train routing (such as switch points and signalling).

4) Self-standing operation under massively disturbed conditions in adjacent networks

a. Context

The increasing risk of large-scale disruptions—whether from cyberattacks, climate extremes, or regional conflict—necessitates the ability for rail networks to operate in isolated or "emergency island" mode. Self-standing operation under such conditions requires decentralised control, localised communications, fallback rolling stock, and resilient asset management tools independent of central systems or public networks.

Nevertheless, a solution should be implemented for making those “island” able to communicate and allowing interoperability and connectivity across the European network.

b. Objective

By 2035, enable certified, safe, and interoperable self-standing rail operations ("island mode") on key strategic corridors, including fallback communication, decentralised traffic control, resilient positioning, and autonomous infrastructure monitoring—ensuring operational continuity during extended disruptions and supporting civil and military emergency response.

c. Pre-deployment activities

- Implement and test local communication technologies (e.g. UWB, direct radio, secure satellite links) for train-to-train and train-to-trackside connectivity in isolated areas.
- Validate autonomous route-setting, relative positioning, and localised traffic management systems (TMS/CMS) on the basis of a harmonised solution for use when cut off from centralised networks.
- Deploy augmented satellite train positioning (ASTP) with cyber-resilient GNSS solutions for fallback navigation.
- Pilot resilient rolling stock tailored to operate on secondary and fallback lines.
- Implement AI-based asset monitoring and satellite-supported diagnostics (e.g. for terrain shifts or bridge health) in isolation mode.
- Test automated track clearance and demining technologies for dual-use operations under defence or emergency scenarios.
- Validate interoperability and connectivity across the European rail network.
- Deploy condition-based maintenance systems optimized for climate resilience including embedded sensors in climate-vulnerable infrastructure components monitoring thermal stress, moisture ingress, and structural integrity in real-time, automated component replacement scheduling based on climate exposure history, and harmonized European climate maintenance protocols ensuring consistent asset protection across Member States.
- Validate remote maintenance capabilities for extreme climate and cyber-attack scenarios featuring satellite-connected maintenance diagnostic systems operating independently of terrestrial networks during extreme weather, remote-controlled maintenance vehicles capable of operating

safely during hazardous climate conditions, and AI-powered predictive failure analysis preventing climate-related asset failures before they occur.

To maintain safe, reliable operations even when central systems are unavailable—ensuring continued movement of passengers, freight, and defence assets during natural disasters, cyberattacks, or geopolitical crises. This supports EU priorities on climate resilience, military mobility, and infrastructure sovereignty.

Considerable number of targets within the capabilities to be developed for the rail sector can be enhanced in connection with the Earth Observation Component of the European Space Programme developed by EUSPA, Copernicus, especially with their services component based on satellite monitoring technology, measurements and data available from the current Sentinel missions and their further evolution, and even the Copernicus Contributing Missions (CCMs).

Target cross-border TEN-T corridors and fallback rail nodes near high-risk regions or critical infrastructure. Pilot "island mode" operations in corridors with existing military mobility relevance and climate vulnerability.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL:

- work on localised TMS/CMS integration, are ongoing in FA1
- Predictive maintenance platforms are ongoing in FA3
- satellite-based positioning work is ongoing in both the System Pillar and FA2.

e. R&I and harmonisation activities

- Develop and certify fallback communications protocols integrated with FRMCS and satellite constellations (e.g. IRIS², GovSatCom).
- Test and validate decentralised train control systems, short-range headway management, and autonomous local routing algorithms.
- Finalise ASTP safety cases and integration procedures with ETCS/ATO for degraded networks.
- Standardise specifications for minimal viable rolling stock and track elements for fallback service.
- Expand cybersecure AI-based diagnostics and confirm satellite imagery as a trusted asset monitoring channel.
- Integrate dual-use clearance and demining robotics with EU defence logistics and resilience operations.
- Create and distribute operational handbooks and training for infrastructure managers (IMs) and railway undertakings (RUs) for self-standing operation scenarios.
- Research integrated maintenance-operations systems for climate / cyber-security resilience developing maintenance protocols that maintain asset availability during climate emergencies while ensuring safety standards, automated maintenance priority systems reallocating resources based on real-time climate /military threat assessment, and cross-border maintenance coordination protocols enabling rapid European mutual assistance during widespread climate events.

5) Integration for Resilience and Recovery.

a. Context

To maintain operational continuity during major crises—whether caused by cyberattacks, natural disasters, or geopolitical conflict—Europe's rail network must ensure that mainlines and backup secondary lines can interoperate under stress. This includes seamless rerouting, rapid infrastructure recovery, and support for the fast deployment of military assets. Integration of resilient digital systems, standardised rolling stock and infrastructure, and automated processes is key to delivering this objective.

b. Objective

By 2038, ensure full-scale deployment of resilient, dual-use railway capabilities, enabling rapid recovery, remote control operations, and seamless interoperability between main and fallback networks—supporting both civilian traffic continuity and 96-hour EU-wide military deployment across the TEN-T network.

c. Pre-deployment activities

- Enable remote traffic operations (RTO) for seamless handover between control centres during cyber or physical disruptions.
- Deploy modular and precast infrastructure solutions featuring plug-and-play trackside equipment designed for rapid replacement during extreme weather events, to restore thermally affected rail tracks, damaged lines or bridges within hours or days.
- Pilot wind-resistant infrastructure standards including enhanced structure design specifications for sustained winds up to 150 km/h, active wind monitoring systems with automatic speed restriction protocols, and aerodynamically optimized rolling stock profiles for high-wind corridor operations.
- Deploy climate-hardened rolling stock designs capable of operating in extreme temperature conditions from -40°C to +60°C ambient temperature, including enhanced HVAC systems, thermally stable braking systems, and climate-adaptive traction control for both passenger and freight applications.
- Validate flood-resistant rolling stock systems with waterproof traction equipment up to 300mm water depth, emergency buoyancy systems for passenger coaches, and rapid-drain designs for freight wagons, tested on flood-prone corridor sections.
- Implement autonomous climate-adaptive maintenance systems featuring weather-resistant robotic inspection units capable of operating in temperatures from -30°C to +50°C, automated track geometry correction systems responding to thermal expansion effects, and drone-based infrastructure monitoring with enhanced sensors for climate-related deterioration detection.
- Develop input into standards for dual-use assets (e.g., rolling stock, traction, gauge clearance) to enable traffic on both main and fallback lines.
- Automate military convoy tracking, authorisation, and exceptional routing, including NRBQ (nuclear, radiological, biological, chemical) detection.
- Integrate cyber-physical protection systems for critical infrastructure, with AI-driven surveillance and anti-drone technologies.
- Secure power supply resilience for signalling and telecom systems via decentralised, autonomous energy sources (renewables, batteries, fuel cells, hydrogen).

These activities ensure that during disruptions, Europe's rail system can continue operations securely and efficiently, enabling fast civil recovery and uninterrupted military logistics.

- Priority focus on TEN-T corridors, cross-border nodes, terminals, and strategic fallback routes—particularly those relevant for defence mobility or climate risk, e.g. Eastern frontiers, Alpine crossings, and coastal or flood-prone areas.

d. EU-Rail activities

This work will build on ongoing work already in EU-RAIL:

- EU-RAIL has initiated activities on modular infrastructure components developed in FA3
- Work on climate change adaptation done in FA4 (risk assessment, adaptation, mitigation, etc…)

e. R&I and harmonisation activities

- Validate in demonstrators remote traffic operations (RTO) and cross-border OCC fallback procedures using degraded communications.
- Field-test and standardise modular bridge and telecom infrastructure for EU-wide rapid deployment.
- Pilot automatic gauge-change, dual-power locomotives, and harmonised TMS/CMS interfaces for mainline–secondary integration.
- Deploy AI-enhanced cyber/physical surveillance systems, including anti-drone countermeasures integrated with operational control centres.
- Certify energy-resilient signalling and telecom assets, capable of autonomous operation for ≥72 hours using renewable or hybrid systems.
- Develop advanced materials research for extreme climate railway applications including ultra-high temperature rail steels maintaining structural integrity up to 70°C rail surface temperature, composite materials for trackside equipment with enhanced UV and thermal cycling resistance, and self-monitoring smart materials with embedded climate condition sensing capabilities.
- Investigate climate-resilient infrastructure protection technologies including automated infrastructure shading systems for extreme heat protection, rapid-deployment flood barriers for railway corridors, and real-time structural health monitoring systems detecting climate-induced infrastructure degradation with predictive failure analysis.
- Research adaptive rolling stock thermal management systems featuring AI-powered climate control optimizing energy consumption during extreme temperature operations, phase-change material cooling systems for critical onboard electronics, and predictive thermal stress monitoring for traction motors and braking systems under harsh climate conditions.
- Develop harmonised climate resilience standards for European rolling stock and infrastructure establishing unified testing protocols for extreme climate operation validation, standardized climate adaptation retrofit specifications for existing fleet and infrastructure.
- Validate in demonstrators integrated climate-security systems combining climate monitoring with cybersecurity threat detection recognizing that extreme weather events can create vulnerabilities exploited by cyber threats, and developing resilient communication systems maintaining operation during combined climate-cyber incidents affecting multiple infrastructure domains simultaneously.
- Research autonomous maintenance robotics for extreme climate operations including development of all-weather robotic platforms capable of performing critical maintenance tasks during extreme temperature, wind, and precipitation conditions, AI-powered diagnostic systems detecting climate-specific asset deterioration patterns invisible to human inspection, and swarm robotics for coordinated large-scale infrastructure inspection during post-storm recovery operations.
- Develop predictive maintenance algorithms for climate-stressed assets featuring machine learning models analysing the correlation between climate exposure patterns and asset degradation rates, digital twin technology modelling infrastructure behaviour under various climate scenarios to optimize maintenance timing, and quantum computing applications for complex optimization of maintenance resource allocation during multiple simultaneous climate events.

- Investigate advanced climate-resistant maintenance materials and techniques including self-healing materials for infrastructure components exposed to thermal cycling, nanotechnology-enhanced protective coatings extending asset life in harsh climate conditions, and bio-inspired maintenance solutions adapting natural climate resistance mechanisms for railway infrastructure applications.

Impacts

Service Quality Enhancement:

Enhanced resilience and digitalisation in rail services lead to greater reliability and punctuality, even during crises or cyber incidents. Automated inspections and improved surveillance reduce delays and human error by 50%, fostering user confidence in both passenger and freight services.

Cost-effective Solutions:

Proactive investments in resilience, cybersecurity, and digital technologies significantly reduce long-term costs by minimising emergency repairs **by 20-30%,** manual processes, and service downtimes. Embedding security and automation at the design phase avoids costly retrofits and boosts operational efficiency.

System Optimisation:

Flexible infrastructure, secure digital platforms, and real-time data integration enable dynamic rerouting, optimised traffic management, and more efficient use of network capacity and terminal resources. These capabilities support faster recovery from disruptions and higher throughput without major infrastructure expansion. Increase terminal throughput by **15–20%** without major infrastructure upgrades.

Resilience and Improved Security:

A harmonised approach to infrastructure reinforcement, cybersecurity, and dual-use capabilities strengthens the rail system's role in both civil and defence contexts. Advanced surveillance, anomaly detection, and cybersecurity frameworks ensure continued operations and protection against both physical and digital threats. **Achieve 99 % system availability** during cyber incidents and maintain **85% capacity during extreme weather events** through real-time system monitoring, condition-based maintenance, and adaptive operations based on real-time data. Enable dual-use capacity on 6 strategic corridors supporting both civilian operations and 96-hour EU-wide military deployment capability.

4.4 Flagship Initiative 4: Innovative EU High-Speed Rail Corridors

Note: *This flagship initiative is currently in its early drafting stage and will be further extended and complemented based on the strategic vision set in the recently published Commission communication: Connecting Europe through High-Speed Rail[6], which provides a comprehensive policy direction and deployment priorities for European high-speed rail development.*

Europe's high-speed rail network is central to achieving faster, cleaner, and more connected mobility across the continent. As the EU pursues ambitious modal shift targets and seeks to triple high-speed rail traffic by 2050, the sector faces significant challenges: fragmented national approaches to high-speed development, rising infrastructure and rolling stock costs, inconsistent energy integration, and the need for seamless cross-border interoperability. New high-speed development must evolve beyond today's fragmented architecture, integrating next-generation digital and clean technologies within a single European framework.

The Innovative EU High-Speed Rail Corridors flagship initiative addresses these challenges by developing a harmonised, fully digital, and climate-resilient high-speed system that ensures efficient, zero-emission

[6] https://transport.ec.europa.eu/document/download/774e79c9-1ece-4514-8f16-a2b98049c82e_en?filename=COM_2025_903_HSR.pdf

operations across national borders. By unifying traffic management, advancing traction technologies, deploying digital twins, pioneering materials innovation, and implementing predictive maintenance within an interoperable European model, this initiative enables dramatic improvements in reliability, cost efficiency, and energy performance.

Through harmonised corridors implemented as early pre-deployment pilots, the initiative will contribute to reducing travel times between major European urban nodes, create seamless multimodal links with regional networks and airports, and strengthen Europe's industrial and technological sovereignty in high-speed mobility. It also addresses key socio-economic objectives: balancing the benefits of high-speed connectivity while mitigating territorial exclusion through integrated planning and ensuring equitable accessibility to all regions.

The flagship builds on outcomes of Europe's Rail Joint Undertaking, notably on traction systems, ERTMS, traffic management systems (TMS), and cybersecurity. While Europe's Rail has provided foundational core technologies, this flagship represents the first dedicated, system-level focus on integrated high-speed innovation at European scale. The initiative will pioneer harmonised pre-deployment corridors serving as early implementation pilots for future pan-European high-speed expansion, testing new technologies—including ETCS Level 2-only operations, predictive maintenance, and harmonised EU capacity management—under real operational conditions, ensuring safe, reliable, and cost-effective scaling.

Pre-deployment coordinated activities across EU and associated R&I

Pre-deployment is essential because the transformation that Innovative EU High-Speed Rail Corridors envisions cannot be implemented through isolated national initiatives. Harmonised European high-speed mobility requires coordinated testing and validation across multiple Member States to prove interoperability, operational efficiency, and economic viability at system level before large-scale deployment.

Areas of pre-deployment and associated research and innovation coordinated activities for or Innovative EU High-Speed Rail Corridors

1) Next-generation high-speed rolling stock and infrastructure

European high-speed rail will evolve to meet increasingly stringent environmental targets, deliver enhanced passenger experience, and maintain global technological leadership. Current high-speed rolling stock, while technologically advanced, could benefit from improvements in energy efficiency, operational flexibility, and lifecycle cost optimization. New materials, aerodynamic innovations, and advanced traction systems offer opportunities to dramatically reduce energy consumption while increasing reliability and reducing maintenance requirements.

High-speed infrastructure similarly faces challenges of climate resilience, energy integration, and cost-effective lifecycle management. Standardised, climate-resilient infrastructure designs adaptable to extreme weather conditions across diverse European climatic zones are essential for reliable pan-European operations.

2) Harmonised high-speed traffic management and ETCS Level 2-only operations

Efficient, high-capacity operation of European high-speed corridors requires harmonised traffic management systems enabling dynamic capacity optimization, seamless cross-border operations, and integration with conventional rail networks. Current fragmentation of traffic management approaches across Member States limits capacity utilization and creates operational inefficiencies at borders.

Multi-network capability is needed to enabling seamless operation across national and regional networks.

High-speed operation based exclusively on ETCS Level 2, without legacy side signalling, offers significant opportunities for cost reduction, operational simplification, and enhanced performance. However, this requires comprehensive validation of harmonised operational rules, standardised trackside configurations, and integrated capacity management across multiple networks.

3) Predictive maintenance and digital twins for high-speed assets

High-speed rail assets—both rolling stock and infrastructure—operate under extreme mechanical and thermal stresses requiring complex maintenance strategies to ensure safety, reliability, and cost-effectiveness. Traditional time-based maintenance approaches result in over-maintenance of some components and under-maintenance of others, increasing lifecycle costs and reducing availability.

Predictive maintenance enabled by digital twins, AI analytics, and comprehensive sensor networks offers opportunities to optimize maintenance scheduling, reduce unplanned failures, extend asset lifecycles, and significantly reduce operational costs. However, harmonised approaches validated across diverse European operational contexts are essential to enable industrial-scale implementation.

Impacts

The impacts of Flagship Initiative 4 represent a transformational advancement for European high-speed mobility, delivering enhanced service quality, cost-effectiveness, system optimization, and environmental performance while strengthening European industrial leadership.

Service Quality Enhancement

Reduced travel times between major European urban nodes through optimized operations and higher operational speeds, enhanced reliability and punctuality through predictive maintenance and advanced traffic management, improved passenger comfort through next-generation rolling stock designs, and seamless multimodal integration with regional networks and airports enabling convenient door-to-door journeys.

Cost-effective Solutions:

Reductions in lifecycle costs via predictive maintenance and optimized asset utilization, simplified ETCS Level 2-only infrastructure reducing deployment and maintenance costs, standardised European designs enabling economies of scale for manufacturers, and energy efficiency improvements reducing operational expenses while supporting climate objectives.

System Optimisation:

Increases through AI-supported traffic management, harmonised operational rules enabling seamless cross-border operations without delays, validated migration pathways from current systems to simplified future architectures, and enhanced integration between high-speed and conventional networks maximizing overall system efficiency.

Resilience and Improved Security:

Strengthen European mobility through climate-resilient infrastructure and rolling stock designed to withstand extreme weather conditions, ensuring reliable operations despite increasingly frequent climate events. Cybersecure digital systems protect critical high-speed operations from cyber threats. Ensure equitable accessibility across all EU regions through integrated planning preventing territorial exclusion, improved connectivity for peripheral regions. Strategic autonomy is reinforced through European technological sovereignty in critical high-speed systems—eliminating dependence on non-EU suppliers for essential technologies including traction systems, traffic management, and cybersecurity solutions, including by dual-use design.

4.5 Horizontal R&I framework

This section introduces R&I topics that can be considered as horizontal and complementary to the Flagship Initiatives developed earlier in this document. It focuses on using artificial intelligence, digital tools, and modular technologies to make trains more autonomous, efficient, and easier to upgrade. It also includes the use of drones, robots, and satellite communication to reduce reliance on fixed infrastructure. Special attention is given to cybersecurity, staff training, and better coordination between Member States—especially for cross-border and military-civil operations.

It also provides a framework for more disruptive or fast-paced R&I into marketable solution.

Below some examples that could be expanded based on the technical progress and needs:

1. **Artificial Intelligence & Autonomy**

AI Certification & Safety Integration

- Develop a European AI certification framework for rail aligned with safety standards (e.g., EN 50126/8/9).

AI for Autonomous Operations

- Develop SIL2+ AI perception modules for environment recognition, obstacle detection, and image-based navigation.
- Complement ETCS L2/3 to enable GoA3/4 autonomous train operations (incl. decentralized route setting, dynamic TSR management).

2. **Modularity, Interfaces & Virtual Certification**

Modular Architecture

- Shift towards modular sub-systems with stable, scalable, data-centric interfaces.

Virtual Certification

- Use digital twins and behavioural models for certification of software/electronic updates.

3. **Drones & Robot Swarms**

- Develop common EU specs and shared middleware for multi-vendor drone/robot fleets.

4. **Training & Change Management**

- Coordinate EU-wide staff training programs.
- Harmonise procedures for semi-automated/remote operations.
- Provide certified translation tools for driver–TMS/traffic management communication.
- Address human factors for automation and workforce transformation.

5. **Data, Cybersecurity & Sovereignty**

- Develop EU-compliant data sharing protocols, using role/entity-based access.

6. **Resilience, Security & Dual-Use Preparedness**

Design for Resilience

- Standardise interfaces for cross-useability and scalability (e.g., automatic gauge change, dual-power systems).
- Reduce dependency on infrastructure using vehicle intelligence.

Asset Protection

- Use AI surveillance, anti-drone tech, cybersecurity protocols, and dual-use military technologies.

7. Fast & Safe Adoption of Functional Change

- Develop safety models and behavioural digital twins.

8. Operations Under Fundamental Uncertainty

- Develop adaptive planning and non-probabilistic resilience strategies.
- Build comprehensive situational awareness from incomplete/low-quality data.

9. Cross-Cutting R&I Priorities

Human-Machine Interface (HMI) & Workforce

- Research human factors, training needs, and inclusive automation.
- Support safe transition to digital systems.

Lifecycle Costing

- Use full lifecycle analysis in design, asset management, procurement, and maintenance.
- Balance cost, reliability, and sustainability.

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