Deliverable D 5.1

Documentation of maglev-based transport system use cases, operational, system, standardisation and regulatory requirements generated by the introduction of the technology in the European Rail system

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Report contributors		
Francesca C. Antonacci Paolino Trinchese	FSI (RFI)	Overall document supervision, management and review. Chapters: 1, 2, 3, 4, 9,10
Francesco Inzirillo	MERMEC	Chapter 6
Wictor Radwan Paweł Radziszewski Michael Schultz-Wildelau	NEVOMO	Chapter 7
Arbra Bardhi Stefano Ricci	DITS	Chapter 7 Document Review
Gerard Coquery	TACV Lab	Chapter 8
Simon Collart-Dutilleul	Uni.Eiffel	Document Review
Giuseppe Carcasi Angela Nocita Marjorie de Belen Camilo Patiño Puerta Cecilia Interdonato Giovanni De Blasio	RFI	Document Review

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1 Executive Summary

The deliverable "Documentation of maglev-based transport system use cases, operational, system, standardization, and regulatory requirements" provides a comprehensive analysis of integrating maglev-derived systems (MDS) into the European rail network. This analysis explores MDS's infrastructural, operational, environmental, and socio-economic benefits and its transformative potential in modernizing rail transport.

Maglev-derived systems leverage advanced technologies like linear motors and electromagnetic suspension, enabling higher speeds, reduced energy consumption, and lower maintenance costs. The deliverable identifies the potential for significant performance improvements by upgrading existing railway corridors, preserving the efficiency of current networks, and enhancing interoperability with future infrastructure like hyperloops. Additionally, the report emphasizes the importance of comparative studies to address compatibility with existing systems, particularly the European Train Control System (ETCS) Level 2, and the need for developing solutions for train detection systems (TDS) and Eurobalise compatibility Actually, a key aspect of this analysis is the cross-checking of findings of Work Packages 2, 3 and 4 with the activities under the System Pillar framework. By integrating the results from the previous work packages, this deliverable underscores the need for standardization efforts to accommodate MDS technologies within existing infrastructure.

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
ATO	Automatic Train Operation
ATP	Automatic Train Protection
BTM-Antenna	Balise Module Transmission Antenna
CCS	Command Control and Signalling
EDS	Electro-Dynamic Suspension
EDW	Electro-Dynamic Wheels
EMS	Electromagnetic System
ETCS	European Train Control System
EVC	Emergency Voice Communication
GSM-R	Global System for Mobile Communications – Railway
ITS-G5	Intelligent Transport Systems – 5G
LIM	Linear Induction Motor
LSM	Linear Synchronous Motor
LTE	Long Term Evolution
MDS	Maglev-derived System
PRAMS	Performance, Reliability, Availability, Maintainability and Safety
RBC	Radio Block Center
TDS	Train Detection System
TSI	Technical Specifications for Interoperability
U-LIM	U-shaped Linear Induction Motors

3 Background

The present document constitutes the Deliverable 5.1 “Documentation of maglev-based transport system use cases, operational, system, standardisation and regulatory requirements generated by the introduction of the technology in the European Rail system” in the framework of the Flagship Area 7 – Innovation on new approaches for guided transport modes as described in the EU-RAIL MAWP.

4 Objective/Aim

In order to ensure that a transportation based on maglev-derived technology becomes a constituent part of the overall interoperable and seamlessly operated European Rail System, work package 5 aims to complement the study of its technical feasibility with this specific deliverable dedicated to a comparative analysis of operational procedures, system architecture and interface specifications, standardisation, and regulation requirements between the maglev-based and conventional transportation systems.

The deliverable will compare the specifics of the introduction of maglev-based transport systems in the European Rail Systems cross-checked with operational concepts, processes, and rules, and with system architecture specifications developed by the System Pillar in tasks 1, 2 and 3, while taking into consideration the results of WP2, WP3 and WP4.

5 State of the art of MDS

The project identified several configurations for MDS, with the potential capability of integrating maglev-derived technologies into existing railway systems The integration of maglev technology with railway infrastructure enables both MDS and traditional trains to operate seamlessly. For most configurations analysed within the MaDe4Rail project, the linear motor (stator) is embedded in the railway track, with the counterpart located on the vehicle, facilitating efficient propulsion. Other configurations like the “hybrid MDS based on air levitation” have the stator located on the vehicle, making the infrastructure less complex but requiring a direct power supply for the vehicle (such as a catenary).

Levitation and guidance are provided externally by the railway track or integrated into the vehicle, ensuring stable and controlled movement. Capsule movements are governed by Automatic Train Operations (ATO) with Grade of Automation of at least 3 (GOA3), which enables automated operations. In the applications with GOA4, a central control centre manages the circulation of capsules and adjusts their speed, allowing for shorter headways. The Traffic Management System (TMS) is based on advancements in railway technologies, which is covered in Flagship Area(FA) 1. High accuracy in vehicle positioning, with deviations below 5 cm, is achieved through the combination of linear motor technology, communication with the TMS, and systems such as GNSS and multisensors. Single track bidirectional operations are possible, enhancing the flexibility and efficiency of the infrastructure, with vehicles that are compatible with standard gauge tracks.

For configurations that require new vehicles, bogies will be designed to be integrated into trainsets with either mechanical or virtual coupling. Lightweight pods, accommodating 50-70 passenger seats and weighing approximately 20 tons with a length of 25 meters, do not require onboard traction motors. Steel wheel-to-rail interaction is utilized up to speeds of 30-50 km/h, with stable passive levitation occurring at higher speeds without the need for external power for levitation. The maximum operational speed for regional lines is set at 250 km/h, which is compatible with existing track alignments by increasing the cant deficiency. Acceleration and operational deceleration are set at 1.5 m/s^2, with higher accelerations and emergency deceleration capabilities available if necessary.

Building upon the foundational features of maglev-derived systems, their benefits are multifaceted, encompassing infrastructural, operational, environmental, and socio-economic aspects.

Maglev-derived systems offer significant infrastructural benefits. Upgrading existing railway corridors leads to substantial performance improvements, including electrification “from below.” This approach reduces construction costs and delivery times, as linear motors replace onboard motors, catenaries, signalling, and safety devices. The use of existing railway stations preserves city centre-to-city centre connections, maintaining the efficiency of current networks. High levels of interconnectivity ensure robust interoperability and intermodality, preserving the network effect. Additionally, these systems have the potential for a possible interoperability with future hyperloop infrastructure, ensuring scalability and future-proofing transportation networks.

Operational benefits are equally compelling. Enhanced vehicle dynamics on the same alignment allow for higher speeds, acceleration, and deceleration rates, significantly improving travel times. The technology supports shorter headways between vehicles, increasing system capacity. The absence of catenary-to-pantograph interactions on most of the analysed configurations, and reduced steel-on-steel friction lowers operational expenditures (OPEX). Remote-controlled, automatic, and autonomous operations, managed by advanced Traffic Management Systems (TMS) and Command Control and Signalling (CCS) systems, ensure efficient and safe operation. Furthermore, maglev systems facilitate the bridging of different technological stages of infrastructure and rolling stock, enabling seamless cross-border operations. These systems remain performance-invulnerable to weather conditions and topology, ensuring reliability.

From an environmental perspective, maglev-derived systems offer considerable benefits. They reduce noise, vibration, and dust pollution, contributing to a quieter and cleaner environment. The lower carbon footprint of these systems supports global sustainability goals. Importantly, there is no need for additional land occupation to build new infrastructure, preserving natural landscapes and minimizing ecological disruption.

Socio-economic benefits include increased flexibility and frequency of services, making public transport more convenient and attractive. The introduction of new business models, such as on-demand services, brings the potential to revolutionize the transport sector. Passengers experience, increased comfort and improved travel experiences foster a positive modal shift towards collective transport. This shift not only benefits the environment but also enhances urban mobility and reduces traffic congestion.

In summary, the integration of maglev-derived systems into existing railway networks presents a transformative opportunity. The combined infrastructural, operational, environmental, and socio-economic benefits position maglev technology as a pivotal advancement in modern transportation, promising a more efficient, sustainable, and user-friendly future.

5.1 Comparative analysis of the technical development

An MDS is composed of several integrated subsystems, categorized into four primary areas: Vehicle, Infrastructure, Energy, and Command and Control. The Vehicle subsystem includes the structure, propulsion (vehicle part), suspension, guidance, braking, vehicle control system, electrical system, and monitoring and safety. The infrastructure subsystem encompasses the guideway, switches, propulsion (infrastructure part), and substructure. The Energy subsystem is comprised of the power supply substation, electrical system, sensing and communication, and segment switches. Finally, the Command and Control subsystem includes the Traffic Management System (TMS), control centre, monitoring and safety, communication, and positioning. Each of the subsystems is assessed, and different configurations are compared. In cases where only one configuration is available, no comparison is provided.

5.1.1Vehicle – Structure

When considering the vehicle structure, two possible setups can be considered: Structure for Hybrid MDS interoperable with railway infrastructure and Structure of Rail vehicle upgraded with MDS subsystems or technologies.

Function:

- Both structures are designed to safely transfer internal and external forces and to support various components such as the linear motor mover, suspension, onboard electronics, and safety systems. The Hybrid MDS structure is specifically designed to be lightweight to enhance levitation performance.

Development History and Status:

- The Hybrid MDS structure combines principles from maglev systems and the aerospace industry. It is currently in the testing phase with a full-scale bogie prototype, and has reached TRL of 5.
- The structure of Rail Vehicle Upgraded with MDS subsystems adapts traditional railway structures for linear motors. This structure is also in development and has a TRL of 5.

Relevant Environment:

- The Hybrid MDS structure operates on existing railway networks, which can be either closed or open.
- The upgraded rail vehicle structure is designed for use within existing railway networks, both closed and open.

Comparison of Environments:

- The Hybrid MDS has been demonstrated in a simplified environment on a straight railway track without switches. The next steps include building and validating a full-scale vehicle.
- The structure adapted for linear motors in upgraded rail vehicles needs reauthorization and has not been fully validated yet.

Operational Requirement and Test Results:

- The Hybrid MDS structure must safely transfer forces from linear motor operations and meet defined safety requirements. Test conducted at the Nowa Sarzyna Test Track have shown successful levitation and speed achievements.
- Similarly, the upgraded rail vehicle structure must also safely handle forces from linear motor operations. Tests at on a retrofitted freight platform equipped with a linear synchronous motor mover at the Nowa Sarzyna Test Track have demonstrated successful operation.

SUMMARY:

Both the Hybrid MDS and the Upgraded Rail Vehicle structures are in the testing phase, with a Technology Readiness Level of 5. They share similar operational environments and requirements but differ in their specific design focus — Hybrid MDS prioritizes lightweight construction for better levitation, while the Upgraded Rail Vehicle focuses on adapting existing structures for new technologies. Both systems have shown successful initial test results, but further validation and reauthorization are needed.

5.1.2Vehicle – Propulsion

Two linear motor technologies must be distinguished, the synchronous linear motor (LSM), and the asynchronous (or induction) linear motor (LIM).

Linear Induction Motor (LIM):

- Function: The Linear Induction Motor (LIM) is an asynchronous electric machine consisting of two parts: an active part (typically a 3-phase winding) that generates an electromagnetic field and a reaction plate where eddy currents are generated. The active part is usually mounted on the vehicle.
- Development History and Status: they tested successfully in various commercial metro lines in Canada, Japan, and China at speeds up to 110km/h, and with full-scale tests demonstrating speeds up to 300 km/h.They are currently at technology Readiness Level (TRL) 9.
- Relevant Environment: The relevant environment for the railway-compatible MDS linear motors is a railway network or railway sidings.
- Comparison of Environments: LIM prototypes have not yet met all regulatory requirements in railway environment, including environmental conditions and EMC. No tests have been conducted involving switches and road-rail crossings.
- Operational Requirement and Test Results: LIMs require an additional power supply on the vehicle side. They have been tested successfully in various metro lines in Canada, Japan, and China, with full-scale tests demonstrating speeds up to 300 km/h,

today about 500 km of metro lines are using LIMs mainly in Asia such as Japan, and China, and in Canada).

Linear Synchronous Motor (LSM):

- Function: The linear synchronous motor (also called "Long Stator Motor") is a synchronous electric machine consisting of two parts: an active part (typically a 3-phase winding) that generates an electromagnetic field and a magnetic part that generates the north and south poles generate by using coil supplied by DC generators, or by using permanent magnet, to hold on to the sliding magnetic field of the active part. The active part is mounted on the track.
- Development History and Status: LSM have been in use for over 50 years and have been proven in projects such as M-Bahn, Transrapid, and Chuo Shinkansen. They are currently at technology Readiness Level (TRL) 9.
- Relevant Environment: The relevant environment for the railway-compatible MDS linear motors is a railway network or railway sidings.
- Comparison of Environments: in specific applications lines (Germany and Asia: Japan, China) LSM prototypes have met all regulatory requirements, including environmental conditions and EMC. Tests have been conducted involving switches, but not road-rail crossings.
- Operational Requirement and Test Results: LSM require specific power supply along the line to deliver variable frequency and voltage. They have been tested successfully in Japan and China, with full-scale tests demonstrating speeds up to 500 km/h.

Linear Synchronous Motor (LSM) for Hybrid MDS:

- Function: The Linear Synchronous Motor (LSM) is a synchronous electric machine typically consisting of a vehicle-mounted set of NdFeB magnets in a Halbach array and a 3-phase winding installed in the track. The interaction between these components generates the propulsion force.
- Development History and Status: The first tests of the permanent magnet linear synchronous motor were performed in 2019. By 2021, the system had been tested in its final configuration with railway tracks. The current full-scale system is undergoing testing, capable of accelerating vehicles up to 130 km/h. The technology is currently at TRL 6-7.
- Relevant Environment: The relevant environment for LSMs is a railway network or railway sidings.
- Comparison of Environments: Railway-compatible prototype LSMs have yet to meet all regulatory requirements (environmental conditions, EMC, etc.). Moreover, no tests involving switches and road-rail crossings have been conducted.

- Operational Requirement and Test Results: LSMs require precise position monitoring and additional power supply on the infrastructure side. Wile, prototype tests have been successfully completed, further operational, interoperability, and safety tests are necessary.

Linear Asynchronous Motor (LIM) for Hybrid MDS:

- Function: It can be distinguished two functions: the local booster function and long distance traction function. For the local booster, the Linear Induction Motor (LIM) is a asynchronous electric machine typically consisting of a vehicle-mounted set of a simple rail armature made of a steel sheet colaminated with a thin copper or aluminium sheet. and a 3-phase winding installed in the track. The interaction between these components generates the propulsion force. In the long-distance traction, the two part are reversed. The 3-phase winding is installed on the vehicle which can be used a traction converter system close to the today existing on the train.
- Development History and Status: Such system was already tested but not working in railway exploitation.

Lateral Wheel-Based Propulsion/Braking:

- Function: This technology involves traction/braking subsystems designed to work with ferromagnetic passive levitation or other magnetic levitation systems. It includes multiple pairs of vertical axis wheels coupled with electric motors.
- Development History and Status: Electric traction wheels are widely adopted and robust solutions for vehicle propulsion. Ironlev is currently testing the integration of these wheels with magnetic levitation technology on a 50E5 track.
- Relevant Environment: This system operates under normal conditions in the railway sector.
- Comparison of Environments: The lateral wheel-based system requires vertical axis wheels for coupling with levitation systems. For custom rail applications, the wheels can be coupled with a rubber track for optimal traction and cooling.
- Operational Requirement and Test Results: Key features include efficiency, reliability, and the capability to operate across a wide range of speeds. Test results from Ironlev indicate successful concept and prototype stages.

Electro-Dynamic Wheels (EDW):

- Function: In EDWs, a cylindrical permanent magnet (PM) Halbach array rotates to induce a field over a passive conducting surface, generating eddy currents that oppose the induced field. EDWs can generate both levitation and thrust forces simultaneously.
- Development History and Status: EDW technology has been developed to TRL 6-7, with commercial activities demonstrating its feasibility.

- Relevant Environment: EDWs can be incorporated into current maglev trains or used to replace LIMs.
- Comparison of Environments: Current validations are based on scaled and numerical models, with further studies required for full-scale tests. Initial applications are in port freight transportation.
- Operational Requirement and Test Results: EDWs have lower track construction costs compared to LIMs and require a conductive surface, such as an aluminium plate. Test results from various studies indicate successful operation in specific applications.

Electromagnetic System (EMS):

- Function: This system uses magnetically attractive forces between the guideway and the on-board electromagnets installed below the guideway for accomplishing levitation. This design produces levitation even at zero speed.
- Development History and Status: EMS technology has been in development since the 1960s. Examples include the Transrapid in Germany and urban maglev systems in China and Korea. The technology is currently at TRL 9.
- Relevant Environment: EMS systems are used in various maglev projects worldwide, such as the Shanghai Maglev and the Incheon Airport Maglev.
- Comparison of Environments: EMS systems are suitable for both high-speed and low-speed applications, depending on the configuration of levitation and guidance circuits. High-speed applications require separation of these circuits to avoid interference.
- Operational Requirement and Test Results: EMS systems need continuous control of the levitation air gap. They have been successfully tested and are operational in several projects, including urban transit systems.

SUMMARY:

Maglev-Derived Systems (MDS) use various propulsion and levitation technologies, including **Linear Induction Motors (LIMs)** and **Linear Synchronous Motors (LSMs)** for efficient traction. Hybrid MDS configurations integrate LIMs/LSMs for rail compatibility. Other innovations like **Electro-Dynamic Wheels (EDWs)** and **Electromagnetic Suspension (EMS)** enhance performance, offering scalable, high-speed, and energy-efficient rail solutions.

5.1.3Vehicle – Suspension

Electrodynamic Systems (EDS) based on Permanent Magnets:

- Function: Counteracts vertical load and maintains the vertical position of the MDS vehicle.
- Relationship to Other Components: Does not require super-cooled magnets or cryogenic systems. Needs auxiliary wheels for initial acceleration.
- Development History and Status: Developed by Dr. Richard Post at LLNL. The technology is under trial and has achieved TRL 5.
- Relevant Environment: In case of power failure, the vehicle can slow down and rest on auxiliary wheels.
- Comparison of Environments: Tested by General Atomics in the USA and under trial in China. Not yet operational.
- Operational Requirement and Test Results: Employs a Halbach array to produce a repulsive levitating force. Considered low-cost due to the absence of super-conductors. Test reports indicate successful trials.

Air Levitation Systems:

- Function: Creates an air cushion underneath the vehicle for levitation.
- Relationship to Other Components: Propulsion is typically separate from the levitation system, using jet engines, linear induction motors, or electrodynamic wheels. Integrated with air-cushion guidance systems.
- Development History and Status: Studied since the 1950s with notable projects like the French Aérotrain. The technology is at TRL 9 for suspension, with varying TRLs for propulsion systems.
- Relevant Environment: Suitable for multiple environmental conditions (water, mud, land). Lower track construction costs compared to maglev systems.
- Comparison of Environments: No commercial Airlev trains currently operate. Airport mini-metros use air-cushion suspension with cable propulsion.
- Operational Requirement and Test Results: Air suspension pads lift the vehicle, while guidance pads prevent lateral contact. Historical projects like Aérotrain demonstrated speeds up to 430 km/h.

Ferromagnetic Passive Levitation Technology:

- Function: Counteracts vertical load and maintains the vertical position of the MDS vehicle.
- Relationship to Other Components: Does not require super-cooled magnets or auxiliary systems. Can be coupled with guidance systems for lateral centering and traction systems.

- Development History and Status: Patented in 2016, with tests demonstrating feasibility at different load scales. Currently under testing for speed conditions. The technology is at TRL 5-6 for railway applications and TRL 9 for other fields.
- Relevant Environment: Works seamlessly in static and dynamic conditions.
- Comparison of Environments: Tested under various conditions, including temperature and salt spray. Custom rail development is ongoing for high performance.
- Operational Requirement and Test Results: Compatible with standard railroad shapes. Provides passive levitation without cryogenic systems, offering energy efficiency and versatility. Successful tests reported in different applications.

SUMMARY:

The suspension technologies described include EDS based on Permanent Magnets, Air Levitation Systems, and Ferromagnetic Passive Levitation Technology. The EDS based on Permanent Magnets and Air Levitation Systems provide innovative approaches, focusing on cost-effectiveness and adaptability to various environments. Ferromagnetic Passive Levitation Technology by Ironlev demonstrates versatility and energy efficiency, suitable for static and dynamic conditions. Each technology has unique operational environments, development statuses, and readiness levels, contributing to the advancement of maglev-derived systems.

5.1.4Vehicle – Guidance

Comparison of Guidance Technologies in "5.3.4.1.3 Guidance"

Lateral Wheels or Traditional Bogie Guidance:

- Function: This subsystem provides lateral stability and guidance to the vehicle, ensuring it stays on the intended path.
- Relationship to Other Components: Works in conjunction with the suspension system and is directly integrated into the vehicle structure.
- Development History and Status: The technology is well-established in conventional railway systems and is currently being adapted for maglev-derived systems. Nevomo uses modified railway wheels for guidance at low speeds, and Ironlev has proven lateral wheels guidance in static conditions with dynamic condition testing in progress. The technology is at TRL 5-6.
- Relevant Environment: Suitable for both traditional railway environments and hybrid systems that combine maglev and conventional rail technologies.

- Comparison of Environments: This guidance system has been tested in both conventional rail and hybrid maglev environments, demonstrating adaptability and effectiveness in maintaining vehicle stability and path adherence.
- Operational Requirement and Test Results: Tests have shown that lateral wheels or traditional bogie guidance can provide reliable performance in both static and dynamic conditions. Further testing is ongoing to refine the integration with maglev systems.

Air Levitation Technology-Based Guidance:

- Function: Uses air pressure differentials to create a cushion that lifts the vehicle slightly off the ground, providing both levitation and guidance.
- Relationship to Other Components: Integrated with air-cushion technology-based guidance systems, often used in conjunction with separate propulsion systems.
- Development History and Status: Air levitation technology has been studied since the 1950s, with notable projects including the French Aérotrain. The technology has reached TRL 8, demonstrating high-speed performance in historical projects like Aérotrain, which achieved speeds up to 430 km/h.
- Relevant Environment: Suitable for a variety of environmental conditions, including water, mud, and land. Lower track construction costs compared to maglev systems.
- Comparison of Environments: Currently, no commercial Airlev trains are in operation. Existing applications are limited to airport mini-metros using air-cushion suspension with cable propulsion.
- Operational Requirement and Test Results: Historical projects demonstrated the potential of air levitation technology, but operational challenges like noise management and energy efficiency remain. The technology has shown promising results in controlled environments, with further research needed for commercial applications.

SUMMARY:

The guidance technologies described include Lateral Wheels or Traditional Bogie Guidance and Air Levitation Technology-Based Guidance. Lateral Wheels or Traditional Bogie Guidance is a well-established technology in conventional railway systems, currently being adapted for hybrid maglev systems with successful static and dynamic tests. Air Levitation Technology-Based Guidance offers an innovative approach with historical high-speed performance but faces operational challenges. Both technologies contribute to the advancement of maglev-derived systems, with unique operational environments, development statuses, and readiness levels.

5.1.5Vehicle – Braking

Linear Motor:

- Function: Linear motors provide both traction and braking. When braking, the linear motor operates in reverse, converting the train's kinetic energy into electrical energy, which can be fed back into the electrical network. Linear motors can be used for service braking, normal emergency braking, severe emergency braking, and regenerative braking.
- Relationship to Other Components: Directly related to the propulsion system and integrated with the train control system.
- Development History and Status: Linear motors have been used in maglev systems for propulsion and braking since their inception. Examples include the Transrapid maglev system and CHSST. The technology is at TRL 9.
- Relevant Environment: Linear motors are used in various braking scenarios, including service braking initiated by the central control system, normal emergency braking providing at least 0.25 g reverse thrust, and severe emergency braking for rare events.
- Comparison of Environments: Systems like the Transrapid use synchronous long stator linear motors for both propulsion and braking. Superconducting maglev systems have additional braking methods such as wheel disc brakes and aerodynamic brakes for high-speed scenarios.
- Operational Requirement and Test Results: Linear motors require additional power supply. Projects like Transrapid, Chuo Shinkansen, and Ecobee maglev have demonstrated the technology's full operational capabilities. CHSST's braking performance has been extensively tested and documented.

Electro-Dynamic Wheels (EDW):

- Function: EDWs generate thrust forces for both acceleration and deceleration. Rolling the EDW in the opposite direction induces braking by generating eddy currents in a passive conducting surface.
- Relationship to Other Components: Provides levitation, propulsion, and braking when wheels roll in different directions.
- Development History and Status: EDW technology is at TRL 6-7, with commercial activities developing and validating the solution through scaled and numerical models.
- Relevant Environment: Can be incorporated into current maglev trains or replace LIMs.
- Comparison of Environments: Scaled and numerical models have validated EDW design, with applications identified in port freight transportation. Further studies are needed for full-scale model testing and high-speed railway applications.
- Operational Requirement and Test Results: EDWs require lower track construction costs than LIMs, needing a conductive surface like an aluminum plate. Test results have been published in various studies and patents.

SUMMARY:

The braking technologies described include Linear Motors and Electro-Dynamic Wheels (EDW). Linear Motors are well-established, providing reliable service and emergency braking in maglev systems, with additional methods for high-speed braking scenarios. EDWs offer a versatile approach, providing levitation, propulsion, and braking, with promising applications in freight transportation. Both technologies have unique operational environments, development statuses, and readiness levels, contributing to the advancement of maglev-derived systems.

5.1.6Vehicle – Electrical system

Current Contact Shoe and Power Rail:

- Function: Provides electric power supply from the infrastructure to the vehicle for levitation, guidance, propulsion, onboard electrical equipment, battery recharging, etc.
- Relationship to Other Components: Related to track sectioning, onboard batteries, magnetic levitation and guidance, onboard auxiliary systems, and traction power.
- Development History and Status: Established technology, similar to metro systems. Current collectors extend from the car body to reach two conducting rails on both sides. Focuses on third rail materials and efficient pad-rail contacts. The technology is at TRL 9.
- Relevant Environment: Suitable for low-speed maglev systems with limitations due to speed and voltage.
- Comparison of Environments: For use on conventional railway tracks (MDS), a third rail is necessary. If the vehicle lacks wheel-rail contact, a secondary cable or rail is required for the returning current.
- Operational Requirement and Test Results: Third rails are cost-effective but less safe due to accessibility. Widely used in conventional urban railway systems. References include Han and Kim (2016) and Liu Z et al. (2022).

Pantograph and Overhead Catenary:

- Function: Provides electric power supply from the infrastructure to the vehicle for levitation, guidance, propulsion, onboard electrical equipment, battery recharging, etc.
- Relationship to Other Components: Related to track sectioning, onboard batteries, magnetic levitation and guidance, onboard auxiliary systems, and traction power.
- Development History and Status: Very established technology used for high-speed and high-voltage AC systems. Latest developments focus on dynamics at high speeds, reduced wear, and better energy transfer efficiencies. The technology is at TRL 9.

- Relevant Environment: Suitable for conventional railways. Flexible cable catenary is common, with rigid catenary used in tunnels.
- Comparison of Environments: Catenary systems are necessary for conventional railway tracks (MDS). Requires secondary cable or rail for returning current if the vehicle lacks wheel-rail contact. Limitations exist in very high-speed operations.
- Operational Requirement and Test Results: Catenary systems can be costly and are susceptible to wind and cable breaks. Widely used in real-life operations. References include Han and Kim (2016) and Liu Z et al. (2022).

Wireless Power Transfer:

- Function: Provides non-contact electric power supply from the infrastructure to the vehicle, essential for high-speed maglev trains.
- Relationship to Other Components: Related to track sectioning, onboard batteries, magnetic levitation and guidance, onboard auxiliary systems, and traction power.
- Development History and Status: Used in German Transrapid trains and Japanese MLX maglev systems. The technology is at TRL 9.
- Relevant Environment: Suitable for high-speed maglev systems with specific track configurations.
- Comparison of Environments: For use on conventional railway tracks (MDS), an inductive plate in the infrastructure is necessary.
- Operational Requirement and Test Results: Requires a certain speed to generate electric energy and is not capable of transferring energy at a standstill. Widely used in real-life operations. References include Han and Kim (2016) and Liu Z et al. (2022).

Battery On-board:

- Function: Stores electrical energy to ensure continuous and consistent power supply to all on-board electrical systems.
- Relationship to Other Components: Related to energy transfer systems (pantograph, shoe, contactless), magnetic levitation and guidance, onboard auxiliary systems, and traction power.
- Development History and Status: Established technology with rapid development due to the electrification of the automotive industry. Common battery types include Lithium-Ion, LFP, LMO, and LTO. The technology is at TRL 9.
- Relevant Environment: On-board storage requires lightweight and compact designs with safety considerations for overheating and fires.
- Comparison of Environments: Widely used in conventional rail vehicles and other systems.

- Operational Requirement and Test Results: Numerous existing norms and regulations govern battery-electric vehicles. Common issues include the influence of environmental temperatures on efficiency and self-discharge. Widely used in real-life operations. References include ISO standards for testing.

SUMMARY:

The electrical systems described include Current Contact Shoe and Power Rail, Pantograph and Overhead Catenary, Wireless Power Transfer, and Battery Onboard. Each system provides critical power supply functions for maglev-derived systems, with established technologies in conventional railway applications. Current Contact Shoe and Power Rail, and Pantograph and Overhead Catenary are well-suited for low-speed and high-speed systems, respectively, with proven operational capabilities. Wireless Power Transfer offers non-contact energy solutions for high-speed maglev trains, while onboard batteries ensure continuous power supply. Each technology has unique operational environments, development statuses, and readiness levels, contributing to the advancement of maglev-derived systems.

5.1.7Infrastructure – Switches

Switches for Dedicated Separate Infrastructure:

- Function: High-speed maglev systems like Transrapid use bending switches or transfer tables for track changes. Bending switches are used for smooth transitions between tracks, with electro-mechanical rack and pinion drive units and locking mechanisms to ensure beam positioning. Low-speed systems, such as the Maglev Changsha Airport Express Line, use 3-girder switches with fixed rotating centers.
- Relationship to Other Components: Related to the vehicle, suspension, guidance, and propulsion systems.
- Development History and Status: Maglev systems employ specific solutions for switching.
- Relevant Environment: Dedicated maglev infrastructure.
- Comparison of Environments: No significant differences between relevant and demonstrated environments.
- Technology Readiness Level Determination: TRL 9.
- Operational Requirement and Test Results: Transrapid low-speed switches (used near stations) weigh 300 tons with a 78 m beam length, allowing 100 km/h turnout speeds and full operating speed in the straight position. High-speed switches weigh 600 tons with a 148 m beam length, allowing 200 km/h turnout speeds. Bending switches have

a service life of about a million cycles, or 20-30 years. Transfer tables are used in off-line situations, such as maintenance areas, to provide compact access to multiple tracks.

Switches for Existing or Updated Conventional Railway Infrastructure (Hybrid MDS):

- Function: Enables changing guideways from one track to another to alter route direction or platform. Standard railway systems use tapering rails and electromechanical systems for lateral point movement, while customized systems are designed for MDS upgrades.
- Relationship to Other Components: Part of the infrastructure, connected with the substructure, guideways, and ballast, and in contact with vehicle wheels. In MDS upgrades, the system could interact with the stator for linear motor and magnetic levitation systems.
- Development History and Status: Standard railway switches are well-established and widely adopted. TRL 9 systems exist for railway systems upgraded with LIM. LSM integration systems are at a conceptual level with TRL 2.
- Relevant Environment: Railway environment - infrastructure part.
- Comparison of Environments: For standard switches integrated with LIM, the demonstrated environment is similar to the relevant one. The main difference is the need to consider another CCS system when implementing such a switch in an open railway network. No demonstrated environment exists for LSM switches as the component is still conceptual.
- Technology Readiness Level Determination: TRL 9 for standard railway switches and LIM integration, TRL 2 for LSM integration.
- Operational Requirement and Test Results: Switches must handle vertical and lateral loads (guidance loads) and ensure propulsion and braking during switch crossing. MDS upgraded systems must interact with levitation systems for support and guidance. Standard switches are widely adopted, with examples including the LIM Vancouver SkyTrain and Japanese lines. LSM upgraded railway switches are in the research phase by Nevomo.

SUMMARY:

The switch technologies described include those for Dedicated Separate Infrastructure and Existing or Updated Conventional Railway Infrastructure (Hybrid MDS). High-speed maglev systems use specialized switches such as bending switches and transfer tables, designed for smooth transitions and compact track access. These systems are well-established with a TRL of 9. Standard railway switches are widely adopted and proven for LIM integration, while LSM integration remains conceptual. Each technology addresses specific operational requirements and environments, contributing to the advancement of maglev-derived systems.

5.1.8Infrastructure – Propulsion

Linear Synchronous Motor (LSM) in Existing or Upgraded Conventional Railway Infrastructure (Hybrid MDS):

- Function: The primary function of the LSM is to convert electrical energy into mechanical motion along a track. The motion of the motor is synchronized with the frequency of the applied electrical power, maximizing efficiency.
- Relationship to Other Components: The mover (vehicle part of the LSM) consists of NdFeB magnets arranged in the Halbach array. Interfaces include the vehicle structure, onboard sensors (monitoring gap, magnetic field, etc.), and the infrastructure part of the linear motor. If the vehicle operates on the railway network, relationships to railway subsystems and constraints (e.g., structure gauge, EMC) should be considered.
- Development History and Status: The first tests of the permanent magnet LSM were performed in 2019, proving the concept. The second iteration in 2021 tested the final configuration with railway tracks. Currently, the third full-scale system is built, and tests are ongoing, with the linear motor demonstrator accelerating vehicles up to 130 km/h.
- Relevant Environment: Railway network or railway sidings.
- Comparison of Environments: The railway-compatible prototype LSM does not meet all regulatory requirements (environmental conditions, EMC). No integration with switches and road-rail crossings has been tested.
- Technology Readiness Level Determination: TRL 6-7 for interoperable linear motors with the railway system.
- Operational Requirement and Test Results: Linear synchronous motors require an additional power supply on the infrastructure side. Prototype tests have been successful, but further operational, interoperability, and safety aspects need testing.

U-LIM (U Shape Armature):

- Function: The U-LIM is a short primary stator with multi-phase winding using a U-shaped armature. Coils are onboard, and conducting sheets are on the guideway. The vertical sides of the U-shaped armature can be used as a magnetic guidance system (EMS guidance type).
- Relationship to Other Components: Related to vehicle subsystems, energy, and control systems. Powered in sections, each connected to an independent traction inverter.
- Development History and Status: The U-LIM technology, initially compared to the flat LIM in the French Aérotrain program, was patented in 1979. It has been upgraded with innovative materials and compact power inverters. U-LIM is mature in a few industrial applications, offering higher efficiency and power factor compared to flat LIM.
- Relevant Environment: Suitable for railway applications, with high efficiency and compact design advantageous for vehicle design.

- Comparison of Environments: U-LIM meets regulatory railway requirements (gauge, environmental conditions, EMC), but validation tests on real railway tracks are pending. Switch and railroad crossing requirements can be met by locally removing the U-shaped armature.
- Technology Readiness Level Determination: TRL 9 in industrial applications, TRL 8 on railway tracks (not yet tested in a railway environment).
- Operational Requirement and Test Results: U-LIM requires an additional power supply on the vehicle or infrastructure side. Preferred for speeds up to 300 km/h due to its efficiency, power factor, and lower cost. Features include simplicity, reliability, robustness, and low maintenance. Test results indicate successful use in various applications, including the Grenoble wheel test bench.

SUMMARY:

The propulsion technologies described include Linear Synchronous Motors (LSM) and U-shaped Linear Induction Motors (U-LIM). LSMs are designed for high efficiency and synchronized motion, with ongoing testing for railway integration. U-LIMs offer high efficiency, compact design, and are mature in industrial applications, with pending validation for railway use. Each technology has unique operational requirements, environments, and readiness levels, contributing to the advancement of maglev-derived systems.

5.1.9Energy – Segment Switches

Segment Switches for Dedicated Separate Infrastructure:

- Function: High-speed maglev systems use trackside long-stator linear motors divided into segments to reduce energy loss and maintain an acceptable power factor. Segment switches energize the trackside stator segments when the maglev train is within the segment and turn off the power when the train leaves the segment.
- Relationship to Other Components: Operate based on the position of the maglev train, detected and transmitted by sensing and communication systems. Segment switches control the length of the energized trackside stator sections.
- Development History and Status: Used by the German Transrapid system.
- Relevant Environment: No strict requirements available.
- Comparison of Environments: Mature technology with no significant differences between the relevant and demonstrated environments.
- Technology Readiness Level Determination: TRL 9.

- Operational Requirement and Test Results: Only one maglev train is allowed to run within one segment. This technology is already in use and is considered mature.

Segment Switches for Existing or Upgraded Railway Infrastructure (Hybrid MDS):

- Function: Segment switches supply three-phase AC voltage to selected sections of the linear motor stator, controlled by the inverter. This reduces the number of required inverters and increases energy efficiency by only powering the motor stators in the area where the vehicle is located.
- Relationship to Other Components: Work directly with inverter systems and linear motor stator sections. The inverter circuits provide the appropriate voltage to the linear motor stator through the segment switches.
- Development History and Status: Developed by Nevomo since 2019 and successfully tested for vehicles achieving velocities of approximately 150 km/h. Patent filed in 2021.
- Relevant Environment: No strict requirements available.
- Comparison of Environments: Designed for vehicles above 300 km/h but only tested up to 150 km/h so far.
- Technology Readiness Level Determination: TRL 6.
- Operational Requirement and Test Results: Only one MDS train is allowed to run within one segment. The technology has been tested successfully up to speeds of 150 km/h.

SUMMARY:

The segment switch technologies described include those for Dedicated Separate Infrastructure and Existing or Upgraded Railway Infrastructure (Hybrid MDS). High-speed maglev systems use mature segment switch technology to reduce energy loss and maintain power factors, with systems like German Transrapid demonstrating reliability. Hybrid MDS segment switches, developed by Nevomo, aim to increase energy efficiency and reduce power electronics costs by selectively energizing linear motor stator sections. Although designed for higher speeds, testing has so far been limited to 150 km/h. Each technology addresses specific operational requirements and environments, contributing to the advancement of maglev-derived systems.

5.1.10 Command and control – TMS

Existing Command and Control Signalling System in Railway Systems:

- Function: Main areas of impact include radio communications, EUROBALISE transponders, and Train Detection Systems (TDS). Preventive analyses and field tests ensure maglev systems do not interfere with these components. ERTMS/ETCS ensures interoperability across Europe, while CBTC is tailored for metropolitan lines.

- Relationship to Other Components: Potential remote interference with onboard systems should be verified during the integration phase of the maglev vehicle. CCS systems interact with various train components and external infrastructure.
- Development History and Status: All maglev systems use automatic operation. No ERTMS/ETCS implementations exist for maglev systems. Systems like the Japanese ATC are used for high-speed trains. Projects like SHIFT2RAIL IP2 and EU Rail R2DATO are advancing ETCS Level 3 and ATO up to GoA4.
- Relevant Environment: Requires interoperability with trains using different traction systems in a railway environment.
- Comparison of Environments: Tests will be conducted on dedicated railway lines with various railway systems and trains using different traction systems.
- Technology Readiness Level Determination: TRL 9 in existing ERTMS (ETCS and ATO) systems.
- Operational Requirement and Test Results: Operational aspects are similar to those of existing railway lines, requiring the same use cases for traditional and high-speed lines. Interoperability tests for ERTMS/ETCS systems are defined and necessary for rolling stock and line tests.

Specific TMS Used in Maglev Systems:

- Function: The TMS regulates train movement within its area, ensuring trains arrive on time according to a defined timetable. It collects information from various line systems, signalling systems, and diagnostic systems to choose the best route for each train.
- Relationship to Other Components: Interfaces mainly with interlocking, ATO, and diagnostic systems.
- Development History and Status: All maglevs use automatic operation, even at high speeds. The TMS is applicable to both maglev and traditional railway systems.
- Relevant Environment: Operates within a railway environment without specific issues related to maglev solutions.
- Comparison of Environments: No specific issues compared to traditional railway environments.
- Technology Readiness Level Determination: Existing TMS systems can be used for maglev operations.

- Operational Requirement and Test Results: Operational aspects are similar to those applied to traditional and high-speed railway lines. The same checks for TMS use in other railway areas apply.

SUMMARY:

The comparison of TMS technologies includes existing Command and Control Signalling Systems (CCS) in railway systems and specific TMS used in maglev systems. ERTMS/ETCS ensures interoperability across Europe, while CBTC is designed for metropolitan lines. Key areas of concern include radio communications, EUROBALISE transponders, and Train Detection Systems (TDS), requiring thorough testing to prevent interference. Specific TMS for maglev systems regulates train movement and integrates with interlocking, ATO, and diagnostic systems. Both systems aim to ensure efficient and safe train operations, with existing technologies being adaptable for maglev use. Each system has unique operational requirements, environments, and readiness levels, contributing to the advancement of maglev-derived systems.

5.1.11 Command and control – Communication Systems

Existing Communication Systems in Railway Systems:

- Function: Current train-to-ground and train-to-train communication in rail systems rely on wireless communication, crucial for train operation, maintenance, and passenger information. GSM-R is widely used in Europe, providing safe voice and data transmissions, and will be replaced by FRMCS based on the 5G standard. Wi-Fi-derived systems are used for CBTC applications in metros, and Ethernet networks are used inside trains for passenger services.
- Relationship to Other Components: Communication systems are key for train operation, control, command, maintenance, and passenger information.
- Development History and Status: In existing maglev systems like the German Transrapid and Shanghai lines, 3G radio communication is used for vehicle control and passenger information. GSM-R is deployed on 150,000 km of European railway lines and will be phased out by 2030, replaced by FRMCS. Ongoing projects like X2RAIL1, X2RAIL3, X2RAIL5, 5GRAIL, and 5GMED are developing and testing FRMCS.
- Relevant Environment: No specific environment needed except the railway context.
- Comparison of Environments: No significant differences; applicable in the railway environment.
- Technology Readiness Level Determination: TRL 9 for GSM-R, which is widely deployed. FRMCS is nearing TRL 9 for some applications.

- Operational Requirement and Test Results: Specific key performance indicators (KPI) must be met, including throughput, packet error rate, latency, jitter, handover time, resistance to Doppler, and interference. Tests for MDS should be similar to those for high-speed trains.

Future Communication Systems Used in Railway Systems:

- Function: Future systems will include FRMCS based on 5G networks, replacing GSM-R. These systems will handle communications for train control and command, maintenance, and passenger services. LTE, ITS-G5, mmWave, and satellite communications are also being explored for various applications.
- Relationship to Other Components: Key for train operation, control, command, maintenance, and passenger information.
- Development History and Status: Ongoing research and development activities at the international level for millimetric waves, satellite communication, and future 6G networks. Projects like Safe4rail3 and IAM4RAIL are working on these technologies.
- Relevant Environment: No specific environment needed for MDS compared to high-speed trains.
- Comparison of Environments: No significant differences; applicable in the railway environment.
- Technology Readiness Level Determination: TRL varies depending on the technology, with most at TRL 6 when demonstrators are available.
- Operational Requirement and Test Results: Specific KPIs must be met, similar to existing systems. Tests should be conducted as for high-speed trains.

SUMMARY:

The comparison of communication systems in railway systems includes existing systems like GSM-R and future systems like FRMCS. GSM-R, widely deployed across Europe, will be replaced by FRMCS, which leverages 5G technology. Existing communication systems are crucial for safe and efficient train operation, maintenance, and passenger services, with ongoing projects advancing their capabilities. Future communication systems aim to enhance these functionalities with advanced technologies like LTE, ITS-G5, mmWave, and satellite communications. Both existing and future systems must meet rigorous operational requirements and performance indicators to ensure reliability and safety in railway environments.

5.1.12 Command and control – Positioning Systems

Positioning Systems Used in Conventional Railways:

- Function: Provide safe train position information to the control and command system. The positioning data is obtained onboard and transmitted to the control center.
- Relationship to Other Components: Integrated with communication systems, control and command, maintenance, and passenger information systems.
- Development History and Status: These technologies are mature and already in use. Ongoing projects like SHIFT2RAIL IP2, X2RAIL-2, X2RAIL-5, and EU RAIL R2DATO are exploring additional sensors for positioning.
- Relevant Environment: No specific issues, similar to conventional high-speed trains.
- Comparison of Environments: No significant differences between relevant and demonstrated environments.
- Technology Readiness Level Determination: TRL 9 for Eurobalise, KVB, and track circuits; TRL 6 for some GNSS and multi-sensor solutions.
- Operational Requirement and Test Results: Requires positioning accuracy, resilience to interference, and availability of information. Tests are similar to those for conventional high-speed trains.

Specific Positioning Systems Based on Maglev Technology:

- Function: In the Transrapid system, vehicle location is identified using an onboard detection system and communicated via radio transmission. The Ecobee system uses a pattern belt for speed and distance detection.
- Relationship to Other Components: Positioning and speed data are obtained onboard and transmitted to ground operation control and traction systems. Mobile communication between the ground and the vehicle is required. Systems like the German TVE Maglev test line and Shanghai line use 3G radio communication for vehicle control and passenger information.
- Development History and Status: Technologies are implemented in the German Transrapid Maglev test line and the Shanghai line, as well as in the Ecobee system.
- Relevant Environment: Devices are installed in both the train and track.
- Comparison of Environments: Mature technology with no significant differences between the relevant and demonstrated environments.
- Technology Readiness Level Determination: TRL 9, as demonstrated by implementations in German Transrapid and Shanghai lines, and the Ecobee system.
- Operational Requirement and Test Results: Suitable for maglev lines with Linear Induction Motors (LIM). References include Liu et al. (2015).

SUMMARY:

The comparison of positioning systems includes those used in conventional railways and those based on maglev technology. Conventional railway systems use technologies like Eurobalise, KVB, and track circuits for control and command, with ongoing development of GNSS-based solutions. These systems are mature and widely implemented, requiring accurate and reliable positioning data. Maglev systems use specific technologies like digitally encoded location flags and pattern belts for positioning and speed detection, with mature implementations in systems like the German Transrapid and Shanghai lines. Both types of systems integrate closely with communication, control, and command components, ensuring safe and efficient train operations.

6 CCS implication based on defined configurations and use cases

From the Use Cases examined, it emerged that the ETCS signalling system currently adopted by various railways is not perfectly suitable for MDS applications.

This might suggest that it is not feasible for conventional trains and maglev derived trains to coexist on the same line. However, this is not the conclusion reached during this project. It is necessary to evaluate how much time it might take to migrate from the current line configuration, such as equipped with ETCS level 2, to one that can also operate maglev-derived trains.

It is also necessary to evaluate the economic aspects that will influence the transformation. The introduction of MDS technology will undoubtedly offer advantages in terms of reliability and reduction of energy consumption.

This will guide the introduction of the management of this type of train in the CCS context. The most relevant aspects are defined by the fact that the ETCS level 2 signalling system is based on:

- Train Detection Systems (track circuits or axle counters) installed along the line
- Eurobalises installed on the track sleepers
- Radio Communication between EVC on the train and RBC on the line.

While Radio communication seems to have no side effects due to the use of MDS trains, the scenario changes for Train Detection Systems and EUROBALISEs along the tracks.

6.1 Train Detection System

The Train Detection System (TDS) is used by the system to identify which portion of the track the train should occupy. These systems, in the case of track circuits, could be affected by electromagnetic interference produced by the vehicle.

Depending on the effort applied, the MDS vehicle can produce an in-band signal that could be confused by the track circuit, making this technology unusable in parallel track conditions. If, however, the single-track condition is in place, it is necessary to investigate the effects on the preceding TDS and the one that has been overtaken.

For track circuits, it must be demonstrated that there are no destructive situations due to the active passage of a magnetic levitation train. If it is found that in the presence of MDS vehicles the TDS provide incorrect values, this could be mitigated by the fact that other methods may be feasible.

Furthermore, since we are talking about levitation, magnetic or air flow based, with respect to the tracks, the contact between the wheels and the track is lost and therefore the short circuit functions exercised by the axles between the two tracks and the concatenated currents are also lost. For this reason, track circuits are not reliable for recognizing the presence of an MDS vehicle along the line.

For axle counters, depending on the type of MDS solution adopted, in addition to having conditions to verify for electromagnetic compatibility, there are also mechanical constraints that could prove destructive for axle counters installed near the tracks.

In conclusion, the MDS vehicle seems to be incompatible with the current solutions installed along the line in Europe.

6.2 Eurobalise

For Eurobalises, possible tests to be performed to demonstrate their feasibility of use have already been identified. The greatest risk highlighted, though unconfirmed, lies in the interference that the MDS vehicle produces towards the airgap between Eurobalises and BTM Antenna. In this context, it is essential to conduct an in-depth test campaign. The outcome of this measurement campaign will define once and for all what the signal levels are and whether they can impair the proper functioning of the BTM-Antenna in relation to the Eurobalise.

6.3 CCS approach

The strategy adopted to integrate MDS trains into the railway context is to maintain the current signalling system for the management of conventional trains while adding, when possible, solutions that allow coexistence on the same line without upsetting the existing system. The target adopted is the ETCS Level 2 system. This signalling system, as already mentioned, is based on the “continuous” exchange of radio messages between the trackside system and the on-board system. To identify the presence of the train on the line, the TDS is used, which section the line and define in which portion of it the train is located. The management of the TDS is operated by the interlocking that communicates the status of the sections of the line (whether occupied by a train or free) to the RBC. The RBC manages the Movement Authority based on the status of the sections in front of each train, whether these are free or occupied.

Since, as previously indicated, the current TDS (track circuit and axle counters) are not compatible with MDS vehicles, it is necessary to find an alternative way to safely detect the presence of an MDS vehicle along the line, assuming that MDS vehicles do not cause remote side effects on adjacent sections in the current and parallel tracks.

Therefore, the hypothesis is to have an independent system that can determine the presence of MDS vehicle based on the activation of levitation and traction.

This information could initially be collected from two different systems and compared to unambiguously identify the presence of a train in the specific section. To avoid divergences, the management of the sections, in terms of length, will be the same for both conventional trains and MDS vehicles.

In this scenario, the interlocking system provides to RBC the status of the sections for both conventional and MDS trains.

To resolve the potential inconsistency of MDS vehicles with Eurobalises, the concept of virtual balise is used.

A virtual balise is a balise that does not physically exist but is ideally positioned in the same location as the physical Eurobalise.

The hypothesis is to maintain the same spatial configuration of the physical Eurobalises to position the virtual ones. Therefore, each group of physical Eurobalises corresponds to a group of virtual balises. Engineering rules are applied only once for the placement of the Eurobalises.

The reason for adopting this principle is due to the fact that the MDS vehicle has very precise odometry because of its interaction with the electromagnetic fields produced by the track system. This interaction allows the on-board system to know the distance travelled precisely.

By exploiting this principle and associating it with a map of the line and a satellite locator (a project that is being implemented in R2DATO WP21 and WP22), this information can become the trigger element to send the equivalent of the Eurobalise (Virtual Balise) present in that position to the on-board system. The on-board system (EVC) will send the position Reports to RBC based on the Virtual Balises encountered, similarly to what currently happens for physical Eurobalises.

This obviously complicates the RBC, because it will have to manage two types of train, one that sends information based on physical Eurobalises and one based on Virtual Balises.

This management preserves the current macro-setting of the systems that make up the ETCS system.

It is clear that ad hoc developments must be made to integrate the two management types, but the effect is that no changes will have to be made to existing systems and interoperability is preserved.

These last two concepts make the proposal extremely interesting, and this is the reason why we are proposing this approach in this project.

Following the proposed approach, no changes would be needed in the management of the interfaces with the TMS and likewise for ATO for both the wayside and on-board parts.

6.4 Impact on use cases

In this paragraph, the specific impacts for the three identified use cases are highlighted.

The use cases identified are as follows:

1. Rail vehicle upgraded MDS configuration, incline pusher.
2. Hybrid MDS based on air levitation configuration.
3. Hybrid MDS based on magnetic levitation configuration.

The three use cases identified will be analysed considering two scenarios:

- Scenario A) maglev-derived systems with minimum requirements.
- Scenario B) maglev-derived systems with needed adaptations to fully exploit the maximum performance.

From signalling point of view, to ensure interoperability between MDS vehicles and traditional vehicles, there are no substantial differences between Scenarios A & B. The sensitive points concern compatibility with Eurobalises and TDS.

For each use case, considerations of the impacts on technologies and the feasibility of the solution are reported. For all three use cases, regarding the signalling aspects, there are no significant differences, meaning that the same solution could be adopted for all:

- Rail vehicle upgraded MDS configuration, incline pusher.
- Hybrid MDS based on air levitation configuration
- Hybrid MDS based on magnetic levitation configuration

In the full configuration of the solutions could be some constrains for the installation of the Eurobalises.

This fact could impact the possible interoperability with traditional vehicles.

It must be carefully evaluated how to set the roadmap for the introduction of different technologies while ensuring the simultaneous circulation of traditional vehicles and MDS ones.

This last point must necessarily be taken into consideration to define the final solution to be adopted for the lines and their management.

This also impacts the amount of investments that will have to be made over the years.

All these points will have to be explored in the subsequent steps of the project to provide a consistent solution.

7 Comparative studies to operational concepts, processes and rules

Comparative studies between traditional railway systems and those upgraded with maglev technology, typically examine various aspects such as operational concepts, processes, and rules to evaluate their differences and potential advantages. Here's a breakdown of what such studies might cover:

- Technology and Infrastructure
- Speed and Efficiency
- Energy Consumption and Environmental Impact
- Safety and Reliability

Overall, comparative studies between traditional railways and maglev systems aim to provide insights into the strengths, weaknesses, and practical considerations of each technology to inform decision-making and investment strategies in the transportation sector.

In work package 7 an assessment of the technical and economic feasibility of MDS into the common European mobility network has been developed. For the 3 use cases selected in task 7.1, several pieces of information have been collected.

The use cases identified are:

1. Rail vehicle upgraded MDS configuration.
2. Hybrid MDS based on air levitation configuration.
3. Hybrid MDS based on magnetic levitation configuration.

The three use cases identified have been analysed considering two different scenarios:

- Scenario A) maglev-derived systems with minimum requirements.
- Scenario B) maglev-derived systems with needed adaptations to fully exploit the maximum performance.

Use Case 1: Rail Vehicle Upgraded MDS (Sweden)

A 60 km section of a single-track, curvy railway was examined, facing capacity and speed constraints. The upgraded MDS on wheels aims to improve transport efficiency for both freight and passenger services, enhancing load capacity and speed with minimal infrastructure modifications.

Use Case 2: Hybrid MDS with Air Levitation (Italy)

A 36.9 km railway connecting two cities in Northeast Italy was analysed to address increasing commuter demand. Air levitation MDS reduces friction, maintenance needs, and noise pollution while enabling higher speeds (up to 200 km/h). The system integrates with the existing infrastructure, prioritizing passenger service enhancement without major modifications.

Use Case 3: Hybrid MDS with Magnetic Levitation (Italy)

A 585 km regional route through four major cities was considered, evaluating MDS as an alternative to new high-speed rail (HSR). The proposed system integrates maglev pods operating under GoA4 automation, reaching 300 km/h with dynamic speed control for optimized performance. The goal is to expand coverage while improving acceleration, deceleration, and overall efficiency, making the service more attractive.

<u>Across all cases, MDS aims to enhance rail transport with minimal infrastructure changes while maximizing operational benefits.</u>

8 Integrating MDS into Europe's Railway Network: The Strategic Role of the System Pillar

The successful integration of MDS into Europe's railway network depends on harmonizing operational, architectural, and regulatory frameworks within the System Pillar. This alignment is essential to create a unified, sustainable, and high-performance rail system capable of accommodating both traditional and innovative technologies. By ensuring interoperability and fostering collaboration among stakeholders, the System Pillar supports the development of a standardized, modular architecture that balances incremental improvements with the adoption of disruptive technologies like MDS.

The System Pillar could have an advisory function, providing feedback, expert opinion, and advice, for the following topics:

- Harmonization of operational and regulatory standards, including updates to Technical Specifications for Interoperability (TSIs) and the implementation of cybersecurity frameworks.
- Migration pathways that would allow MDS and conventional rail to coexist through phased technological adoption.
- Testing and validation to confirm the viability of MDS integration in the European rail system.

By leveraging this coordinated approach, Europe can position itself as a global leader in next-generation transportation solutions, promoting innovation, sustainability, and economic growth. The System Pillar's role ensures that MDS technologies not only integrate effectively into existing rail infrastructure but also pave the way for a more agile and competitive European railway sector.

8.1 Harmonizing MDS with Europe's Railway Framework: Alignment with System Pillar Tasks

Achieving seamless integration of MDS into Europe's railway network requires addressing harmonization needs across operational, architectural, and regulatory dimensions, under the guidance of the System Pillar framework that should take into account that the update of TSIs is critical for addressing electromagnetic compatibility, safety validation, and certification of MDS technologies.

The following table presents information derived from the deliverables completed in WP2 (D2.1, Chapter 7), WP3 (D3.2, Chapter 11), and WP4 (D4.2, Chapter 6). These deliverables have been systematically cross-checked with the activities of the System Pillar, specifically:

- Task 1 (Railway System) – Supports infrastructure adaptations necessary for MDS, such as segment switches, wireless power transfer, and inductive charging standardization to enable integration with the current network.
- Task 2 (Command, Control, and Signalling) – Focuses on interoperability by aligning MDS technologies (e.g., electromagnetic levitation) with ETCS Level 2 and EULYNX Baseline 4, ensuring smooth integration with existing signalling and control frameworks.
- Task 3 (Traffic and Capacity Management) - Defines system architecture alignment, ensuring MDS can coexist with traditional rail traffic through modular TMS integration and advanced communication systems.

Work Package	Key Findings	System Pillar Alignment
WP2: Technology and Digital Enabler Requirements	Identifies digital enablers (ATO, cybersecurity, secure communication) and system architecture needs.	PRAMS framework validates cybersecurity requirements; Migration and Roadmap ensures scalable implementation; Trackside & Traffic Control confirm real-time data exchange necessity.
WP3: Standardization and Safety Regulations	Regulatory compliance for MDS; need for revised TSIs and risk assessment frameworks.	PRAMS policies reinforce cybersecurity and data integrity; Operational Design harmonizes safety protocols; Traffic & Capacity Management requires operational constraints for MDS.
WP4: Vehicle Subsystem and Interoperability	ATP/ATO integration for MDS vehicles and interoperability with conventional rail systems.	Train Control and Supervision ensures localization and control compatibility; Migration and Roadmap outlines MDS adoption pathways; Traffic Management confirms dynamic capacity allocation needs.

This cross-checking exercise confirms strong alignment among WP2, WP3, and WP4 outcomes with System Pillar activities. Key areas of convergence include:

- Cybersecurity measures and digital enablers for MDS (WP2 → PRAMS, Migration and Roadmap)
- Adaptation of TSIs and inclusion of MDS operations in safety regulations (WP3 → PRAMS, Traffic Control and Supervision).

- Adoption of ETCS/ATO and modernisation of control systems for interoperability (WP4 → Train Control and Supervision, Traffic Management).

There must be a synergy between the Innovation Pillar and the System Pillar to ensure that MDS technologies are not only compatible with existing railway networks but also enhance overall system efficiency and interoperability. Future work should refine regulatory frameworks and test MDS implementations in real-world scenarios to guarantee smooth and safe integration into the European rail system.

9 Conclusions

The integration of maglev-derived systems into European rail networks presents a groundbreaking opportunity to transform rail transport. MDS can potentially offer unparalleled benefits in speed, efficiency, environmental impact, and passenger experience. The deliverable highlights key advancements in MDS technology, including vehicle structure, propulsion systems, energy management, and command/control integration, all designed to meet future transportation demands sustainably and efficiently.

For the successful integration of MDS into the European rail system, a close synergy between the Innovation Pillar and the System Pillar is essential. This collaboration is necessary to develop a standardized, modular framework that allows for smooth and effective incorporation. Future efforts should focus on pilot implementations and regulatory adaptations that could enable MDS to operate effectively and efficiently within Europe's evolving rail network.

Challenges remain, particularly in ensuring compatibility with existing signalling systems, overcoming technical barriers in train detection, and harmonizing regulatory standards across borders. Addressing these challenges will require collaborative efforts among stakeholders, extensive testing, and strategic investments in infrastructure upgrades.

Furthermore, the comparison between pure Maglev and MDS system demonstrates MDS's compatibility with existing rail infrastructure, cost-effectiveness, and sustainability, contrasting with pure maglev's higher speed but requiring exclusive, costly infrastructure and limited adaptability.

Overall, MDS has the potential to redefine rail transport by bridging technological gaps, enhancing network connectivity, and contributing to global sustainability goals. The continued focus on innovation, standardization, and interoperability will ensure MDS becomes a cornerstone of a modern, resilient, and user-friendly European rail system.