Deliverable D7.4
Roadmap for maglev-derived systems

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1 Executive Summary

This document aims to provide a roadmap for the extension of maglev-derived systems, focusing on the technological solutions identified in previous tasks. Workshops and use case analyses will be employed to understand business needs and evaluate potential deployment routes/sites at both national and European levels, while also considering a global perspective. The results from WP7 will inform the development of a European roadmap for implementing maglev-derived systems, assessing their feasibility and scalability. Four specific use cases have been analysed (shunting automation, inclined pusher, regional line activator, airport shuttle), adopting different tools, highlighting the technological and operational advantages over traditional rail technologies.

A step-by-step approach is proposed to integrate the existing railway network with a maglev-derived network, which includes a transition plan and a cost-benefit analysis. Market consultations have indicated a positive interest in new technologies, particularly in areas such as upgrade of shunting automation, incline pushers, congestion mitigation accelerators for heavily trafficked lines. An industrial roadmap outlines key steps and milestones for achieving the commercial readiness of maglev-derived systems. This includes advanced research, modelling and simulation, testing, design and planning of maglev-derived systems (MDS), engineering development of solutions, and validation activities.

The methodology adopted involves defining use cases, summarizing feasibility studies, analysing the commercial and operational benefits and constraints, and conducting market consultations to ensure alignment with industry requirements. Additionally, a global perspective is integrated by examining existing maglev systems worldwide to understand demand and stakeholder interest. This comprehensive approach ensures that the proposed roadmap is both feasible and scalable, addressing the needs of various stakeholders and potential deployment scenarios.

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
ATO	Automatic Train Operations
CAPEX	Capital Expenditures
CBA	Cost-benefit analysis
CBTC	Communications Based Train Control
CCS	Control Command and Signalling
CO2	Carbon Dioxide
DAC	Digital Automatic Coupling
EMC	Electromagnetic compatibility
ESS	Electrical Substations
ETCS	European Train Control System
EU-RAIL MAWP	Europe's Rail Multi-Annual Work Programme
FRMC	Future Railway Mobile Communication System
GoA	Grade of Automation
HSR	High-Speed Rail
ICE	InterCity Express
LIM	Linear Induction Motor
LSM	Linear Synchronous Motor
M4R	MaDe4Rail
MDS	Maglev-Derived System
NOx	Nitrogen Oxides
OPEX	Operational Expenditure
PM	Particulate Matter
PSO	Public Service Obligation
PSO	Public Service Obligation
R&D	Research and Development
SJ	Statens Järnvägar
TEN-T	Trans-European Transport Network.
TGV	Train à Grande Vitesse
TMS	Traffic Management System
TRLs	Technology Readiness Levels
UC	Use Case
WP	Work Package

3 Background

The present document constitutes the Deliverable D7.4 “Roadmap for maglev-derived systems” in the framework of the MaDe4Rail project from the Innovation Pillar’s Flagship Area 7 – Innovation on new approaches for guided transport modes as described in the EU-RAIL MAWP.

4 Objective/Aim

This document has been prepared to provide a possible roadmap for the extension of maglev-derived systems, focusing on the technological solutions identified in the previous tasks.

The outputs of the workshops conducted in Task 7.1 will be utilised to understand the business needs of the interested parties and stakeholders.

An outlook of the different maglev-derived systems on a global perspective would also be considered in this activity to understand the interests of the other players outside Europe.

The results of WP7 would serve as an input to develop a European Roadmap for the possible implementation of the maglev-derived systems, taking into consideration its feasibility and scalability.

For the use cases analysed in Task 7.2 and Task 7.3, based on the information provided in those deliverables and more generally in the MaDe4Rail project, stakeholders will be able to evaluate the national context for implementation of these technologies, identifying for each use case the routes/sites of interest for potential deployment. The same evaluations will be performed in other European countries, starting from those of the other organisation participating to the Consortium.

Quantitative analysis will support the decision, also recurring to workshops with different transport operators, infrastructure managers, railway undertakings, national and/or regional administrations and institutions and other experts, including – in particular- those providing support letter to this project. It is worth mentioning that some routes/sites of interest have been proposed and discussed in the preparatory workshops for task 7.1 and are included in the respective deliverable. In this phase, the identified routes/sites should be mapped on the European network and a stepwise approach must be followed to integrate the existing railway network into a maglev-derived coexisting network according to the strategy outlined in this document, proposing a transition plan, high-level evaluation of cost-benefits, and high-level estimation of potential market for each use cases inside and outside of the EU.

With the aim to provide a balanced and objective method analysis for the three technological configurations selected in the use cases, the following chapters are structured with a common format, where, general principles are stated and then are evaluated for each selected use case.

5 Summary of feasibility studies performed and MDS applications

5.1 Use Case Analysis in general

A series of workshops were held in October 2023 for the MaDe4Rail project, focused on understanding railway market needs and exploring MDS applications. Participants engaged in structured discussions, leading to the formulation of market-aligned use cases. The workshops facilitated valuable exchanges, concluding with a comprehensive set of the identified use cases.

In total, more than 40 participants from over than 15 different companies were involved. The participating organizations are from the field of railways, with Infrastructure Managers, Railway Undertakings, Terminal Operators besides Tech companies, R&D organizations and potential end-customers in logistics.

Here an overview of the participating organizations:

Figure 1 - Involved organizations in the use case workshops (WP 7.1)

19 use cases were identified within the workshops. For more details, see Deliverable D7.1. Based on a Multi-Criteria-Analysis, three dedicated use cases were selected for a deeper analysis within the performed feasibility studies (WP7.2 and WP7.3).

#	Name	Short description	Category
1	Shunting automation	Automatic shunting via MDS for cost reduction and flexibility & capacity increase	Cargo
2	Electrification of terminals	Allow electrified operations also under the cranes via MDS	Cargo
3	Incline pusher	Additional traction force on uphill sections of inclines, enable higher loading limits and increase line capacity	Cargo
4	Automated last mile	Automatic shunting via MDS for cost reduction and flexibility & capacity increase	Cargo
5	Electrification of freight wagons	Enable power on unelectrified freight wagons, e.g. for Reefer containers	Cargo
6	Heavy haul pusher	Increased train dynamics especially for heavy freight trains (acceleration & braking forces), enabling higher average speeds and capacity	Cargo
7	Congested line accelerator	Reacceleration of trains in congested areas is decreasing the capacity. Acceleration lanes would increase the capacity, e.g. congested city centres or after passing tracks	Cargo & Passenger
8	Weather independence	Especially in winter conditions a MDS system could have significant benefits, via the direct drive, no catenary need, etc.	Cargo & Passenger
9	Maintenance minimizer	MDS via the direct drive capability will reduce the wear of the wheelsets, brakes and rails.	Cargo & Passenger
10	Electrification of tunnels & bridges	Narrow tunnels & bridges are blocking broader electrification of the lines. Using MDS within the tunnels could allow for faster overall electrification while saving high CAPEX on tunnel reconstruction	Cargo & Passenger

#	Name	Short description	Category
11	Additional wagons in peak times	High automation grade is allowing for adaptation to peak demands via providing more (or less) vehicles	Cargo & Passenger
12	Tunnel safety	MDS infrastructure could be used for tunnel evacuations or automatic fire fighting	Cargo & Passenger
13	Magnetic brake	MDS has very precise and strong braking capabilities, which enables higher average speeds and precise stopping allowing for faster boarding & onboarding and longer trains	Cargo & Passenger
14	Train length optimizer	Longer trains could split up automatically and reconnect (e.g. restricted track length at stations), also allows for short trains (Pod size) adding flexibility to the schedule	Cargo & Passenger
15	Railway highway	Connect cities with MDS lines for very flexible, high capacity and high velocity operations	Cargo & Passenger
16	Regional line activator	MDS (hybrid) systems to be used for rural lines, reducing the need for heavy train operations, small, light vehicles propelled by the infrastructure in a flexible and adaptable way	Passenger
17	Airport shuttle	MDS technology to be used for high frequency, high-capacity application on a specific line (shuttle), e.g. airport - city	Passenger
18	High speed accelerator I	Usage of MDS to accelerate HSR trains to recover from delays, e.g. after stations and for precise stopping at the stations	Passenger
19	High speed accelerator II	Upgrade of existing lines to high-speed operations via MDS. Faster deployment at less CAPEX of high-speed railway networks	Passenger

Table 1 - Use case overview

The selected use cases are:

- Use case 1: Incline Pusher, based on the “rail-vehicle upgrade MDS configuration”;

- Use case 2 and 3: Regional line activator separately based on "Hybrid MDS on air levitation configuration" (passenger shuttle, use case 2) and on "Hybrid MDS on magnetic levitation configuration" (passenger line accelerator, use case 3);
- Use case 4: Terminal automation, based on the "rail-vehicle upgrade MDS configuration".

Besides the detailed use cases, where MaDe4Rail has gathered deep insights and performed the in-depth feasibility studies (outcomes of analysis are illustrated in D7.3), the remaining use cases were analysed on a higher level and integrated into the roadmap and stepwise implementation approach, as described in Chapter 10.2 of this deliverable.

It is worth mentioning that the route analysed for use case 3 allowed also for the preliminary technical and economic evaluation of the airport shuttle use case leading to positive results (please make reference to D7.3) that highlight the suitability of those technologies for this specific operational context.

5.2 Use Case 1: Incline pusher description

Context and Objectives

The proposed use case involves implementing an upgraded MDS configuration on the rail connection between two cities in Sweden. Currently, there is a single-track line between these two cities, although it is not heavily utilised. To enhance rail infrastructure, a new high-speed line is already being planned.

This project aims to evaluate whether a new propulsion system can enhance capacity and service quality on the existing line. Additionally, it will explore the feasibility of using a linear motor to plan with higher gradients on the new line, potentially reducing construction costs.

Route and Infrastructure

The use case is proposed in Sweden on a railway line linking two cities. Today's railway between the two points consists of the Coast-to-Coast railway line, which continues to connect other municipalities. The existing line is single-track, curvy, and has limitations in capacity, speed, and travel time. The route is one of Sweden's largest commuting areas, and the existing railway is not a competitive alternative to road traffic. Commuting in the route today is mainly made by car or bus. The same applies to trips to and from the closest airport, which currently has no rail connection.

A new railway line between the two points would provide faster train journeys, smoother work commuting, and increased accessibility to and from the airport.

Transportation Demand and Network

The main infrastructure system in the route consists of a motorway and the coast-to-coast railway. Travel on this route is dominated by car, with the majority driving on a four-lane motorway between the cities. Driving end-to-end takes between 40 and 65 minutes. The road is an important connection and has regional importance for work commuting. It is also of national importance for long-distance freight and passenger transport.

Long-distance freight transport takes place to a large extent to and from the adjacent port and the coast-to-Coast line. The railway includes transport for the automotive industry, and container traffic. Between the two cities, there were seven one-way freight trains per day in 2021.

The coast-to-coast line is served by Regional trains that have intermediate stops and direct trains that connect only the two cities. The coast-to-coast line is a single-track, electrified, and remote-block railway that stretches between different cities. It is served by both freight and passenger trains, including interregional, regional, and local services.

Parallel to the train traffic, the route is also served by bus traffic. A bus service is the main alternative for trips between the two cities, with intermediate stops. The bus service has frequent departures every five minutes during peak traffic. Additionally, other bus services operate with additional trips during rush hours.

Public transport's share of total travel on the route is 25%, and buses account for 97% of this.

The adjacent airport is one of the most important in Sweden. The number of air travelers was approximately 6.7 million in 2019. The airport is served by airport buses from both cities, as well as by public transport from a travel center, where buses to the airport run every twenty minutes. Many travelers choose to take the car via the motorway.

Operational Scenario for MDS

The technical scenario A is the existing line, which has a speed limitation that makes it impossible to run high-speed trains because of the top speed differences in mixed traffic operation and the challenge of freight vehicles maintaining full speed in different sections of the line (Scenario A.1). Due to this corridor being a critical link in the Swedish network, a High-Speed line (250km/h) has been proposed, with the planning phase ongoing at the moment (Scenario B.1); this would allow a significant capacity increase by duplicating the number of tracks between the two cities, and by segregating traffic with different speeds where passenger services run mainly in the HS line. Building a new HS line has very high investment costs while significantly impacting the capacity of the corridor. The benefits and drawbacks of creating a new high-speed line parallel to the existing connection have already been studied by Trafikverket with their CBA methodology.

This scenario could benefit of introducing Uphill Boosters / Incline Pushers, where additional power is introduced in uphill sections. The studied cases are the following:

- **Capacity increase in mixed-traffic lines**: upgrade the existing line introducing Uphill Boosters in existing uphill gradients to allow heavy freight trains to maintain top speed even in challenging adhesion limit scenarios (Scenario A).

- **Cost-savings for new infrastructure**: modify the design of the high-speed line by including higher gradients with incline pushers (Scenario B). This would allow to build the new line with less earthworks and/or bridges, reducing the costs and emissions related to the construction phase, which are one of the most limiting factors in new projects.

Scenario Analysis

Two scenarios are proposed to evaluate the feasibility and performance of the hybrid MDS:

Scenario A: Minimal Technological Upgrades of the existing line

- Propulsion: Linear Synchronous Motor (LSM).
- Levitation: no levitation.
- Rolling Stock: existing rail freight wagons upgraded with permanent magnets as counterpart of the stator, which will be installed on the existing tracks.
- Existing line alignment will be retained.
- In this scenario, the MDS will utilise existing infrastructure with minimal upgrades, focusing on achieving the minimum technical requirements necessary for operation.

Scenario B: Comprehensive planning parameters for the new line to save

- Propulsion: Linear Synchronous Motor (LSM).
- Levitation: no levitation.
- Rolling Stock: new high-speed trains upgraded with permanent magnets as counterpart of the stator which will be installed on the tracks.
- Adapted line alignment in the planning of the new line.

Technical Specifications

The main components of the propulsion system in both scenarios are:

- Stator installed in between the existing rails, fixed to the sleepers or slab track.
- Mover equipped with permanent magnets attached to the vehicles.
- Control center to command the linear motor.
- Inverter stations to deliver needed power to the linear motor.

Operational Considerations

In both scenarios trains will operate under today's given regime. Freight trains on the existing line will run with a conventional locomotive and driver, and the high-speed trains will also operate in a conventional way with a driver. Infrastructure will be equipped with a signaling system as required in the national or international regulations.

The additional propulsion from the MDS will compensate for the gap in needed traction force to maintain the speed and the available traction force of the locomotive or train.

Conclusion

The proposed (MDS) presents a promising alternative for

- supporting freight traffic on steep inclines for existing lines, granting increased speed, length and transported mass for cargo services on more direct routes with positive effects in terms of reduction in the speed gap between freight and passengers trains, increased capacity usage, reduction in operational costs;
- significantly reducing construction costs related to earthworks, tunnels, and bridges. This cost reduction is achieved by adjusting line planning parameters in a more comprehensive manner. The feasibility study offered crucial insights into the technical and operational viability of this innovative transportation solution, potentially establishing a new standard for planning parameters, especially regarding gradients. Although the specific line selected presented a benefit to cost ratio below parity (B/C < 1) due to low traffic volumes that affect the selected route, other geographical context with higher level of traffic and demand should provide positive results for the cost-benefit analysis (B/C > 1) as well.

For more details, please refer to Deliverable D7.2 and D7.3 of the MaDe4Rail project.

5.3 Use Case 2: Passenger shuttle description

Hybrid MDS based on Air Levitation Configuration on a short distance line in Italy

The proposed use case involves implementing a hybrid Air Levitation System (AIRLEV) on the existing line connecting two important cities within the same region. This use case focuses on evaluating the feasibility of upgrading the existing line with AIRLEV technology to potentially increase capacity, speed and performance of vehicles.

Context

The two cities are located approximately 40 km apart from each other. Together, they account for ca. 40% of the region's total population. These cities also attract a significant number of tourists.

Operational Scenario

The entire route has an extension of ca. 40 km and the current travel time with intercity and high-speed trains on this line is around 30 minutes.

The operational context for air levitation includes environmental conditions, operational conditions, daily operations and example scenarios, vehicle dynamics, passenger and cargo handling, integration with existing infrastructure as well as futureproofing and scalability.

Conclusions

Air levitation technology offers a slight reduction in energy consumption compared to conventional trains operating at similar speeds. However, it does not improve travel times.

Implementing air levitation requires specific infrastructural adjustments, such as the addition of track slabs, and potential issues with noise and vibrations in sensitive areas must be addressed.

The overall costs of implementing air levitation exceed the benefits (B/C<1). Given its lower maturity level compared to other technologies analysed, air levitation does not yet offer clear advantages over alternative configurations examined in the project.

5.4 Use Case 3: Passenger line accelerator description

Proposal for Implementing Hybrid Magnetic Levitation (Maglev) on a long-distance historical line

Context and Objectives

The proposed use case involves implementing a hybrid Magnetic Levitation System (MDS) on a historical regional in Italy. This project aims to evaluate the performance of a hybrid MDS on a regional line, particularly focusing on technical conditions such as speed, travel times, and capacity.

Route and Infrastructure

The route spans around ca. 600 km and consists of six line-sections and four nodes. The current high-speed services cover the same route for running on a dedicated line in some sections, and on conventional infrastructure shared by both HSR, IC, Regional and freight services. Currently, modern **HSR trains** complete the journey in approximately **4 h, IC trains** complete the journey in around **6h** while **regional trains** can take **at minimum 8 h** with 3 changes (there are no direct regional services, according to calculations a direct regional service without stops would take approximately 8 h as well). The selected route traverses an important Mountain range and includes stops in major cities.

Transportation Demand and Network

The two cities connected by the line are major tourist and economic hubs, necessitating a robust and adaptable transportation network. The transportation links between these cities include highways, trains, and air connections. The highway network, facilitates car travel with an average travel time of 6 hours.

Air travel between the cities is well serviced, with a flight time of approximately 1 hour.. However, rail travel offers a competitive and environmentally friendly alternative, with high-speed trains providing fast and efficient connections at speeds up to 300 km/h in some sections.

Operational Scenario for MDS

The hybrid MDS implementation will be based on the existing regional line, integrating magnetic levitation and traditional rail technology. Capsules will operate with GoA4 automation, achieving maximum speeds of 220 km/h with an acceleration of 1.5 m/s² and higher limits on emergency deceleration capabilities. The system will be managed by a control center ensuring efficient and safe operations, including automatic checks and adjustments in case of disruptions.

Scenario Analysis

Two scenarios are proposed to evaluate the feasibility and performance of the hybrid MDS:

Scenario A: Minimal Technological Upgrades

- Propulsion: Linear Synchronous Motor (LSM)
- Levitation: U-shaped sliders on existing rails.
- Rolling Stock: Newly designed M4R-pods, capable of carrying 70 passengers at speeds up to 220 km/h.
- Existing line alignment will be retained.
- In this scenario, the MDS will utilise existing infrastructure with minimal upgrades, focusing on achieving the minimum technical requirements necessary for operation.

Scenario B: Comprehensive Technological and Infrastructural Upgrades

- Propulsion: LSM
- Levitation: Sliders on additional levitation beams attached to the rails.
- Rolling Stock: Newly designed M4R-pods, capable of carrying 70 passengers at speeds up to 220 km/h.
- Adapted line alignment to prevent speed drops and optimize performance.
- This scenario involves significant technological and infrastructural upgrades, including the installation of additional levitation beams and modifications to the track alignment to enhance performance and minimize speed drops.

Technical Specifications

Two possible propulsion systems for both scenarios:

1. **Linear Synchronous Motor (LSM)**: Utilising neodymium-iron-boron permanent magnets on a steel core, the LSM activates when electrical power is supplied to the stator, creating an electromagnetic force that propels the vehicle.
2. **Linear Induction Motor (LIM)**: Featuring an inductor with windings around a magnetic core and a U-shaped armature, the LIM operates on the principle of electromagnetic induction to move the vehicle.

For this study like described in the deliverables D7.2 and D7.3, the LSM system from NEVOMO will be the technological basis for the estimations. This shouldn't be understood as a decision for later implementations but will help to estimate the technological needs and possibilities for one of the possible solutions.

The levitation system in Scenario A relies on ferromagnetic interaction between U-shaped sliders and a ferromagnetic rail, while Scenario B includes additional levitation beams to enhance stability and performance.

Operational Considerations

The MDS capsules will undergo automatic pre-departure checks to ensure all systems, including magnetic levitation and propulsion, are functioning correctly. Passenger operations, including embarkation and disembarkation, will be autonomous, and onboard staff will provide assistance and emergency support as needed. Upon arrival, capsules will undergo preventive checks and cleaning to prepare for subsequent journeys.

Conclusion

The proposed hybrid MDS shows potential to provide enhanced speed (see D7.2), better acceleration and deceleration on existing rail alignments. These improvements would allow for more frequent connections and higher-quality transport services, promoting a shift towards rail transport. The hybrid series configuration (levitation and guidance is applied directly to existing rails) shows favourable results, while the parallel configuration (additional beams are added to the infrastructure for guidance and levitation) present higher capital expenses related to the infrastructure retrofitting, though showing potential for optimization in different contexts (e.g. more homogeneous in terms of service coverage and technical characteristics in relation to the length of the line) could generate total benefits exceeding total cost as well.

For more details, please refer to Deliverable D7.2 and D7.3 of the MaDe4Rail project.

5.5 Use Case 4: Terminal automation description

Overview and Use Cases

This chapter explores the potential implementation of linear motor propulsion in container terminals, focusing on improving efficiency, sustainability, and operational performance. We will discuss various use cases and propose a specific solution for a terminal in Italy.

Current Situation and Challenges

Currently, container terminal operations often rely on diesel shunting locomotives due to the absence of classical catenary electrification. This practice presents several challenges:

- **Pollution**: Diesel locomotives emit pollutants such as nitrogen oxides (NOx), particulate matter (PM), and carbon dioxide (CO2), contributing to air pollution and climate change.
- **Noise**: Diesel locomotives are noisy, especially during low-speed operations, with consequences for both workers and neighbouring communities.
- **Fuel Consumption**: Diesel locomotives consume fuel even when idling, resulting in higher operating costs.
- **Operational Efficiency**: Inefficient shunting practices can cause congestion, delays, and increased costs.

Considering these concerns, it makes sense to explore modern solutions using MDS technologies in terminals. Seven different secondary use cases are considered:

1. **Pull-in Service**: Shunting of trains arriving at/departing from the terminal and their connection to the station of arrival/departure from/for long-distance journeys, include connections to loading and unloading tracks.
2. **Inter-terminal Shuttle**: Creation of cross-connections between terminals of larger industrial zones.
3. **Terminal to Port Shuttle**: Establish a fast and automated connection between bimodal terminals, creating a virtual trimodal terminal.
4. **Terminal to Warehouse Shuttle**: Direct and automated connections between terminals and warehouses to improve efficiency.
5. **Terminal to Depot Shuttle**: Connecting container depots with terminals using automated MDS services and reach stackers.
6. **Depot to Truck Parking Shuttle**: Connecting outside depots with truck parking facilities using automated shuttle wagons.
7. **Automated Wagon Parking**: Moving unused wagons to parking tracks for reactivation when needed.

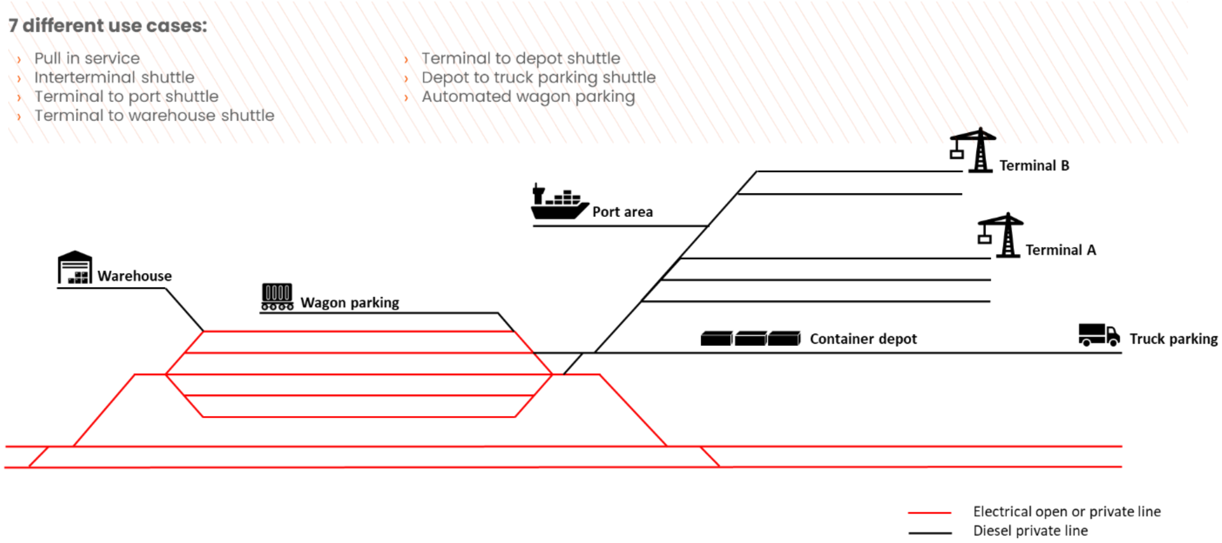

Figure 2 - Possible terminal use cases

Specific Use Case: Italian terminal

MaDe4Rail project focused on the first use case, specifically implementing MDS technology to manoeuvre arriving trains into the terminal tracks on the more critical sections of the terminal.

Infrastructure and Operations

- **Infrastructure**: The terminal operates with three infrastructure owners. The terminal has seven electrified arrival tracks for long-distance electric locomotives and diesel shunting locomotives for in-terminal manoeuvres. Containers are handled by reach stackers.
- **Operations**: Trains arrive on electrified tracks, where long-distance electric locomotives are decoupled and coupled to departing trains. Diesel shunting locomotives then manoeuvre trains within the terminal.
- **Electrified Tracks**: Arrival and departure station with several electrified tracks.
- **Terminal Tracks**: Different terminal areas managed by various infrastructure managers, but non-electrified.

Operational Goals:

- Automate rail operations up to GoA 3/4.
- Enhance sustainability and reduce greenhouse gas emissions.

Operational Model

- **Current Operations**: The terminal operates 24 hours on weekdays and 16 hours on weekends, handling 60 trains per week. Two diesel shunting locomotives are currently used, causing waiting times during peak hours.

- **Optimization Goals**: Implement advanced automation to enhance efficiency, reduce greenhouse gas emissions, and address workforce challenges.

Solution Design

- **Proposed MDS Technology**
  The new MDS technology involves using linear motors and upgraded vehicles for shunting operations. Key components include:
  - **Equipped Wagons**: A group of two MDS-equipped wagons will operate like a shunting locomotive.
  - **Partial Track Equipment**: Linear motors will be installed only on parts of the tracks, not the full length.

  - **Track Length**: Total track length to be equipped is 6.4 km.
    - Entrance tracks: 800m
    - Shunting connection: 1,200m
    - Shunting tracks: 1,200m
    - Terminal tracks: 3,200m

Operational Concept

1. **Arrival**: The container train arrives at the arrival station, and the electric locomotive is decoupled.
2. **Shunting**: MDS-equipped wagons move to the train, couple to it, and shunt it to the terminal tracks.
3. **Loading/Unloading**: Containers are handled by reach stackers.
4. **Departure**: After loading, the MDS-equipped wagons shunt the train back to the arrival tracks, where it is coupled to a long-distance locomotive.

Implementation Steps

The implementation will follow a step-by-step approach to allow a consequential but safe automation.

- **Step 1**: Remote control of the system by a shunting operator on the vehicles.
- **Step 2**: Remote control from a central control room using cameras and sensors.
- **Step 3**: Fully automated movements with defined orders.

Conclusion

Implementing MDS technology at the terminal can significantly enhance operational efficiency, reduce greenhouse gas emissions, and address workforce challenges. The proposed solution offers a practical and sustainable approach to modernizing rail operations in container terminals.

For more details, please refer to Deliverable D7.2 and D7.3 of the MaDe4Rail project.

6 Identifying the candidate situations to apply the maglev-derived systems

To identify the situations which are best suited to adopt maglev-derived systems, a fair approach firstly requires to identify the commercial and operational constraints that the new system will be subjected to when applied on existing lines. Those constraints are only partially connected with the technical feasibility studied in the previous work packages. A second step requires to quantify the feasibility, the effort required and the complexity of achieving comparable results with traditional rail technologies.

Then, specific criteria should be set to measure whether and when the adoption of the maglev-derived technologies provides non-marginal benefits compared to the traditional rail technology and, finally, criteria are needed to geographically locate the existing rail network segments where the adoption of the maglev-derived technologies should be beneficial.

6.1 Commercial / operational constraints and benefits

Commercial constraints, as here considered, relate to the compatibility of technically attainable performances with typical exigencies from end-users or railway undertakings. Operational constraints, as here considered, relate to the efficient use of infrastructural capacity. These two aspects should be evaluated properly, as they could set limitations to dynamical performances technically feasible or could lead to mismatches to basic aspects in existing infrastructure utilisation principles.

Benefits should be quantified after considering the limitations posed by those constraints and evaluating the potential connected with the applications of maglev related technologies within the limits set by those constraints.

6.1.1 General principles

This paragraph aims to identify commercial and operational constraints that potentially are not compatible with the benefits technically achievable by the maglev-derived systems, on the commercial and operational point of view. The constraints listed are referred to maglev-derived systems operating on existing railway lines.

6.1.2 Common passenger and freight constraints

As a general principle, rail infrastructural capacity is increasingly saturating, as clearly recognized by European legislation in directive 2012/34/EU, recital 58. According to such legislation, infrastructure capacity is meant as the potential to schedule train paths requested for an element of infrastructure on a certain period. Strict criteria are provided to ensure that Infrastructure Managers carry out capacity allocation and capacity management through equitable and non-discriminatory processes. Each Member State has established a Regulatory Body, legally distinct and independent from any other public or private entity, to supervise this process, with the power to request information and issue penalties.

Therefore, the operation of MDS on hybrid infrastructure must be compatible with the path-based approach at the basis of the current legislation and practice. Technologically speaking, paths are programmed by infrastructure managers with headways of around 5 minutes on mainlines, down to 2.5 to 3 minutes on congested sections. This requires programming timetables with a resolution of 30 to 60 seconds. Therefore, any operational procedure thought for the maglev-derived systems must be able to ensure, in normal conditions, such a scheduling resolution.

6.1.3 Passenger traffic constraints

In this paragraph a series of requisites commonly assumed by passenger traffic is listed:

Commercial constraints

- Any excessive additional physical discomfort imposed on passengers during the journey should be carefully evaluated and considered unacceptable, as counter-productive to the objective to divert travel from air and road modes to rail.
  Therefore, the MDS performance evaluation should consider lateral accelerations and variations of lateral acceleration per time unit applied to the traveller, which must be compatible with the traveller's comfort, considering the cant and the length of transition curves on existing lines. Studies and practice on tilting trains about limiting those parameters could be used as a reference, as well as limits imposed on acceleration in other comparable transport systems (including metro systems and maglev trains) could be used as a reference to define the max operative performance of MDS.
- The possibility to walk in safety along a train during the journey should be considered not negotiable for comfort reasons, being connected with some of the basics expectations from customers choosing rail mode (e.g. possibility to use a toilet, possibility to relieve leg stress). It should be considered that walking limitation on air travels is usually limited to specific and brief moments (take-off and landing), whereas travels with weather conditions determining prolonged limitations are usually perceived as highly uncomfortable. About the MDS, in the case walking limitations

should be connected to the infrastructural layout, they, in principle, could be active for the whole journey, putting rail services in significant comfort disadvantage compared to air sector.

Therefore, the maglev-derived system performance evaluation should consider lateral accelerations and variations of lateral acceleration per time unit applied to the traveller, which must be compatible with safe walking, considering the cant and length of transition curves on existing lines.

Limited discomfort during walking compared to the present rail condition could be evaluated for application with expected short travel times, where the need to move along the train to access comfort-related services (e.g. toilet) should be considered unlikely; mass transit average travelling times and admitted discomfort could be taken as a reference.

- Customers require that short and medium-distance trains, especially PSO services, must be accessible without reservation, as the possibility to adapt one's daily programming has shown to be a basic requisite for service appeal. High-frequency services are considered to give a quantum leap in service quality, as the traveller often accesses the rail system without even knowing the scheduled timetable. Compulsory reservations on short and medium-distance PSO service could also raise legal issues. Therefore, travellers should be admitted on short and medium distance maglev-derived trains also without reservation.

  As for long-distance services, if reservations were mandatory, railway undertakings could weigh the performance benefits against the loss of customers by admitting standing passengers today.
- Typically, rail travel does not entail any limitation to luggage transport, giving a significant competitive advantage to rail compared to air travel. Also, large luggage is usually admitted, without any previous luggage reservation. Luggage handling is left to the traveller, with significant benefits on luggage security. In addition, bike transport is expected on short- and medium-distance services and on most long-distance services. Therefore, MDS should allow the possibility to carry large luggage, preferably but non-compulsorily in dedicated spaces, with luggage handling under the traveller's responsibility and without any compulsory luggage reservation. Also, bike transport with traveller's handling should be possible.

Operational constraints

- The punctuality expected from the rail mode is significantly higher than in any other transport mode. Passenger punctuality performance is assessed relating to different thresholds for passenger trains, which differ country by country but usually range from

3 to 5 minutes for short-distance PSO services and High-Speed trains, and from 3 to 15 minutes for long-distance trains.
Therefore, any operational procedure designed for maglev-derived systems must be able to ensure such scheduling and operational resolution under normal conditions.

- Both the punctuality requirements and the path-based capacity usage require trains to depart when their time is scheduled, with very limited tolerances. An aeroplane-like model, where the cabin crew checks seatbelt fastening and luggage-compartment locking before authorizing take-off, is utterly incompatible with the rail system. Moreover, the presence in each carriage of safety staff to insist with reluctant travellers to sit and fasten seatbelts, or to lock luggage compartments, is not compatible with actual train staffing and its economic impact on operation.
Therefore, any safety need that requires travellers to have their seatbelt fastened on MDS travels should be considered unacceptable, and kinematical parameter limitation should be defined not to request such a requirement. Travelling conditions requiring, for safety reasons, to have all passengers' seatbelts fastened must require an automatic fastening detection system. Responsibility handover to the traveller can hardly be considered admittable considering the railway regulation mindset. Such a detection system should be connected to emergency systems (including braking systems) or procedures.

6.1.4 Freight traffic constraints

In this paragraph a series of requisites commonly assumed by the freight traffic are listed:

- Typically, the rail freight market works with tight economical margins, that require a strong effort to cut costs for any system element. Therefore, it is very important that maglev-derived systems require limited additional vehicle construction costs.
- Maintenance of freight wagons is carried out for the most part with limited equipment usually transported by a van, directly in freight yards, without taking the wagon out of its trainset. Only major maintenance works require the wagon to be treated in a workshop. It is important that light maintenance for wagons equipped with maglev-derived systems could be carried out in compliance with this maintenance setting, without requiring more frequent workshop treatment.
- Weight constraints on MDS vehicles could make the freight services inviable due to economical margins.

6.2 Potential commercial benefits achievable by the selected MDS use cases compared with traditional rail technology

The selected use cases provide technological characteristics that could offer significant benefits for rail undertakers and end users compared to traditional wheel-on-rail technologies, here defined as commercial benefits. Some benefit categories, such as the possibility to increase the number of vehicles per time unit on the infrastructure should not be considered, as they are not inherently connected to the substitution of the wheel-on-rail contact but are related to the adopted signalling system, unless this is enhanced as a result directly relate to the introduction of MDS.

In a context close to the rail system, mass transit, CBTC technologies (Communications Based Train Control), incorporating a mobile-block approach, achieve significant results in increasing vehicle density on infrastructure.

These technologies have been developed and applied for about 30 years and have proven to be efficient and reliable. They are often used for unmanned operation and are widely applied the worldwide, becoming a consolidated standard. Under suitable conditions, they can easily manage headways lesser than 1 minute, according to the dynamic performance of trains. The ETCS level 3 signalling system converges in performance with CBTC. Therefore, a CBTC or ETCS level 3 signalling system could be applied to any MDS, utilising at best its dynamical performances. **An important factor influencing decisions in the signalling field is whether it is mandatory to have coexistence of MDS vehicles and traditional vehicles on the same line, alongside interoperability.** Interoperability requires vehicles that operating on other lines be equipped with a signalling system that facilitates seamless transition. If coexistence is essential, it is necessary to identify a signalling system that can be applied to all vehicles. For example, for MDS vehicles, tasks 7.1 and 7.2 revealed potential issues with Eurobalises and track-based train recognition, such as track circuit or axle counters. Therefore, since the constraints of interoperability and coexistence must be satisfied, it is necessary to evaluate which signalling system is most suitable and has the best cost/benefit ratio. More details are presented in D8.1.

Considering the selected use cases, three main categories of commercial benefits can arise from adopting the new technologies compared to the traditional ones:

1. The possibility to concentrate technology-intensive devices on limited track stretches;
2. The possibility to achieve improved longitudinal accelerations (i.e. quicker acceleration and braking) and, potentially, higher mainline top speed;
3. The possibility to sustain higher lateral acceleration, leading this way to higher speed on curves.

Benefits 1 sounds important for use case 1 (incline pusher) whereas benefits 2 and 3 sound most relevant for use cases 2 and 3 (air levitation and passenger line acceleration).

6.2.1 Evaluating commercial benefit on steep incline

The performance of heavy trains on steep inclines is limited by locomotive power and coupling resistance. This power limitation is due to current draining cap imposed by electrical substations (ESS) and the overhead conductor's section. In some cases, this limitation forces headways between heavy trains to be to no shorter than 8-10 minutes, or even longer, which constrains rail operations. Overcoming such limitations requires significant infrastructural investments, both on overhead wiring and ESS improvement.

Locomotive performance is typically calculated based on the minimum acceleration required for a train stopped on an incline. For freight braking, a setting of the braking system, known as freight braking, is used for the heaviest trains, to overcome the problem of static friction. Static friction, which is higher than dynamic friction, is mitigated by initiating movement in each wagon sequentially, that requires the locomotive to exert the most effort on one wagon per time.

After the whole train has been moved, the force required to accelerate it depends, through a simple formula, on the train mass and the incline grade. Sharp curves introduce further resistance that can be assimilated to some more points of incline grade. Until a few decades ago, rheostatic starting locomotives had serious technological problems sustaining low speeds, resulting from very low accelerations, for a prolonged time. Nowadays, electronic starts have mostly overcome this technological problem, but accelerations that are too low and subsequently extended travel times can lead to unacceptable infrastructural capacity consumption. Therefore, a minimum acceleration is requested also for trains exceptionally stopping at the steepest locations (never below 0,03 m/s^2 in Italy [1]).

Based on the calculations mentioned, the number of tons locomotives can haul depends on the line they are traveling on. For example, reference locomotives on the Italian stretch of the Brenner line can haul more than 2100 metric tons on the sub-horizontal stretches and no more than 800 tons climbing up the mountain pass. Since market-required trains can nowadays easily exceed 2000 tons, either the train is equipped with three locomotives throughout its route, or the second and third locomotives must be coupled to the train where the incline begins and decoupled where it ends. With the first solution, capital-intensive assets as locos are carried around non-active for many hours, while wearing out their mechanics. For example, a typical Verona to Munich freight trains spanning 442 km needs auxiliary locos only on the mountain stretch Bolzano to Innsbruck, that is only 130 km long. Coupling and decoupling locos along the route is, on the other hand, time consuming and expensive, as expensive is marshalling itself, organizational efforts are required to the rail undertakers and the infrastructure manager must build and maintain dedicated stations or yards.

Additionally, because the strain on couplings increases with incline, auxiliary locomotives must be positioned in specific points along the train, such as both the head and the tail of the train, making coupling and decoupling process even more complex.

Another drawback, is that additional locomotives reduce the usable length of the train. For examples, with approximately 20 meters per locomotives, the addition of two auxiliary locomotives reduces the train's paying load by about 6% on a 740-meter European high-performance train.

Incline pushers aim to implement technology at specific locations where grade is steep, and a power boost is needed. They could prevent the need to use auxiliary locomotives, as the additional power is provided only locally. Assuming the technological upgrade on waggons, consisting basically of a reaction plate, is economically negligible compared to the capital investment for a locomotive, one locomotive could haul the train throughout the route, no intermediate marshalling would be needed, and train length occupied by auxiliary locomotives could be used for paying load. Infrastructure managed could save on the upgrades on the overhead wiring supply system, provided they have increased cost related to the new MDS infrastructure.

6.2.2 Evaluating commercial benefit of higher longitudinal acceleration values

Benefit 2 concerns the possibility of higher longitudinal acceleration values, to be used before and after stops. This benefit is more relevant for rail services with many stops, such as local trains with a public service obligation. Currently, most local trainsets can guarantee 1.25 m/s^2 acceleration and deceleration; this value can also be considered a threshold for a comfortable ride. Some metro trainsets are capable also of 1.5 m/s^2 accelerations, but this must be considered a limit not to exceeded for safety reasons, as passengers on metro systems are recommended to always hold onto handgrips [2]. For examples, higher deceleration values due to undue intervention of high-performance emergency braking on the new Milano metro trainsets caused injures and legal problems for the operator in 2021. See as reference the table below, taken from [2].

From: Passenger Stability Within Moving Railway Vehicles: Limits on Maximum Longitudinal Acceleration

Vehicle	Maximum acceleration (m/s²)		
	Traction	Service brakes	Emergency brakes
Class 390 Pendolino (intercity EMU)	0.37	0.88	1.18
Class 156 Super Sprinter (regional DMU)	0.75	0.7–0.8	0.7–0.8
Class 323 (suburban EMU)	0.99	0.88	1.18
London Underground 1992 tube stock	1.3	1.15	1.4
Tyne and Wear Metrocar	1.0	1.15	2.1 (*)
Manchester tram (Ansaldo T-68)	1.3	1.3	2.6 (*)
Sheffield Supertram (Siemens-Düwag)	1.3	1.5	3.0 (*)
Croydon tram (Bombardier FLEXITY)	1.2	1.3	2.73 (*)
Nottingham tram (Bombardier)	1.2	1.4	2.5 (*)

Table 1 - Example maximum accelerations for railway vehicles in Great Britain

A quick comparison on kinematic results can help to assess the relevance of possible improvements. Acceleration time between 0 and 100 km/h (a reasonable cap for a service stopping every three minutes or so) is about 22 seconds at 1.25 m/s^2 and about 16 seconds at 1.75 m/s^2, provided such an acceleration is admissible considering passenger safety. This means that 12 seconds can theoretically be saved between a stop. Therefore, six stops (five stretches) would be needed to gain a single minute. With a 3-minutes travelling time between stops before the adoption of the new technology and a full minute dwell time at each intermediate stop, the total travel time could be at most reduced from 19 minutes to 18 minutes, accounting for only about 5% reduction. On the other hand, timetabling resolution is 30" on most European network and 20" in very few cases; thus, the estimated time savings are too small to be practically considered in timetabling.

Additionally, the variation in acceleration per time must consider a comfort limit. The maximum admitted value of this parameter (jerk) is a constraint already taken into account and usually reached in the design phase of traditional trainsets and locos.

Considering that the upper admitted value for longitudinal acceleration is already feasible with traditional rail systems and higher values, where admissible, provide only very limited travel time benefits, Benefit 2 should be considered substantially marginal.

For freight trains additional longitudinal acceleration ability behind often used passing tracks can bring relevant benefits. After the freight train has been overtaken by faster passenger train, it can take long time and distance to reaccelerate to travel speed on the main line. An installed linear motor can help to accelerate the freight train to the allowed speed much faster, leading to shorter occupation times and higher capacity of the main line. This could bring important benefits on heavily used lines with mixed traffic of fast passenger trains and heavy freight trains. However, the benefit of such solutions will always depend on the specific situation of the line and requires a clear analysis of the situation.

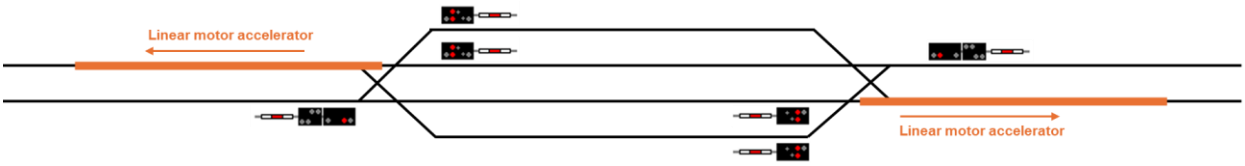

Figure 3: Possible configuration for faster accelerating freight trains after overtaking by passenger trains.

6.2.3 Evaluating commercial benefit of higher lateral acceleration

Benefit 3 concerns the possibility of sustaining a higher lateral acceleration, leading to higher speed on curves. MDS should enable to have lateral acceleration beyond what is currently allowed by the traditional ballasted track and further increase it by adopting a tilting mechanism on MDS vehicles.

Lateral acceleration allowed by traditional ballasted track is limited by later track resistance. The transmitted lateral forces are proportional to the vertical loads (i.e. the heavier the vehicle, the higher the transmitted lateral forces, according to Prud'Homme's formula). A quick review of the technical literature from when tilting trains were developed [3] (in Italy, the first commercially successful vehicles were developed half a century ago) shows that the reference admitted lateral acceleration before track geometry deteriorates is about 2.5 m/s^2. Subsequent technological development, especially with the widespread diffusion of under sleeper pads and further anchoring devices on sharp curves, have significantly raised those values compatibly with limitation to maintenance costs.

Such lateral acceleration can then be increased by applying track cant. The maximum cant admitted by UIC is 160 mm, corresponding to 6°. Since the admitted lateral acceleration for passenger, compatible with standing and walking in trains, is considered to be 1.0 m/s^2, and 0.8 m/s^2 to ensure an optimal comfort level, a 2.5 m/s^2 acceleration at wheel-rail contact can be transmitted if tilting mechanisms are adopted to preserve the passenger from a 2.5 – 0.8 = 1,7 m/s^2 lateral acceleration, corresponding to a 10° tilt created on board.

Therefore, MDS can allow higher speed on curves if they can sustain a lateral acceleration higher than 2.5 m/s^2. However, if higher lateral acceleration is allowed at vehicle-infrastructure contact, a higher lateral resistance for the track (which must accommodate both traditional and MDS vehicles) must be provided. This increased resistance can also be used by traditional rail vehicles to enhance their tilt. Thus, a benefit from MDS technologies can only arise if the corresponding vehicles are significantly lighter than rail ones. The dual rail-MDS track must be able to contain a certain lateral force, corresponding to the vehicle mass multiplied lateral acceleration.

However, after decades of tilting train operation, the tilting angle has been reduced, due to generally reported passenger discomfort problem, similar to seasickness.

This discomfort is associated to the human body's sensitivity to variation in acceleration. For this phenomenon, acceleration must be considered a vectoral quantity: both the magnitude and direction matter. The discomfort is proportional to the rate of change of acceleration and causes nausea. Research has shown that this reaction has an evolutionary perspective, as some poisonous substances cause altered perceptions similar to acceleration variations in the organs responsible for balance.

Tilting mechanisms keep the vehicle horizontal on straight alignment and at full tilt along circular curves. The vehicle rotation occurs along transitional curves, where alignment radius changes from infinite to the finite curve radius and track cant raises from 0 to the maximum cant. While travelling along transitional curves, tilting mechanisms ensure that the lateral acceleration perceived by the passenger doesn't exceed, in any moment, the objective value of 0.8 m/s^2. This acceleration is always parallel to vehicle floor, but as vehicle tilts, it changes from horizontal to an oblique direction pointing upward. The rate of this direction variation depends, kinematically, only on the time during which it happens. For a given length of a transitional curve, the only way to contain this rate is to the time during which the variation occurs; which means having a longer transitional curve. That implies alignment changes. Alignment changes reduce this rate both for traditional and MDS equally.

Before admitting tilting trains on existing lines, infrastructure managers usually perform these alignment changes, lengthening transitional curves, which results in moving the track axis by up to some ten centimetres. As there is no disadvantage in having long transitional curves, they are usually lengthened as much as possible, considering the infrastructural constraints existing. Therefore, it is generally correct to assume that, if a line has already been optimized to admit rail tilting trains, further optimizations require relevant investments on infrastructure. Should this optimization be performed, the same speed increase with the same comfort level could be achieved both by MDS and traditional tilting trains.

In the end, a non-biased evaluation of the commercial performances of MDS on existing lines cannot avoid stating that no speed augmentation could be achieved on curves compared to existing tilting technologies, unless a lower comfort level is accepted for the passenger. With the same comfort level reduction, traditional tilting technology could achieve the same speed performances as MDS vehicles.

MDS, on the other hand, because of their assumed low weight and/or due to distributed forces on infrastructure instead of concentrated loads (see D8.1), could be useful to reduce track maintenance, as the lateral forces transmitted would be proportionally lower, compared to maintaining the track to allow traditional tilting trains travelling at the same speed.

The points developed in this paragraph should be verified in a dedicated subsequent stage of MDS system development, as technological solutions could be envisaged to keep under control the described phenomena. More information about this topic with reference to other studies and the TransRapid Design Manual approved by EBA are reported in D7.2.

6.3 General criteria to quantify whether and when maglev-derived systems could lead to non-marginal benefits

According to the analysis in the chapter before, some criteria are here stated to detect geographically the situations where the three identified MDS could lead to non-marginal benefits. Incline pushers could give place to significant benefits for railway undertakers along the TEN-T network where there are gradients that require a second traction unit, considering that even on 12.5‰ gradients dual traction is usually necessary.

In relation to establish choices of new infrastructure, priority should be given to situations where such a choice has not been made, and in particular to situations where there are important or orographic differences between freight poles of interest, so scenarios involving the construction of base tunnels cannot be decisive.

The other two could be useful only in situations where tilting trains are used and where there are no plans to build alternative more linear and non-twisting itineraries, for the sole purpose of maintenance reduction if the MDS system proves to be convenient from this point of view.

7 High-level evaluation of cost-benefits

The potential benefits of hybrid MDS coexisting with the current European railway network, have been explored extensively in previous analyses. The cost-benefit analysis (CBA) conducted in Deliverable 7.3 highlights that maglev-derived systems can offer significant economic advantages when implemented under specific conditions, enhancing MDS potentialities. This chapter aims to evaluate these benefits at a high level, considering both greenfield and brownfield projects, and the overarching impact on the European railway infrastructure and network.

In greenfield projects, where new railway lines with MDS are constructed, the implementation of these technologies can provide substantial economic benefits. The primary advantages stem from the following factors:

- **Increased performance indicators**: MDS technology allows for higher speeds and more efficient train operations. This can lead to a reduction in travel time, which is a significant benefit for both passenger and freight services, thanks to higher acceleration rates due to friction reduction.
- **Reduction in Civil Engineering Costs**: One of the major advantages of MDS is their ability to operate independently of traditional wheel-rail adhesion. This can lead to optimized civil engineering works, such as lighter and less excavations, reduced need for extensive tunnels, and viaducts, thus lowering overall construction costs.
- **Electrification**: MDS present and alternative to traditional upgrade solutions, such as catenary, allowing to facilitate the electrification of lines that would otherwise be difficult to electrify due to the possible interference with cranes and other logistic operations, and gauge limitations where narrow tunnels and bridges are located or due to landscape preservation constraints on historical lines.
- **Enhanced Infrastructure Reliability**: MDS are less susceptible to wear and tear compared to conventional rail systems. This could lead to lower maintenance costs and increased reliability, which in turn reduces operational disruptions and improves service continuity;
- **Automation**: especially in terminal and shunting areas, MDS can provide efficient automation of operations, allowing for increased capacity of the terminal and reduced operational costs; no distinctive benefit related to automation can be envisaged for mainline application of MDS in comparison to railway automation.

These factors collectively contribute to a high benefit-cost ratio for MDS in greenfield projects, often exceeding the value of 1, indicating a favourable economic impact.

In addition to the benefits above listed, the implementation of MDS systems in brownfield projects, where existing railway lines are upgraded or coexist with new technology, presents a different set of possible challenges and considerations:

- **Compatibility and Integration**: Integrating MDS systems with existing railway infrastructure can be complex and costly. Ensuring compatibility with current signalling, control, existing infrastructural components (e.g., switches), and power systems, requires further analyses and significant investment.
- **Performance Metrics**: In scenarios where existing systems already meet the required performance standards, the incremental benefits of switching to MDS may not justify the high costs. The benefit-cost ratio, while positive, may not always surpass the threshold of 1, indicating that the economic benefits do not outweigh the costs.

The strategic implementation of maglev-derived systems in Europe could lead to several high-level benefits, aligning with broader transportation and economic goals:

- **Sustainable Development**: MDS support sustainable development by reducing energy consumption and greenhouse gas emissions due to their higher efficiency and lower maintenance needs.
- **Regional Connectivity**: Enhanced speed and reliability of MDS can improve regional connectivity, facilitating economic integration and growth across European countries. This is particularly beneficial for the trans-European transport network (TEN-T) corridors.
- **Innovation and Competitiveness**: Adopting cutting-edge MDS technologies can position Europe as a leader in railway innovation, boosting the competitiveness of the European railway industry on a global scale.

The high-level evaluation of the benefits of an MDS coexisting railway network in Europe reveals a wide range of results. While greenfield projects present a clear case for the economic advantages of MDS systems, brownfield projects require careful consideration of integration costs and incremental benefits. Overall, the strategic deployment of MDS technology holds the potential to enhance the efficiency, sustainability, and competitiveness of the European railway network, provided that it is implemented in scenarios where it can deliver the highest value addition.

7.1 General principles

The Cost-Benefit Analysis (CBA) is a technique designed to compare the efficiency of different alternatives (such as public policies, projects, regulatory interventions, etc.) that can be used in a given context, to achieve a well-defined objective. It evaluates whether the benefits that an alternative can bring to the community as a whole (social benefits) are greater than the associated costs (social costs). A project is deemed desirable if the comparison between total benefits and total costs (B/C) shows a predominance of the former, which means that the

community as a whole receives a net benefit from its implementation. When there are multiple intervention alternatives, the option where the benefits most significantly exceed the costs is preferred.
The logic behind the analysis is that a community's resources are limited, and policymakers must allocate them to interventions that maximize the net benefit to society. The result allows for the verification of whether the project is preferable to maintaining the current situation (status quo), thus leading to an implicit comparison between the project scenario and the reference scenario (the future scenario, excluding the intervention).

The cost-benefit analysis for the project in question follows this approach with an "incremental" methodological approach to compare the two scenarios: the "Reference Scenario" (without the intervention) and the "Project Scenario" (with the intervention), by quantifying the costs and benefits resulting from the intervention itself.
Generally, CBA can take different perspectives, which in the technique translate into different approaches depending on the objective to be achieved and the reference parameters. The evaluation procedure used to identify the summary results necessary to determine the preferred scenario is the Economic analysis, to evaluate economic and social benefits and costs.
The profitability indicators derived from the analyses are:

- NPV (Net Present Value).
- IRR (Internal Rate of Return).
- B/C (Benefit-Cost Ratio).

7.2 Cost-Benefit Analysis per step

The Cost-Benefit Analysis (CBA) was conducted through a series of key steps:

1. Defining both the Reference and Project scenarios for each use case scenario.

2. Establishing the time horizon for the analysis and identifying the project's activation year.

3.Determining the discount rate and economic conversion factors to be applied in the analysis.

4. Estimating CAPEX (Capital Expenditures) and OPEX (Operational Expenditures), including investment, maintenance, and operation costs.

5. Assessing both direct benefits and indirect benefits (externalities).

6. Calculating the economic performance indicators.

7.3 High-level evaluation on the European benefits of an MDS coexisting railway network

Large-scale implementation of MDS technology would open up new market opportunities, such as better and faster international connections or upgrading regional and secondary lines connections, avoiding the need to build new dedicated lines, which would otherwise be necessary. These opportunities coincide with the European goal of reducing CO2 emissions in transportation, creating an opportunity to use faster trains with maglev-derived technology to connect cities, instead of planes, expanding the area of convenience between rail travel versus air travel. Of course, capacity assessment must be done on a case-by-case basis to ensure that MDS traffic and standard rail traffic can coexist in this supply model. The share of capacity lost due to heterotachia between systems could paradoxically lead to the non-viability of mixed traffic in coexistence on the line, especially in congested situations, in favour of a homotachia-based supply model, with consequent lowering of speeds. This may occur especially approaching to large nodes, where there is a condensation of traffic due to the presence of commuter services with frequent stops.

On the other hand, a migration to the MDS system of current services would be a step toward traffic homologation with consequent benefits.

In a long-term evolutionary vision, the application of this technology could set the conditions for the building of new lines with more economical routes to serve areas now outside the rail network and improve the modal share in favour of mass transit. Construction of new lines with MDS technology could lead to substantial benefits even in areas of the world where railways are undeveloped, but there is demand for mobility in a growing economic scenario, for example, in South America, or some areas of Africa.

8 Outlook on a global perspective

8.1 Existing maglev applications today in operation in the world

Today, several maglev systems are already in commercial operation worldwide. Even though none of them operates in interoperability with existing railway, as assumed in MaDe4Rail project, interesting insights can be derived. For a complete overview on these systems, please refer to deliverable D2.1.

Particularly interesting, due to their similarities with the selected use case, are the Vancouver Skytrain (Canada), the Shanghai Airport Maglev Line (China) and the Chuo Shinkansen Tokyo-Nagoya line (Japan), which is under construction.

Vancouver SkyTrain bears similarity to Use Case 1 (incline pusher). The Vancouver SkyTrain is known for its ability to handle relatively steep inclines compared to many other transit systems, thanks to its advanced propulsion technology. The use of Linear Induction Motors (LIM) allows the SkyTrain to effectively manage these inclines without significant loss of performance. Here are some key points about inclines and alignment in the SkyTrain system:

Capabilities and Design

- Steep Gradients: The SkyTrain can navigate steep gradients of up to 6%, which is higher than what many traditional rail systems can handle. This capability is particularly beneficial in the hilly and varied terrain of the Vancouver metropolitan area.
- Elevated and Underground Sections: The alignment includes a mix of elevated tracks, at-grade sections, and underground tunnels. Each section is designed to optimize travel efficiency and integrate smoothly with the urban landscape.

Examples of inclines:

- Expo Line: This line includes several elevated sections that transition smoothly from flat to steep areas, particularly as it moves from the city center to suburban regions.
- Millennium Line: The route also manages various elevations, especially notable in areas where it traverses through and around natural and urban obstacles.
- Canada Line: This line includes significant underground segments, especially in Downtown Vancouver, which emerge to elevated tracks as it moves towards Richmond and the airport.

However, the Skytrain is a closed environment, non-compatible with classic railways, also used for passenger services, whereas MaDe4Rail is focusing on freight trains for the incline case.

Shanghai and Tokyo-Nagoya high-speed maglev lines carry instead some resemblances to use case 2 and 3, as their goal is to provide a faster service than high-speed lines on traditional rail. The Shanghai and Tokyo-Nagoya high-speed maglev lines share several similarities: both use magnetic levitation (maglev) technology, which allows trains to float above the tracks and eliminates friction, enabling higher speeds and smoother rides. Both lines are designed to achieve very high speeds. The Shanghai Maglev can reach speeds of up to 431 km/h (268 mph), while the planned Tokyo-Nagoya line aims to reach speeds of around 500 km/h (311 mph). Both projects aim to significantly reduce travel time between major cities. The Shanghai Maglev connects the city center with Pudong International Airport in about 7 minutes, whereas the Tokyo-Nagoya line is expected to reduce the travel time between these cities to approximately 40 minutes. Both lines involve advanced infrastructure engineering, including elevated tracks and specially designed stations to accommodate the unique requirements of maglev technology. Both lines are expected to have substantial economic and urban development impacts, improving connectivity, and fostering economic growth in the regions they serve. These similarities highlight the shared goals of utilising maglev technology to enhance transportation efficiency and drive regional development.

8.2 Outlook on global perspective for MDS systems under MaDe4Rail approach – use case 1

Incline pusher could have a widespread diffusion globally, wherever steep incline with heavy hauls to transport exist. If its development leads to relatively simple devices, it could be employed also in developing countries on lines with relatively weak technological standards, being appliable even on non-electrified lines. Where substantial differences in height need to be climbed, its adoption could avoid long alignments, which are expensive for construction, maintenance and operation, permitting shorter and steeper routes.

8.3 Outlook on global perspective for MDS systems under MaDe4Rail approach – use cases 2 and 3

The introduction of a new technological standard always has to compete with the possibility of upgrading existing technologies, which have the incumbent's advantage about expertise, the possibility to proceed with incremental enhancements, advanced compatibility and continuity with all previous investments. This concerns both the hardware side, with the possibility to operate new infrastructures without changing all the rolling stock or to use new rolling stock on existing infrastructure, and, and the soft-skills side, including the knowledge and training necessary to manage all aspects of a transportation system.

On the other hand, if the gap from the existing railway services to the top-quality rail systems is too wide, the effort required to upgrade hard and soft investments from the existing system to an advanced high-speed system is essentially the same as introducing a brand-new technology. Therefore, the incumbent's traditional railway advantage can be negligible compared to MDS.

In most countries, a rail system was developed in XIX and early XX century. In many non-European countries, it has been completely dismantled or it operates only for minor freight or long-distance slow services. In these situations, the desire to introduce a modern, reliable, and highly performant intercity transportation system should push for serious consideration of adopting a pure MDS, as the new system will likely have no or very few overlaps with the existing ones.

On the other hand, major countries that developed substantial rail system, which were then progressively abandoned due to the rise of private traffic, losing most intercity and freight traffic, exist. Several examples, especially in South America (Brazil, Argentina, Chile), show this trend. Passenger traffic survived as suburban systems around the main metropolises, where the availability of alignments and stations in the heart of the main cities has justified the use of railway systems as proximity public transport. Outside cities, alignments and infrastructure conditions are not fit for modern passenger traffic. Cities are usually more spaced than in the European or Asian reference contexts, so new high-speed traditional lines requiring huge investments have never been constructed. For example, the Rio de Janeiro – Sao Paulo route should be considered, that connects a city with more than 12 million inhabitants to one with more than 6 million, spaced by the ideal high-speed rail distance of 350-400 km and with no existing passenger train connection, despite one of the most intense air traffic in the world.

A MDS system compatible with rail infrastructure, as in the MaDe4Rail approach, could benefit of the traditional rail routes and stations to enter the cities, avoiding the important cost of infrastructure in dense urban areas, and then rely on a MDS specialized alignment outside the cities, likely lighter and therefore less expensive than a traditional rail high-speed line.

A similar approach could be applied also to the United States and Canada, the only G7 countries that failed to realize an effective high-speed system, where non-urban railway lines are mostly used exclusively or almost exclusively for freight traffic, and the maintenance standards are consequently lower.

There are other situations, like in South Africa and Australia, where important short-distance services around the main cities are coupled with an important network used mainly by freight traffic with some intercity services. An important upgrade of speed and quality should carefully consider the possibility to adopt the same approach recommended for South America.

Other Asian countries, such as China, Japan and Saudi Arabia, have already made massive investments to develop an extensive network of traditional high-speed rail lines. Even though two maglev examples in operation come from China and Japan, competition with traditional systems appears challenging. Countries like India and Pakistan, whose networks are highly utilised for passenger traffic and which have no high-speed lines but services with good performances (160 km/h in India), have a distinctly widespread network, with cross-countries connections, reducing the appeal for a new system in the of the upgrade of single rail sections.

Therefore, the introduction of MDS rail-compatible systems to upgrade the networks to high-speed and high-performance standards sounds very appealing in the countries that have conserved XIX/early XX-century passenger alignments in urban areas for short-distance connections, whereas the intercity traffic has been lost. In these cases, the construction of an intercity pure-MDS high-speed line could benefit from cutting costs by sharing urban infrastructure with existing proximity services.

9 Industrial Roadmap

This chapter presents a preliminary industrial roadmap for the development of MDS technologies in Europe. The industrial roadmap outlines a strategy to develop MDS technologies for railway applications, based on the 3 systems configurations that were explored in-depth within the MaDe4Rail project. The roadmap aims to develop the different maglev-derived solutions, through research, modelling, development, engineering, system integration, testing, and validation activities. This chapter provides an overview of the key steps identified, necessary to increase the TRL towards commercial readiness for maglev-derived systems.

The chapter is organized around the technical open points – identified within the MaDe4Rail project for integrating these technologies into existing railway infrastructure – and technical enablers necessary for their implementation, as well as the key steps identified to develop each one of them, aiming for the commercial maturity of MDS. Each chapter then outlines the roadmap, starting with detailed descriptions of the research and innovation activities, followed by the engineering and development of the identified solutions. This process culminates in the final phase of modelling, testing, and validation, leading to full demonstrators that support the commercial maturity of the technologies. The roadmap also addresses the need for regulation and standardization of the new solutions to ensure their viability within the European railway landscape. Additionally, it highlights the hazards associated with the new technologies, as identified within WP3, with the goal of reducing these risks during development.

The roadmap is structured to systematically address technical challenges and leverage the parallel development of the identified enablers through a series of activities, progressing from research and development to full-scale demonstration and commercial deployment. Each phase of the roadmap is designed to increase the Technology Readiness Levels (TRLs) of MDS, ensuring they meet the requirements for integration into existing railway infrastructure.

It has been verified that some components of the technologies are still to be developed, especially with regard to the need for compatibility with the existing network (see D6.1). Below are those with a low TRL level:

- **Infrastructure**
  - Guideway
    - Upgraded Conventional railway infrastructure: 3-6
  - Switches
    - Upgraded Conventional railway infrastructure: 2
  - Propulsion – Infrastructure Part
    - U-LIM: 6
    - 3-Phase winding without core: 6
  - Substructure
    - Railway Slub Truck: 6

- **Vehicle**
  - Structure
    - Structure for Hybrid-MDS Interoperable with infrastructure: 4-5
    - Structure for rail vehicle upgraded with MDS: 2-6
  - Propulsion Vehicle Part
    - LSM for Hybrid MDS: 6
    - Lateral wheel based / Propulsion braking: 5-6
    - EDW: 6-7
  - Suspension
    - EDS: 5-8
    - EDS based on permanent magnets: 6
    - Ferromagnetic passive levitation technology: 6-7
    - Air levitation: 5-8
  - Guidance
    - Lateral wheels or traditional bogie guidance: 6
    - Air levitation technology-based guidance: 5-6
  - Braking
    - Electrodynamic wheel brakes: 6-7
    - Lateral wheel based / Propulsion braking: 2-6
- **Command and Control**
  - TMS
    - Virtual Coupling: 4
  - Communication
    - Future Communication System used in railway systems: 6

The development of components and technologies for each of the 3 configurations should be leveraged to benefit other configurations, as many components are shared completely or partially. Focusing on common elements such as propulsion systems, CCS, and energy storage solutions, advancements and insights can be applied across the different configurations. This approach speeds up the development process, ensuring cost-effectiveness and consistency in performance, reliability and scalability across different MDS configurations.

9.1 Technical Open Points

Maglev-derived technologies could provide a cost-effective solution to improve existing railway systems. However, their integration into existing railway infrastructure presents several technical challenges. The MaDe4Rail project has identified the critical technical open points that must be addressed to ensure the successful deployment of MDS. These include:

- **Geometric compatibility**: In order to introduce MDS technologies into existing railway infrastructure, components must adhere to specific geometric clearance requirements and ensure that there is no physical interference between the linear motor, levitation, and guidance technologies (both on board and on the ground), and trackside equipment such as balises, power supply cables for linear motor, rail fastening, switches and check rails, and level crossings. It is crucial that the MDS technologies, whether installed trackside or onboard. The dynamic gauge refers to the three-dimensional space around a train that must remain clear of obstructions to ensure safe passage at all speeds and under all conditions, accounting for factors such as vehicle sway, track curvature, and loading conditions. Maintaining the integrity of the dynamic gauge is essential for the safe and efficient operation of trains and MDS pods/vehicles. Any intrusion into this space by the new components could result in physical interference with trackside equipment, leading to potential malfunctions or safety hazards. Therefore, careful consideration must be given to the design and placement of MDS elements, especially considering tolerances and exact shape of the existing components, to ensure they remain within the predefined geometric limits and do not encroach upon the dynamic gauge, thereby avoiding any unintended interactions with critical trackside systems. This requires a detailed assessment and precise engineering to validate that all MDS components are compatible with the existing railway infrastructure without compromising the operational safety or functionality of the railway line. On this matter, a proper alignment of the sliders with the rail is crucial, so regular inspection must be considered to ensure geometrical compatibility.
- **Electromagnetic compatibility**: Certain components of the signalling system, such as the BTM-EUROBALISE, Radio Communication System, On-board Train Interface, and Train Detection System (TDS) using axle counters or track circuits, may experience side effects or malfunctions due to the introduction of electromagnetic fields generated by the linear motor and/or levitation and guidance components (including those generated by passing MDS vehicles). For instance, preliminary calculations indicate that the Linear Synchronous Motor generates a magnetic field over 400 times stronger than the limit specified in Eurobalise regulations during transit. This electromagnetic field could potentially affect the balise in two ways: it might damage the balise's components, rendering it unusable, or it might interfere with the balise's operation without causing physical damage, preventing it from transmitting data. To mitigate these risks, a gap may need to be created in the linear motor installed on the track to avoid conflicts with the balise, though this solution requires further research and validation. Additionally, the impact of the electromagnetic field on balises installed on

adjacent tracks should also be investigated.

A second source of electromagnetic interference arises from the levitation/guidance systems. The magnetic field generated by the magnetic sliders is confined between the sliders and the rail. The introduction of levitation components both on board and on the track could generate eddy currents, potentially affecting the infrastructure. This analysis can provide additional feedback on the already discussed geometrical compatibility, through the correct components positioning to reduce the potential electromagnetic interference through an iterative approach.

- **Intelockings, CCS and traffic management systems**: Current interlocking systems are not compatible with the MDS configurations analysed due to the integration of the linear motor and virtual balises in the CCS as a tool to identify the position of the MDS vehicle (synchronous linear motor case) to manage movement dynamics and train interactions. Key challenges include the need to adapt command, control and signalling systems and protocols. To address specific challenges posed by the mixed use of the infrastructure by rail trains and MDS vehicles, it is crucial to develop also traffic management systems based on advanced technologies, such as distributed control and artificial intelligence algorithms, which can ensure optimized trajectory management and prompt reactions to unforeseen events. Additionally, integrating enhanced communication systems between trains and infrastructure can further enhance safety and operational efficiency, enabling continuous cooperation among the various elements of the system.

  Future studies should focus on the design and testing of interlocking prototypes specifically developed for mixed rail-MDS operations, analysing performance in real operational scenarios. Those elements will affect the transport capacity of the line.
- **Track Infrastructure adaptation**: The introduction of MDS technologies might require significant adjustments to track infrastructure elements, especially sleepers, switches, and related components. The MDS generates new forces, such as axle loads and linear/track loads from the linear motor, which current track designs are not equipped to handle, especially longitudinal forces induced by the linear motor. Sleepers may need to be redesigned to support the magnetic components, as the existing ones might not provide the necessary fixations or could suffer from displacement due to the new forces. The integration of the levitation system further complicates the design of the infrastructure, requiring precise alignment and stability that current infrastructure might not meet. Adapting the existing infrastructure to accommodate these components is critical to ensure that MDS can be safely and efficiently implemented, so further analyses on new loads impact on existing rails will be necessary.

- **Existing switches**, in particular, present a challenge because the space required for installing linear motors and levitation systems could interfere with their operation. Potential solutions could involve specially designed switches or interruptions in the linear motor and levitation/guidance systems installation at these points with consequent need for adequate technical solutions on-board (e.g. length of the linear motor on board exceeding the interruption on the track, adoption of motorized conventional boogies, etc.)..
- **Magnetic Levitation Switches**: Magnetic levitation switches are crucial components in magnetic levitation (maglev) railway vehicles, as they play a vital role in ensuring the smooth and efficient operation of the MDS. These switches are responsible for controlling the magnetic fields that enable levitation, guidance, and propulsion of the vehicle without any physical contact with the rails. Additionally, the accurate functioning of these switches is critical in facilitating rapid acceleration and deceleration, smooth transitions between different track segments, and effective navigation through complex networks. The development of magnetic levitation switches could make the MDS pod/vehicle non dependant on conventional bogies on board, thus making the vehicle lighter.
- **Impact on maintenance**: The installation of linear motors and levitation systems between the rails will significantly alter the traditional track maintenance regimes. It will require a thorough re-evaluation of current maintenance procedures. Possible solutions include a remotion of the linear motor during maintenance operations, leading to an increase in time and costs, or a specific design of the linear motor to resist these kinds of operations, leading to an increase of complexity in the linear motor design.

  Another issue regards the frequency of the maintenance task required on the infrastructure. MDS technologies, including the linear motor and levitation components, may require more stringent tolerance to be operated than the existing infrastructure. To ensure the performances and safety requirements for the operation of the MDS systems, maintenance regimes need to be defined for the added MDS components on the vehicle and the infrastructure.
- **Maximum speeds and accelerations on curves**: MDS technologies show the potential to increase speed on existing routes, including those with irregular and curved layouts. The speed on curves in rail systems is fundamentally based on balancing safety, passenger comfort, and infrastructure constraints. When trains navigate curves, the forces acting on them can cause discomfort or even derailment if not properly managed. To mitigate this, railways use techniques like cant (banking the track) and tilting mechanisms in trains. However, tilting angles must be carefully

controlled, as excessive tilt can lead to passenger discomfort. The calculation of maximum allowable speeds on curves takes into account the curve radius, built-in cant, and additional cant from tilting systems, all while adhering to safety regulations that limit the maximum cant and cant deficiency (the difference between actual cant and the ideal cant for a given speed).

The speed increase on curves with MDS technologies is approached through increasing tilts using the levitation systems or by modifying the built-in cant with infrastructural upgrades (that would affect only the levitating vehicles). However, these solutions need to be further studied and validated, considering safety and passenger comfort. In the same way, longitudinal accelerations have to be further evaluated.

- **Electrical Substation**: The development of new electrical substations for MDS is crucial to ensure the efficiency and reliability of these technologies. Current substations, primarily designed for conventional railway networks (mostly in DC), present discrepancies concerning the specific energy requirements of maglev systems: the latter require the integration on inverters and switches to manage the synchronous linear motor as well as continuous and highly modulable power supply, capable of handling not only demand peaks during acceleration and braking but also ensuring a stable supply for maintaining magnetic levitation.

  The challenges associated with this discrepancy include the need for optimized energy flow management that can guarantee high power availability in real time. Additionally, integrating renewable energy sources, such as solar and wind, presents further challenges related to production variability and the necessity for efficient energy storage systems. Another critical issue is the capability of existing infrastructure to support such innovative technologies, which often feature high energy requirements and non-linear demand patterns. To address these challenges, it is essential to develop innovative solutions, such as modular substations that can be easily scaled and adapted to the specific needs of MDS. The implementation of energy storage systems, such as long-duration batteries, could also help smooth out demand peaks, thereby ensuring a continuous and reliable power supply.
- **Coexistence of Sliders and Traditional Bogies on MDS Vehicles**: To ensure hybrid operations, particularly on existing lines without modifying switches or on low-speed segments (e.g., stations), it may be necessary for MDS vehicles to be equipped with both sliders and traditional bogies.

  In an MDS vehicle, the introduction of new onboard sliders poses specific challenges with traditional bogies due to the fundamental differences in how these components interact with the track and manage vehicle dynamics. Traditional bogies, which are wheel-based, rely on direct mechanical contact with the rails to support and guide the vehicle. In contrast, onboard sliders in an MDS use magnetic forces to achieve levitation, eliminating the need for direct contact.

Bogies are designed with suspension systems that absorb shocks and vibrations from the track surface, which is essential for wheel-rail contact systems. Onboard sliders, however, are designed to work with magnetic suspension that stabilizes the vehicle using magnetic fields. The switch from magnetic suspension to mechanical wheels and vice versa must be made while the vehicle is running to ensure that no additional travel time is incurred due to this operation. The switch between the two systems in motion must guarantee the vehicle's guidance and, therefore, must be developed with stringent safety requirements.

Additionally, combining onboard sliders with traditional bogies adds significant complexity to the vehicle's structure. Furthermore, managing two distinct systems can complicate maintenance, increase the risk of mechanical failure, and elevate operational costs.

Finally, traditional bogies and onboard sliders have different requirements for acceleration and braking. Trying to operate both systems on the same vehicle can result in conflicts in speed control and braking dynamics, affecting the smoothness of the ride and potentially leading to safety concerns.

- **Identification of the linear motor configuration:** the choice between the synchronous linear motor and the ULIM entails different configuration on-board and on the ground shifting the technological complexity between the vehicle and the infrastructure. A 360° evaluation should be made to assess the best configuration.
- **Air levitation technologies**: Air levitation technology could potentially enhance the efficiency and performance of MDS, offering some benefits, such as a significant reduction in friction with lower energy consumption and reduced maintenance requirements for infrastructure. However, at the current stage of technological readiness, it does not show significant advantages when compared to other MDS configurations, makes this technology not favourable as an alternative for the analysed use cases. Further developing this concept is needed to help having a better evaluation of the technology itself and assessing its technical and economic viability.

Further elements are provided in detail in D8.1.

9.1.1 Roadmap for the resolution of technical open points towards the development of MDS technologies

9.1.1.1 Advanced Design and R&I

To fully address the Technical Open Points (TOPs) surrounding maglev-derived systems (MDS) integration into existing railway infrastructure in a coherent way, a comprehensive research and innovation (R&I) strategy is essential starting from detailed design of the transport system to allow for a systemic evaluation of the best MDS configuration.

This approach not only aims to provide technical solutions to the identified challenges and TOP taking into account their interdependences, but also to advance the Technology Readiness Levels (TRLs) of MDS technologies, ensuring their compatibility with current rail systems.

Collaborative R&I projects, involving diverse stakeholders such as railway operators, academic researchers, technology developers, engineering firms, and regulatory bodies, are crucial for resolving these issues efficiently and safely. Such collaboration, fostered in environments like EU-Rail, provides an ideal platform to drive these innovations forward. Multidisciplinary collaborative research plays a pivotal role in addressing these complex technical challenges. The railway sector, along with academic institutions, tech developers, engineering firms, and regulatory bodies, brings together a diverse range of expertise and perspectives that are essential for overcoming the TOPs.

9.1.1.2 Modelling and Simulation

Modelling, testing, and validation activities are crucial to evaluate engineering solutions and approaches to ensure the safety and performance of MDS, their components/technologies and subsystems. This approach allows defining the most effective ways to find solutions through modelling and simulations, all before proceeding to testing and demonstrators, ensuring cost efficiency.

For **geometric compatibility**, simulation models can be developed to ensure MDS components fit within the dynamic gauge and avoid interference with trackside equipment, using real-time dynamic simulations that account for vehicle sway, track curvature, and varying loads. Similarly, for **electromagnetic compatibility**, electromagnetic field simulations can assess the impact of MDS components on signalling systems, such as EUROBALISE, and optimize the positioning of linear motors and levitation elements to minimize interference. **Infrastructure adaptation** simulations could evaluate new track designs and sleeper modifications, testing the structural integrity and operational stability of MDS systems under various forces and conditions. Moreover, simulations for **speed optimization on curves** would allow the analysis of tilting mechanisms and dynamic stability, predicting performance and safety limits on different track geometries. Finally, simulations for **maintenance impact** could model the wear and tear on components, helping to predict maintenance intervals and design more resilient systems. These **multidisciplinary simulation models** are essential tools for validating solutions before physical testing, significantly reducing risk and development time while enhancing precision in solving complex rail integration challenges.
Some identified activities for this phase may include:

- **Comprehensive technologies/components modelling:** Create detailed models to test specific components and their performance within the integration with existing railway infrastructure and other technologies.
- **Operational Modelling:** Develop models to simulate and optimize operations under various scenarios to ensure efficiency and reliability.
- **Simulation based on safety, integration, and compatibility aspects:** Create virtual environments to test MDS for potential safety hazards, ensuring they operate without causing harm to passengers or infrastructure. They also evaluate how well these technologies integrate with existing transportation networks and infrastructure, ensuring smooth and efficient functionality.

9.1.1.3 Testing in Relevant Environment of selected technologies

Testing key and selected elements/technologies in a relevant environment is crucial for validating both Research and Innovation (R&I) activities, as well as modelling and simulation results. This process allows for the evaluation of the performance, safety, and reliability of MDS components under real-world conditions, ensuring that they conform to the required standards and specifications for safe railway integration.

By simulating operational scenarios in a controlled environment, potential issues such as geometric or electromagnetic incompatibilities can be identified early, allowing for the optimization of designs and minimizing the risk of costly adjustments during later stages.

9.1.1.4 Update MaDe4Rail Results

The MaDe4Rail results will be updated based on new knowledge obtained from the previous steps.

At least before entering the engineering and development phase of the selected technologies and subsystems – possibly also at previous steps - an update of the hazard log and risk analysis have to be performed. This will ensure that all hazards have been assessed and mitigation measures have been implemented in the design of the MDS systems.

In addition, also technical and socio-economic feasibility analysis have to be updated to ensure that the project remains aligned to the use cases that are more attractive to the market.

9.1.1.5 Design and Planning of MVP Demonstrator

The aim of this phase is to achieve a comprehensive system design for a Minimum Viable Product (MVP) demonstrator, that captures all essential functionalities and performance of the complete MDS system (full scale). This includes the development of designs for various subsystems, which will progressively integrate more complex elements of the MDS solution while ensuring compatibility with existing railway infrastructure. The design phase will focus on ensuring that each component, from the linear motors to levitation systems, works together seamlessly to meet the technical, safety, and operational requirements. By laying the groundwork for future testing and implementation, this phase ensures that the MVP demonstrator is fully equipped to validate the system's capabilities in a relevant environment, paving the way for subsequent testing and optimization. This action is also vital in order to understand the financial requirement and all other resources needed in order to deliver a full scale demonstrator.

9.1.1.6 Engineering and Development of Solutions

Engineering and development of solutions, based on the outcomes of the previous steps, allows to enhance the Technology Readiness Level (TRL) of less mature technologies coherently with the overall solution adopted. This approach ensures a holistic view, addressing technical, operational, and economic aspects.

By systematically evaluating and iterating on prototypes, simulations, and real-world testing, it can be possible to identify and mitigate risks, optimize performance, and accelerate the maturation process. The aim of this phase is to facilitate the transition from conceptual stages to practical, deployable solutions.

9.1.1.7 System integration, testing, and validation

This phase is about system integration, testing and validation of the subsystems towards the development of full-scale demonstrators.

These activities focus on integrating solutions related to individual technologies and components into cohesive subsystems and systems that can be tested/validated. They involve designing and prototyping solutions that address the identified technical open points to enhance system performance.

The essential step will be the construction of a MVP demonstrator along with dedicated tests. A stepwise approach proposed could consider in the first step existing/future dedicated test facilities while in the second step – based on the results – new demonstrators could show the adapted, compliant and resulting new MDS design for European railways, which could then be tested and developed at scale in bigger testing facilities.

Subsequently, implementing pilot projects, such as testing MDS technologies on selected track sections, provides the opportunity to validate the functionality, structural integrity, and performance of components like linear motors, levitation systems, and electromagnetic switches. These tests not only confirm that prototypes meet the operational demands but also help refine the systems for mass deployment by collecting valuable feedback. Pilot projects play a key role in this validation process, acting as a bridge between laboratory and real-world application, ensuring that the MDS technologies are fully optimized and ready for safe, efficient integration into existing railway infrastructure.

9.2 Technical Enablers

Various technical enablers play a crucial role on the development and implementation of MDS solutions:

- **Automatic Train Operations (ATO):** Refer to the use of automated systems to control train movements, enhancing efficiency, safety, and reliability in rail transport. ATO systems can operate at various levels of automation, from driver assistance to fully autonomous operations. These systems manage tasks such as speed regulation, stopping at stations, and ensuring optimal train spacing.
- **Traffic Management System (TMS):** A framework designed to enhance the efficiency and safety of train operations. It integrates advanced technologies such as signalling systems, real-time monitoring, and automated control to manage train movements and schedules. By analysing data on train positions, speeds, and track conditions, TMS can optimize train routing, reduce delays, and prevent collisions.
- **Virtual Coupling:** Allow trains to travel closely together, almost as if they are physically coupled, without the need for traditional mechanical connections. This system uses advanced communication and control technologies to synchronize the movements of multiple trains, maintaining safe distances and speeds.
- **Secure Communication Systems:** Use encrypted data transmission to protect sensitive information from unauthorized access and cyber threats. By employing advanced encryption protocols and real-time monitoring, they ensure that communication between trains, control centres, and trackside equipment remains confidential and tamper-proof.
- **Cybersecurity Measures:** Protect against cyber threats and ensure the safe operation of rail systems. These measures include implementing robust firewalls, intrusion detection systems, and regular security audits to identify and mitigate vulnerabilities. Additionally, employee training on cybersecurity best practices and the use of multi-factor authentication help safeguard sensitive data and communication channels.
- **Sustainable and Long-Duration Energy Storage Systems:** Enhance energy efficiency and reducing carbon emissions. These systems, such as advanced battery technologies and renewable energy integration, enable the storage of excess energy generated during low-demand periods for use during peak times. This not only ensures a reliable power supply but also supports the transition to greener rail operations by minimizing reliance on fossil fuels. New types of storage systems can be considered, with lower costs and higher capacity and performance, better suited to MDS requirements.
- **Regulatory Framework:** Include standards and guidelines for construction, maintenance, and operation of rail systems. It includes regulations on safety protocols, environmental impact assessments, and interoperability requirements to facilitate seamless integration across different regions and technologies.

9.2.1 Roadmap for the development of technical enablers towards the development of MDS technologies

9.2.1.1 Connections with other planned Flagship Projects

Europe's Rail Joint Undertaking (EU-Rail JU) is a collaborative initiative aimed at transforming the European railway system through innovation and integration. It focuses on enhancing the sustainability, efficiency, and competitiveness of rail transport across Europe. The initiative is structured around two main pillars: the System Pillar and the Innovation Pillar, each playing a crucial role in achieving these goals. Additionally, several Flagship Areas and Projects are designed to address specific challenges and opportunities within the railway sector.

- **System Pillar:** The System Pillar acts as the "generic system integrator" for Europe's Rail Joint Undertaking (EU-Rail JU). It aims to deliver a unified operational concept and a functional, safe, and secure system architecture for the European railway network. This includes integrated traffic management, command, control, and signalling systems, ensuring that research and innovation are aligned with commonly agreed customer requirements and operational needs.
- **Innovation Pillar:** The Innovation Pillar steers the research and innovation activities within EU-Rail. It focuses on developing and demonstrating innovative technological and operational solutions. This pillar is organized into several Flagship Areas, each targeting specific aspects of the railway system to enhance sustainability, efficiency, and competitiveness.
- **Flagship Areas/Projects:** Europe's Rail has several Flagship Areas under its Innovation Pillar, each addressing key aspects of the railway system:
  - **FA1 – Network management planning and control & Mobility:** Focuses on mobility and automation.
  - **FA2 – Digital & Automated up to Autonomous Train Operations**: Deals with data-driven operations.
  - **FA3 – Intelligent & Integrated asset management:** Concentrates on infrastructure and asset management.
  - **FA4 – A sustainable and green rail system**: Aims at sustainability and environmental impact.
  - **FA5 – Sustainable Competitive Digital Green Rail Freight Services**: Targets transformation and modernization.
  - **FA6 – Regional rail services / Innovative rail services to revitalise capillary lines**: Looks at future-proofing the railway system.

Another important Flagship Project is the **Future Railway Mobile Communication System (FRMCS) that** is an advanced telecommunication system designed to replace the current GSM-R (Global System for Mobile Communications – Railway). Developed by the International Union of Railways (UIC), FRMCS aims to support the digitalization of rail transport and ensure the continuity of the European Railway Traffic Management System (ERTMS) as GSM-R approaches obsolescence.

These projects collectively aim to deliver interoperable, reliable, efficient, and competitive railway services, contributing to the overall sustainability and energy efficiency of transport and mobility in Europe.

Starting from the integration of the outputs already produced within Europe's Rail, it is crucial to create mutual connections between the activities planned in the future Flagship Projects of the different FA in order to take into account also MDS operations.

Moreover, this integration could be facilitated by the above-mentioned Europe's Rail System Pillar, whose aim is to improve the European railway system by delivering a unified operational concept and a functional, safe, and secure system architecture.

9.2.1.2 Harmonization and integration within System Pillar

Harmonization and integration within the **System Pillar** efforts are critical to establish a unified regulatory and technological framework. This involves aligning standards, protocols, and regulations across regions and stakeholders to ensure interoperability and safety. By fostering collaboration between industry professionals, policy makers, and industry leaders, development processes can be streamlined, redundancies reduced, and adoption of maglev technologies accelerated. This integrated approach not only improves efficiency, but also promotes the innovation in the transportation sector.

In particular, in parallel to the developing of technological solutions, the developing and implementation of regulations and standards is an essential stage in the development of maglev-derived technologies. These frameworks ensure the safety, reliability, and interoperability of the systems, facilitating their integration into existing railway infrastructure.

Some identified activities for this phase include:

- **Identification of safety requirements:** Identify the characteristics of the technologies that needs to be tested in terms of safety and define standard testing procedures to ensure safety and interoperability with the railway system.
- **Regulatory development:** Develop solutions for identified regulatory gaps and requirements, engage with regulatory bodies and certification entities, and develop/adapt draft regulations to cover additional components and operating schemes related specifically to MDS.
- **Standardization efforts:** Introduce MDS requirements to existing standardization bodies, develop interoperability standards and define certification processes to ensure MDS meet all necessary safety and performance criteria.

Harmonization and integration within system pillar tasks will guarantee to achieve a common technological and regulatory framework.

Some of the already identified standardization and regulation specific needs (see D3.2 for reference) include:

- **Electromagnetic compatibility (EMC):** New standards are required to address the electromagnetic interaction between the MDS and existing systems (energy systems, CCS systems, among others). This is crucial to prevent interference that could affect the safety and functionality of both the MDS traditional rail operations.
- **Geometric compatibility:** New standards are required to address the geometrical interaction between the MDS and existing systems (CCS systems, switches, stations, among others).
- **Standards between subsystems:** The integration of MDS into existing rail infrastructure necessitates standardized interfaces between different subsystems, such as propulsion, braking, and communication systems. This ensures that all components work harmoniously without risking system integrity.
- **Safety protocols for new technologies and components:** The deployment of linear motors, levitation/guidance components, as well as other components, require the development of specific safety protocols. These protocols must cover aspects like motor redundancy, magnetic failure modes, emergency landing, and recovery strategies to prevent accidents in case of component failures.

10 Develop a European roadmap

Integrating Maglev-derived systems into European railways presents several concerns, from infrastructure compatibility and electromagnetic compatibility to maintenance adaptations and curve speed considerations. Addressing these challenges requires comprehensive planning, rigorous testing, and close collaboration with regulatory bodies to ensure that the benefits of Maglev technology are realized without compromising the safety and efficiency of existing rail operations, but also to ensure timely introduction of these technology when they are safe, mature and market ready in order to harvest the economic benefits that MDS can generate

As Europe is a railway continent, with a strong industry and a long heritage of railway building, inventions, it should aim to include Maglev features while maintaining the current strength of the railway network. MDS should be seen as an opportunity to overcome some of the historical issues in railways, such as different catenary or signaling systems.

Once the technology is market ready, MDS could be integrated into the European railway network following the steps described in the following paragraphs, taking into consideration its feasibility and scalability.

10.1 Indications from market consultation

To ensure that the use cases developed and evaluated (see chapter 5) match the market requirements, as well as that the developed stepwise approach (see chapter 10.2) will be accepted by the railway industry, the MaDe4Rail project has conducted a broad market consultation.

The project already conducted a series of four workshop in October 2023, where, based on the MDS features, more than 20 use cases were developed (see Deliverable 7.1 for details).
In April 2024, a second market consultation was performed with the aim of:

1. Verifying the identified twenty use cases with the railway industry to gather feedback on them;
2. Verifying the proposed stepwise approach with the railway industry as a base for the MDS roadmap for EU.

In total two workshops were performed with 34 participants from a broad variety of market players. The majority of participants (70%) came directly from the railways, either Infrastructure Managers (56%) or Railway Undertakings (14%). Overall, the whole value chain participated in the workshops. This allowed for a holistic view and a broader discussion with the market.

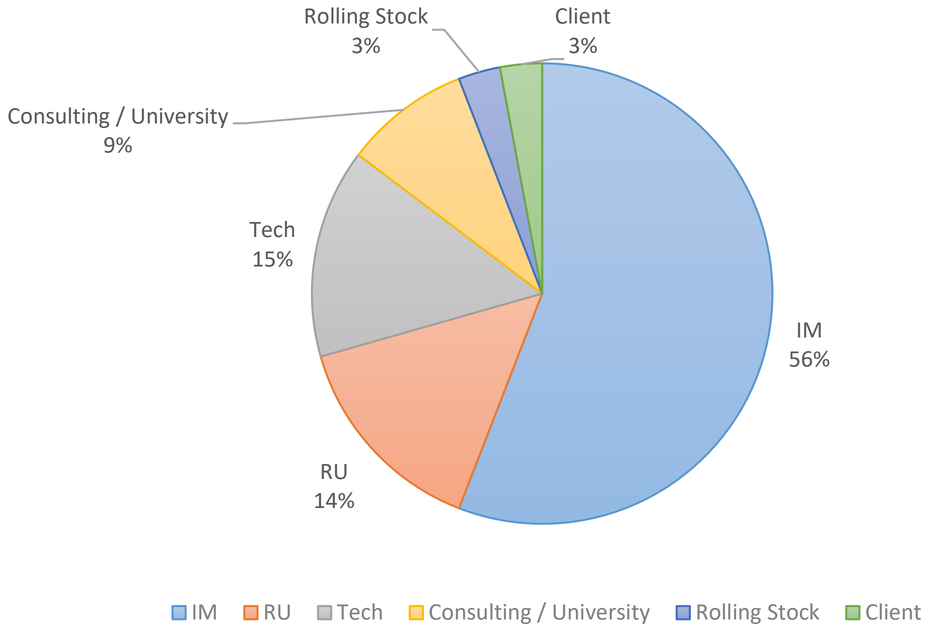

Figure 4: Workshop participants

- 2 workshops carried out in one week,
- More than 30 participants,
- 18 different companies/ organizations involved.

A wide variety of organizations and companies participated:

Figure 5 Involved companies' overview

Covering a broad European perspective:

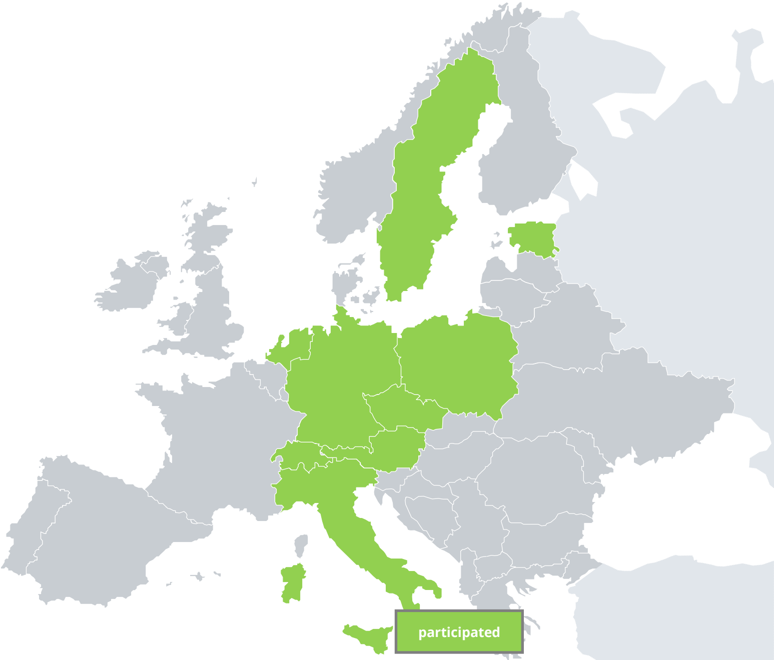

Figure 6 Participants from European countries

The workshop presented an interactive format, based on an interactive whiteboard, allowing participants to comment and vote in parallel in an efficient way.

The participants received an overview presentation of the project and a deep-dive explanation of the identified use cases.

For each use case, participants could comment with digital sticky notes using a colour code: green = positive comment, yellow = add-on to the use case and red = concern.

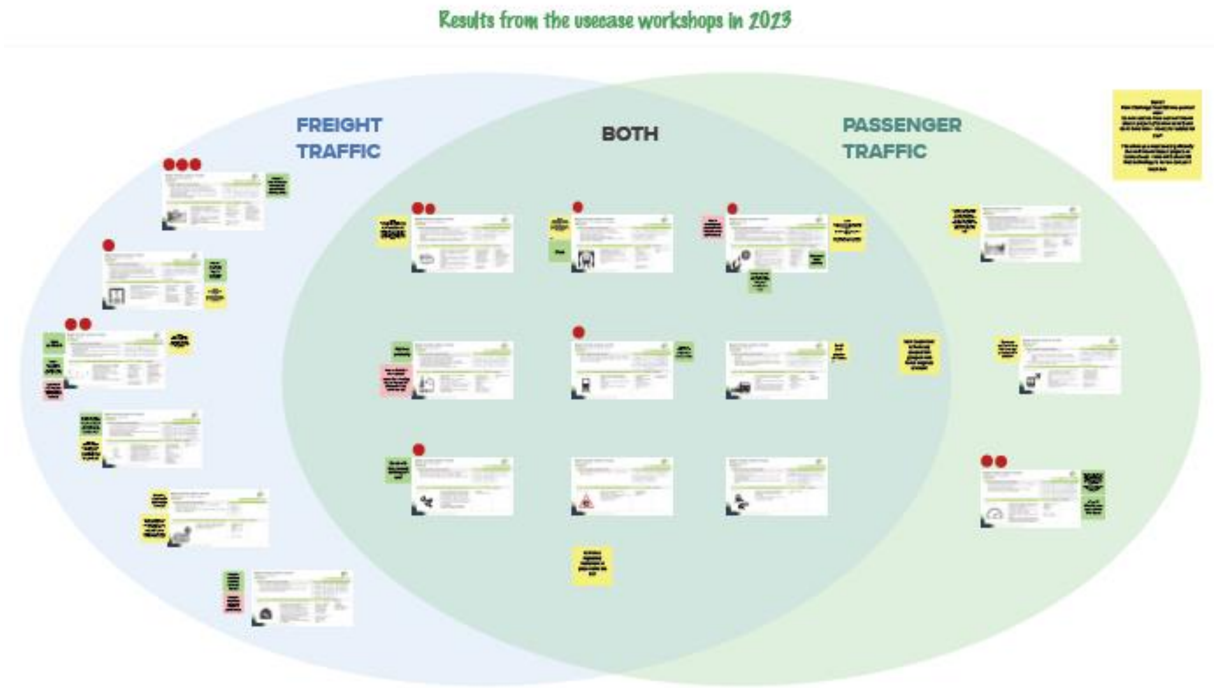

Figure 7 workshop example

In total, the participants where for 90% positively and adding on towards the use cases presented and raised only 10% concerns:

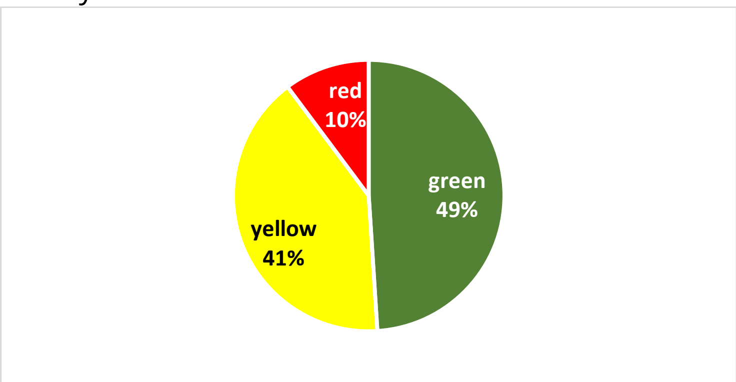

Figure 8 use case review

The comments showed a high level of agreement from the market with the identified use cases, strengthening the project team's positive position towards maglev-derived systems as an add-on technological solution for railways. Summarizing the sentiments raised on the use cases:

Green = positive comment

Efficiency and Operational Improvements:

- A true capacity trigger by adding capabilities to rail, e.g. faster acceleration & deceleration.
- Reduces the need for shunting yards, especially in combination with DAC, making it a good case for real automation.
- Enables tighter scheduling and higher punctuality, allowing for more stops without time losses.
- Small instalments could create big benefits with little interference with the rest of the network, offering an incremental approach, especially in industrial zones like chemistry or steel production, usable with an incremental approach.

Environmental Impact and Infrastructure Efficiency:

- Requires less earthwork during construction.
- Decreases noise pollution, possibly resolving noise issues.
- Lowers impact on wheelsets, reducing maintenance costs.
- Potential reduction of single wagon transport costs.
- Allows for electrification and automation in one solution, could boost electrification of lines, as some "problem areas" might not block classic electrification.
- Possibly usable to bring "higher speeds" to existing non-HSR lines as an upgrade, avoiding heavy HSR infrastructure, big CAPEX, and long deployment times.

Technological Advancements and Enhancements:

- Enabler for other railway technologies, like:
    - Distributed Autonomous Coupling for last-mile services, particularly helpful for single wagon freight transport, also in industrial zones.
    - ETCS L3 moving blocks, where the better train dynamics will be complementing the moving blocks coming from ETCS, resulting in even higher capacity.

By integrating these topics, the advantages of maglev-derived systems technology become more comprehensive, showcasing its potential across various aspects of transportation infrastructure and operations, and the possible market acceptance, clearly understanding the benefits and complementarity of the technologies.

Yellow = add-on to the use case

Main add-ons raised during the workshop:

Infrastructure perspective:

- Limited resources: Infrastructure faces constraints of time and money, prioritizing existing projects over new ideas.
- Demonstrating superiority: new solutions must outperform established projects in terms of cost and time, while also proving technology's transparency and simplicity.
- Opex savings and Integration efficiency needs still to be proven, but potential for significant operational expenditure savings is recognized.
- Integration ease is pivotal for quick adoption into train operations.
- Offers massive capacity savings, particularly beneficial in congested segments and cities with limited space.
- Seamless integration into train operations is crucial for successful implementation.
- Existence of a regulatory framework within the EU is a pertinent consideration for implementation.

Railway undertaking perspective:

- Freight transport promotion, yet viability for small enterprises remains uncertain, retrofit of fleet partially needed.
- Viability of use cases depend on demand levels.

Technical perspective:

- Hybrid solutions, such as combining Mag Propulsion with hydrogen or battery power, present opportunities for lighter trains and reduced infrastructure costs. Innovative solutions like "push & glide" could enhance efficiency and sustainability, especially in areas lacking feasible train solutions.

Red = concern

Operational Risk: Pusher Mechanism and Heavy Trains:

- If the pusher mechanism fails to work, especially when trains are too heavy to be operated manually, it poses a significant operational risk.
- A power failure could exacerbate the operational risk associated with the pusher mechanism not working, potentially leading to further complications.

Maintenance Challenge: Magnetic Properties and Temperature:

- Dealing with changes in magnetic properties due to temperature variations poses a maintenance challenge, especially concerning the lifecycle of the components involved.
- Managing ferromagnetic dust is necessary as it could affect the performance of the system, suggesting another maintenance concern to address.

Feasibility in Rural Areas:

- In rural areas with low passenger volumes, investing in maglev-derived systems might be challenging due to the low demand, indicating a consideration beyond just technological feasibility.

In a second step the participants were able to vote for their favourite use cases (3 votes per participant). The highest votes were:

Rank	Use case	Percentage of votes
1	**Shunting Automation**	**30%**
2	**Incline Pusher**	**19%**
3	**Congested Line Accelerator**	**15%**
4	Electrification of Tunnels & Bridges	11%
5	**High-speed accelerator**	**7%**
6	Electrification of Terminals	4%
6	Add wagons in peak times	4%
6	Maintenance minimizer	4%
6	Magnetic brake	4%
6	Automated last mile	4%

Figure 9 Use case preferences by participants

The ranking matches the chosen use cases that were evaluated in deliverables 7.2 and 7.3 (marked in **bold** in the list above), showing the alignment between the project outcomes and the market requirements.

After the use case market consultation, the project team explained the stepwise approach for a deployment into the European railway network, as described in chapter 10.2. Participants again had the possibility to comment on the approach, using the colour coding scheme: green = positive comment, yellow = add-on to the use case and red = concern.

The stepwise approach was also confirmed during the market consultation, receiving overall very positive feedback, especially for the approach of starting small and growing into the network step-by-step. Small and particular deployments would already create benefits, while maintaining the compatibility with classic railways.

Figure* 10 *workshop example

Results on Cargo approach:

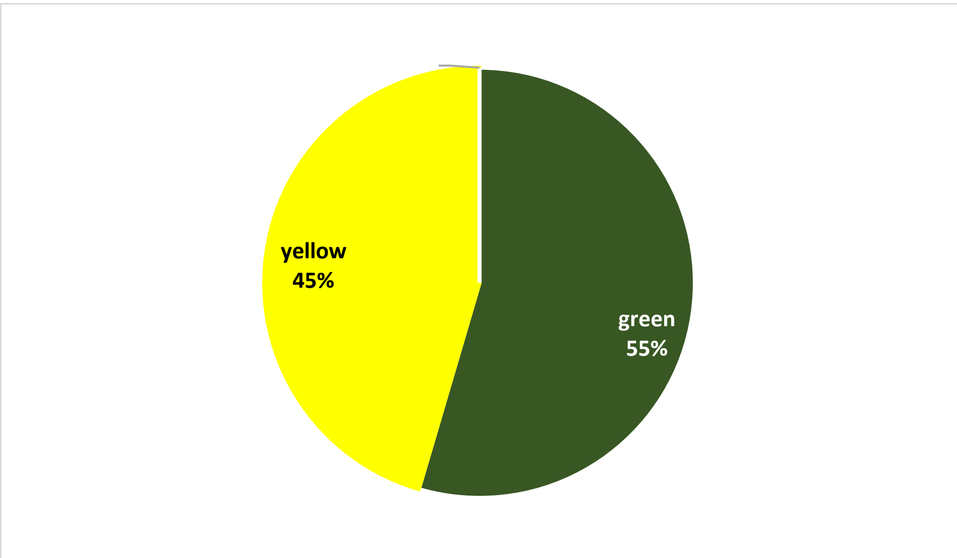

Figure* 11 *Feedback on the cargo stepwise approach

In total the participants where for overall positively and adding on towards the use cases presented and raised no concerns on the Cargo stepwise approach.

Green = positive comment

General sentiment:

- Participants confirmed the stepwise approach to start (in a closed area) and the further steps seemed also natural for expansion within a migration plan.

- Early automation will support railways in becoming more efficient, especially in the last miles (terminals, ports etc.).
- Potential to overcome current infrastructure differences, e.g. TEN-T lines could be retrofitted with MDS technology, such that there is no need to use various catenary power (15KV, 25kV, 3kV, 1.5 KV). This would highly increase interoperability.

Yellow = add-ons

General sentiment:

- Freight and passenger operators are required to invest already in ERTMS, DAC and FRMCS upgrades. Participants propose to evaluate new technologies and potential funding for it to allow retrofits.
- Make sure that the current operational schemes and timetabling is able to handle the new, increased train performance.
- Safety procedures need to be adapted to allow for maglev-derived systems and regular trains on the same infrastructure.

Red = concern

General sentiment

- No concerns raised.

Results on passenger approach:

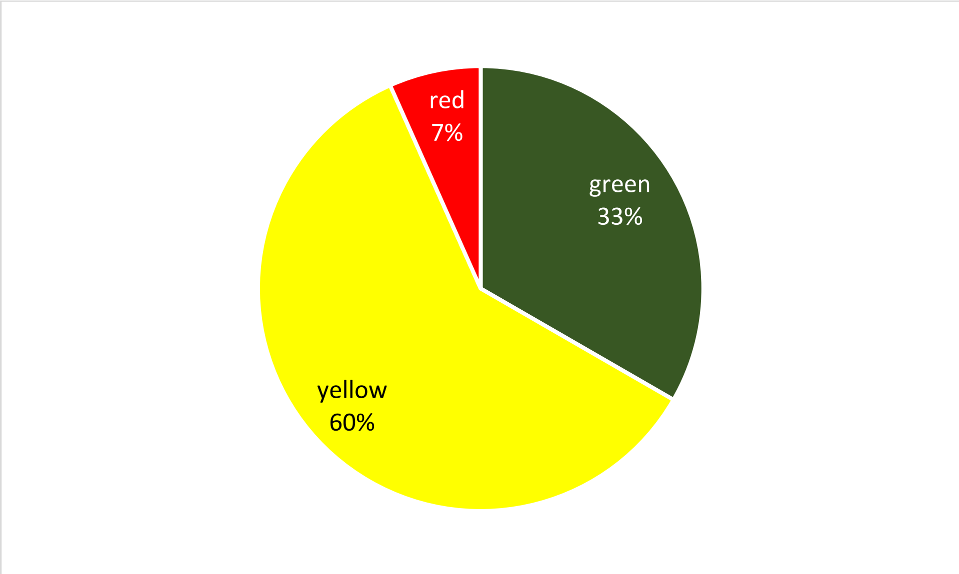

Figure 12 - Feedback on the passenger stepwise approach

In total, the participants where for overall positive and adding on towards the use cases presented and raised only small concerns on the passenger stepwise approach.

Green = positive comment

General sentiment:

- Stepwise approach seems doable and the right approach from participants point of view.
- Interesting approach for better service (frequency, flexibility, travel time) & more capacity.
- The system seems to allow for lower maintenance.
- Potential to overcome current infrastructure differences, e.g. TENT lines could be retrofitted with MDS technology, such that there is no need to use various catenary power (15KV, 25kV, 3kV, 1.5 KV). This would highly increase interoperability.

Yellow = add-ons

General sentiment:

- Safety aspects needs to be properly assessed and tested.
- More a solution for high-frequent applications, due to the heavy infrastructure investments.
- MDS could be also adapted to METRO lines (closed system) as a start.

- Faster Pods could harm the overall capacity, in a mixed operations setup with classic slow and less dynamic trains.

Red = concern

General sentiment:

- At ultra-high speeds passenger comfort and safety needs to be properly assessed.

10.2 A stepwise approach to converge the existing network into a maglev-derived coexisting network

Maglev-derived systems continue to undergo substantial evolution, with ongoing developments. These systems are constantly being improved and innovated as engineers and designers devote considerable effort to improving their capabilities and meeting emerging challenges. Achieving the safety approvals and certifications for full-type homologation requires attention to detail and the application of rigorous testing protocols, a process that demands a significant investment of time and resources while offering realistic benefits for railways.

In addition, integrating maglev technology into existing rail networks present a complex set of considerations and challenges. While potential benefits include increased speed, efficiency, and reduced environmental impact, railway operators must follow a cautious path. There are inherent risks in adopting this transformative technology, and reliability and compatibility must be thoroughly evaluated and mitigated.

As a result, widespread adoption of maglev technology across entire rail networks is expected to proceed cautiously and gradually. Initial implementations may be limited in scope as operators are prudent about managing risks and gaining practical experience with the new technology. The long implementation timelines and technological adaptation cycles of rail infrastructure also require a phased approach rather than a full-scale implementation.

In this specific landscape, collaborative efforts and constructive dialogue among industry stakeholders are of particular importance in setting the course for the future of transportation. By cultivating an environment conducive to innovation and shared learning, the industry can accelerate the integration of maglev technology into mainstream rail operations while maintaining safety, reliability, and sustainability as key principles throughout the journey.

Therefore, an incremental and gradual approach, with small implementations and then steady growth in the network, seems to be the most appropriate approach, for both freight and passenger transport. In particular, it is considered best to start with the implementation of MDS technology applications for freight transport, which can have less restrictive safety and reliability standards than passenger transport. Once the safety of these solutions has been proven at the various stages, it will be possible to carry a widespread implementation in open networks also for passenger applications at the same stages.

10.2.1 Stepwise approach for freight MDS applications

Implementing a phased, risk-free approach for freight applications, as described above, involves starting with smaller, less intrusive implementations and then moving to larger, more intrusive implementations over time. Complexity, in this context, includes technical aspects such as the signalling systems employed and technical diversity, as well as operational considerations such as mixed traffic scenarios, the involvement of various operators, and the degree of automation.

This phased approach serves to mitigate risks associated with the adoption of new technologies while facilitating incremental adjustments and optimizations. By initiating smaller-scale implementations, stakeholders can systematically assess performance, identify potential challenges, and refine operational protocols before scaling up to more extensive deployments. Moreover, the stepwise approach allows for the gradual integration of advanced technological features and operational procedures, ensuring compatibility and seamless adaptation within existing freight logistics frameworks.

As the deployment scope expands, attention must be given to managing the growing complexity inherent in larger-scale operations. This encompasses not only technical complexities but also the coordination of diverse operational elements and stakeholders involved in freight transportation. Furthermore, considerations pertaining to safety, regulatory compliance, and interoperability become increasingly important as deployments evolve to encompass broader geographical regions and diverse logistical networks.

In essence, the application of a de-risked stepwise approach represents a strategic methodology for orchestrating the gradual integration of advanced freight technologies into existing logistical frameworks. By prioritizing systematic progression and comprehensive risk management, stakeholders can navigate the complexities inherent in modern freight operations while realizing the transformative potential of innovative technologies in enhancing efficiency, reliability, and sustainability across supply chain ecosystems.

MaDe4Rail foresees three steps that could be followed to transform the existing railway network into a Maglev-derived system, enabling railways with its subsystems and technological capabilities:

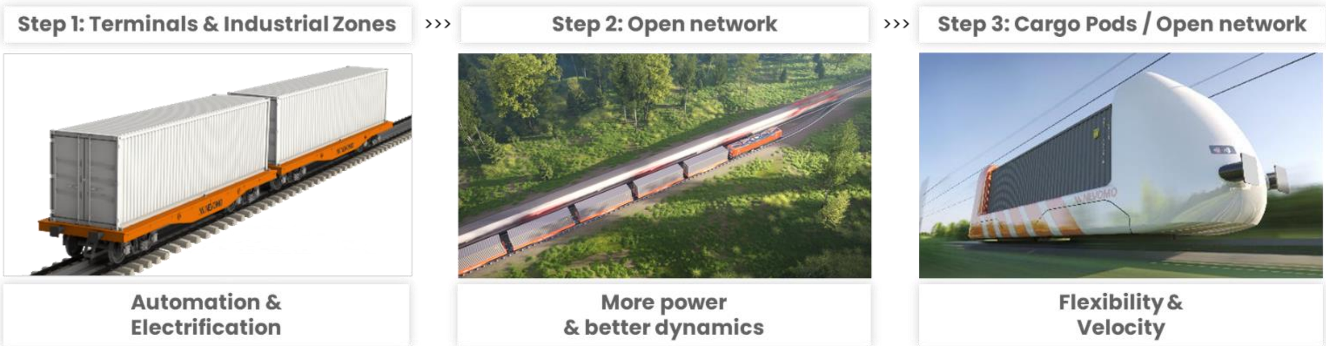

Figure 13 Stepwise approach for MDS in freight

Step 1 – MDS in Terminals & Industrial Zones:

Within terminals, ports, and industrial zones a MDS installation is easier, as the regulations and approvals needed could be reduced mainly to local ones, making deployments simpler and less time-consuming. The projects will also be much smaller, as the sidings are usually shorter than long lines in the open network of railway systems, thus limiting the risk for first customer applications.

The MDS system could be installed only in particular parts of the infrastructure to serve specific needs, reducing the implementation efforts within the siding. Existing freight platforms could be retrofitted to run electrified and (partially) automated on the infrastructure. Operations can be remote controlled or locally supervised semi-automated and later automated, but restricted to the sidings, meaning that the retrofitted wagons will remain within the siding initially.

Typical areas of deployment are ports, terminals, marshalling yards, private sidings and industrial zones and any closed infrastructure, e.g. mining railways. The main benefits would arise from increased automation grade and switching from combustion propulsion (diesel traction) to an electrified, magnetic propulsion system.

Applicable Use cases (based on the catalogue described in D7.1):

- UC2 – Shunting Automation
- UC12 – Electrification of freight wagons
- UC13 – Electrification of terminals

Step 2 – MDS in open network:

After completing the initial projects and deployments in terminals, ports and industrial zones (Step 1), MDS systems could also obtain the approvals and certifications for the open network. Within the open network, initial deployments should focus on specific parts of lines where MDS could bring benefits to current railway operations as an add-on.

Parts of railway lines can be equipped with MDS on the infrastructure. Retrofitted existing freight platforms could be integrated into full trainsets to allow for both MDS and classic traction mode. MDS might then be used as a traction enhancer to the existing locomotives. In areas without MDS, trainsets will operate as classic trains while having special capabilities over MDS infrastructure.

Typical areas of deployment are freight lines with additional demands in traction force and dynamics, such as a steep incline. The main benefits arise from higher capacity in terms of throughput per line, higher loading limits, higher acceleration, deceleration and speeds, electrification and automation of services.

In this regard, the application of MDS technologies should be already considered in all the preliminary planning phases. In particular, in the strategic planning of network upgrades, the use of these technologies opens up the possibility of designing sections of the network with steeper inclines, saving money in railway construction.

Applicable use cases (based on the catalogue described in D7.1):

- UC3 – Congested Line Accelerator
- UC4 – Electrification of tunnels and bridges
- UC5 – Automated Last Mile
- UC15 – Incline Pusher
- UC16 – Heavy Haul

Step 3 – MDS Cargo Pods in open network:

After becoming familiar with MDS in a hybrid version with existing freight operations and gaining trust in the systems and subsystems, plus seeing the arising benefits for railways, railway operators could move forward to achieve the full potential for freight operations and the maximum capacity gain from of the existing infrastructure. While connecting the installations to full lines or networks, Cargo Pods could be introduced. Cargo Pods will be self-propelled – via the MDS infrastructure – smaller vehicles able to run as single wagons or as small wagon sets, without any locomotive and fully automated, resulting in a wide usage of MDS system with retrofitted and newly designed freight platforms. Dedicated pods can operate with high frequency and high flexibility, eliminating the need for long trains based on a loco-driven production model. This would provide the additional benefits of easy adaptation to demand fluctuations (on demand Pod supply).

Additionally, newly designed Cargo Pods could open new market segments of High-Speed cargo transport (250 – 300 kph) allowing for other types of goods to be transported on rails (e.g. time sensitive goods). These high-speed cargo Pods could also operate within the existing HSR-classic-passenger traffic (ICE / TGV type of HSR) to allow for better capacity usage, as the velocity gap would no longer exist, dramatically increasing the overall capacity of the network, through the harmonization of operational velocity.

Typical areas of deployment are all freight lines with high demands in frequency and flexibility, as well as mixed used lines between freight and passenger transport with congestions.

This stage of development might mark the final transition to a MDS system, as the resulting system might be no longer compatible with the path-based approach currently ruling capacity management in railways. Transportation capacity will need to be checked, as the transition to small pods will require the overall transportation capacity provided by heavy-haul trains to be maintained and improved.

Applicable use cases (based on the catalogue described in D7.1):

- UC10 – Train length Optimizer
- UC14 – Additional wagons in peak times

10.2.2 Stepwise approach for passenger applications

Implementing a gradual approach to the introduction of new technologies in passenger transportation involves starting with small changes and gradually expanding to larger ones. This helps address technical aspects like new signalling systems and different technologies, as well as practical considerations such as managing mixed traffic involving various operators.

This method helps mitigate risks associated with adopting new technologies while allowing for incremental adjustments and improvements. Beginning with smaller-scale implementations enables stakeholders to evaluate performance, identify challenges, and refine operational protocols before scaling up to more extensive deployments. Additionally, it facilitates the gradual integration of advanced technological features and operational procedures, ensuring compatibility and smooth adaptation within existing passenger transport frameworks.

As the deployment scope expands, managing the growing complexity inherent in larger-scale operations becomes crucial. This includes addressing technical complexities and coordinating diverse operational elements and stakeholders involved in passenger transportation. Furthermore, considerations related to safety, regulatory compliance, and interoperability become increasingly important, as deployments encompass broader geographical regions and more diverse transportation networks.

In essence, the application of a stepwise approach represents a strategic methodology for integrating advanced passenger transport technologies into existing frameworks. By prioritizing systematic progression and comprehensive risk management, stakeholders can navigate the complexities inherent in modern passenger transport while realizing the transformative potential of innovative technologies in enhancing efficiency, reliability, and sustainability across transportation ecosystems.

MaDe4Rail foresees three consecutive steps that could be adopted to transform the existing railway network into a maglev-derived system, enhancing passenger transport with its subsystems and technological capabilities.

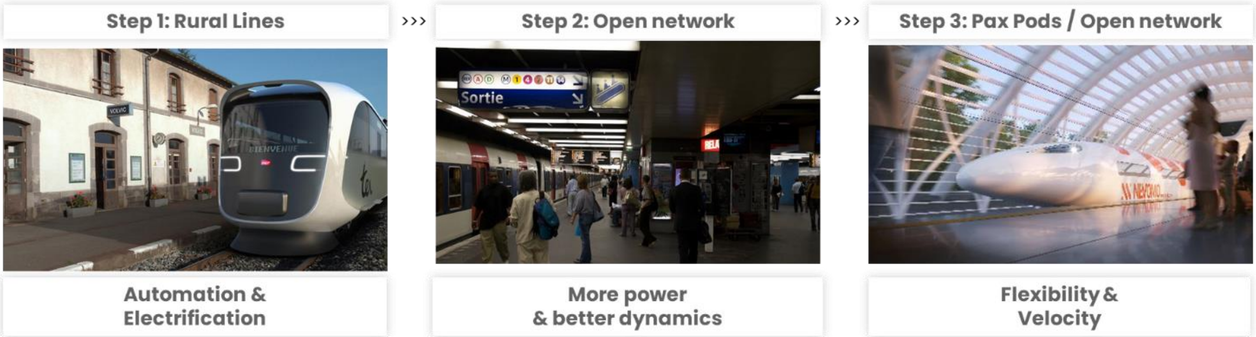

Figure 14 MDS stepwise approach for passenger applications

Step 1 – MDS in rural lines:

Within rural – sometimes unconnected – railway lines a MDS installation is easier, as the regulations and approvals could refer only to the specific local case. From a technological point-of-view, the railway infrastructure is often less technologically evolved, so less "interference" is possible, which make deployments simpler and less time-consuming. The projects will also be much smaller, as the rural are usually shorter than long lines in the open network of railway systems, reducing the risk for first customer applications.

The MDS system should be installed only in particular parts of the infrastructure, to serve specific needs, reducing the implementation efforts within the line. Existing passenger trainsets or new designed lightweight vehicles could be retrofitted to be able to run electrified and (partially) automated on the infrastructure.

The operations are driver-controlled, remote controlled/ surveilled, semi-automated and later automated, but restricted to the specific lines, meaning that the retrofitted MDS trainsets will remain within the line for the start.

Typical areas of deployment are line reactivations, closed lines, and lightweight infrastructure lines. The main benefits arise from an increased automation grade and switching from combustion propulsion (Diesel traction) to an electrified, magnetic propulsion system.

Applicable use cases (based on the catalogue described in D7.1):

- UC1 – Regional or Historical Line Activator I & II
- UC4 – Electrification of tunnels and bridges

Step 2 – MDS in open network:

After completing the initial projects and deployments in rural lines (Step 1), MDS systems might also get the approvals and certifications for the open network. Within the open network, first deployments could focus on specific parts of lines where MDS could bring benefits to current railway operations as an add-on.

Particular parts of railway lines can be equipped with MDS on the infrastructure. Retrofitted existing trainsets can enable for MDS and classic traction mode. MDS is then used as a traction enhancer to the existing traction mode. In areas without MDS, the trainsets will operate as classic trains while having special capabilities over MDS infrastructure. MDS system is then part of regular trainsets, with operations performed by the locomotives and drivers in charge.

Typical areas of deployment are congested lines, unelectrified lines or lines with difficult alignments, reducing the travel times. The main benefits arise from higher capacity in terms of throughput per line, higher acceleration & deceleration & speeds, electrification & automation of services and precise stopping at platforms.

Applicable use cases (based on the catalogue described in D7.1):

- UC3 – Congested Line Accelerator
- UC4 – Electrification of tunnels and bridges
- UC7 – Passenger Line Accelerator I
- UC8 – Magnetic Brake

Step 3 – MDS Passenger Pods in open network:

After becoming familiar with MDS in a hybrid version with existing passenger operations and gaining trust in the systems and subsystems, plus seeing the arising benefits for railways, railway operators could move forward to achieve the full potential for passenger operations and the maximum capacity gain from the existing infrastructure. While connecting the particular installations to full lines or networks, Passenger Pods could be introduced.

Passenger Pods are self-propelled – via the MDS infrastructure – smaller vehicles, able to run as single vehicles, without any locomotive and fully automated, resulting in a wide usage of MDS system with retrofitted and new designed passenger vehicles. Dedicated pods will be able to operate with high frequency and high flexibility, eliminating the need for long trains based on a loco-driven production model. This provides the additional benefits of easy adaptation to demand fluctuations (on demand Pod supply).

Additionally, newly designed High-Speed-Passenger-Pods with full MDS capabilities (levitation) could open new market segments of Ultra-High-Speed Passenger transport (up to 550 km/h) allowing for very competitive Travel Times and opening a new era for high-speed-rail in Europe.

Typical areas of deployment are all lines with high demands in frequency & flexibility or shortened travel times.

This stage of development might mark the final transition to a MDS system, as the resulting system might no longer be compatible with the path-based approach nowadays ruling capacity management in railways. Transportation capacity will need to be checked, as the transition to small pods will require the overall transportation capacity today provided by long high-speed trains to be maintained and improved.

Applicable use cases (based on the catalogue described in D7.1):

- UC6 – Airport Shuttle
- UC7 – Passenger Line Accelerator II
- UC10 – Train length Optimizer
- UC14 – Additional wagons in peak times
- UC18 – Railway highway

11 Conclusions

In this document, a possible roadmap for the extension of maglev-derived systems in the European railway network has been explored, through an analysis of several use cases for different field applications. First, an in-depth overview on the four use cases that have been analysed in detail is given.

Use case 1 foresees the implementation of an upgraded MDS configuration a the single-track railway line in - Sweden (see paragraph 5.2) – which has limitations in capacity, speed and travel time. The aim is to increase capacity by speeding up freight trains with uphill boosters/incline pushers, thereby enhancing the transport capacity of freight per train (scenario A). Additionally, since a new high speed line is under study, this technology may lead to a significant construction cost reductions related to earthworks, tunnels, and bridges due to the steeper gradients permitted (scenario B).

Use case 2 involves a passenger shuttle using a hybrid air levitation system (Airlev) on a short distance line in Italy (see paragraph 5.3). This use case focuses on evaluating the feasibility of upgrading the existing line with Airlev technology to potentially increase capacity, speed, and performance of vehicles.

Use case 3 involves implementing a hybrid magnetic levitation system on a historical regional line (see paragraph 5.4). Two scenarios are proposed: the first with minimal technological upgrades retaining the current line alignment, While the second foresees sliders on additional levitation beams attached to rails instead and an adapted line alignment to prevent speed drops and optimize performance.

Use Case 4 explores the potential implementation of linear motor propulsion in container terminals, focusing on enhancing efficiency, sustainability, and operational performance. The study is located in an Italian terminal (see paragraph 5.5).

Commercial and operational constraints and benefits have been analysed. Since MDS technologies can reach high values of acceleration, deceleration and speed, both in curve and straight paths, passenger comfort of onboard must be considered. Acceleration and deceleration top values must allow passenger to stand and walk safely – e.g., to go to the toilet – and the need to wear seatbelt should be avoided. Generally speaking, passengers should not experience any physical discomfort excessively greater than what they experience during traditional railway travel (or other comparable transport mode). Luggage policy should also not be more restrictive than usual rail transportation. For freight traffic, the major constraint is the operational cost. Typically, the rail freight market operates with tight economical margins, requiring a strong effort to cut costs for every system element. All the elements concerning end-user experience and their potential effect on the system performance have been largely discussed in Chapter 6.

On the other hand, the selected use cases provide some technological characteristics that could offer significant benefits for rail undertakers and end users compared to traditional wheel-on-rail technologies, as discussed in chapter 6.2, provided they are correctly evaluated, taking into proper account all the user-experience related constraints, as well as the limitations arising from the supposed coexistence with traditional railway services on the same infrastructure. Indeed, a market consultation was conducted through a series of workshops, and positive interest in the benefits of the new technology was expressed. Valuable insights about the most promising applications were provided by participants, as well as the most significant operational concerns. The applications that garnered the highest interest from the market were, as above mentioned, Shunting automation, Incline pusher, and Congested line accelerator.

A high-level Cost-Benefit Analysis was then performed on the discussed use cases to identify the magnitude of the economic feasibility of the applications (see chapter 7). The results showed potential benefits, such as increased efficiency, reduction in civil works costs, electrification and enhanced infrastructure reliability, with connected new challenges regarding compatibility and integration with existing railway infrastructure and some benefits that are considered marginal in comparison to investment costs required. In general, the strategic deployment of MDS holds the potential to enhance the European railway network, provided that it is implemented in scenarios where it can deliver the highest added value.

Regarding MDS global perspectives, after an overview of the maglev application in operation, indications about the most promising contexts where the MDS technology could be applied were provided (see chapter 8).

An industrial roadmap was then outlined (see chapter 9), aiming to provide an overview of the key steps and milestones necessary to achieve commercial readiness for maglev-derived systems. Starting from the technological challenges identified within the different conducted analyses within the MaDe4Rail project, a route for the resolutions of these open points have been outlined, through advanced design, research & innovation, modelling and simulation, testing in relevant environment, update of the MaDe4Rail results, design and planning, engineering and development of solutions integration, testing, and validation activities. Then, a focus on the roadmap for the development of the technical enablers identified is given, for which a comprehensive integration with other Flagship Projects of the Innovation Pillar and a harmonization with the System Pillar tasks is required, in order to facilitate MDS integration.

Finally, a stepwise approach to achieve an extended application of MDS technology onto existing European railway network has been outlined, highlighting the most important passages distinctly for passengers and freight applications, highlighting the specific applicable use cases among those emerged from the workshops (see chapter 10). For the freight application, a first implementation in terminal and industrial zones could be foreseen, by exploiting the easier regulations and approvals needed, to then move to open network to finally integrate MDS Cargo Pods after gaining enough familiarity with existing freight operations. For the passenger application, a similar logic could be used, starting with easier application in rural lines to then implement MDS in open networks for a final implementation of Pax Pods.

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