Deliverable D7.2

Technical feasibility study of the maglev-derived system in the use cases selected

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1. Executive Summary

This executive summary presents an overview of the feasibility studies conducted for the three identified use cases and the related two scenarios. The primary objective of this task is to:

- Define operational scenarios for the use cases and identify the related expected demand,
- Identify the technical feasibility,
- Define technical challenges and risks.

This task is essential for the development of the MaDe4Rail project. The feasibility study was initiated to ensure that all critical factors are considered before moving forward with the project and to detail a cost-benefit analysis.

The technical feasibility analysis focused on the technology required for the implementation of the MDS systems and their impact on the current infrastructure. Specifically, the impact on civil works and excavation, signalling systems, and power supply systems was investigated.

The findings suggest that, despite some identified technological challenges, several improvements can be achieved by implementing MDS systems.

Deliverable 7.2 aims to present the analysis conducted for the development of the technical feasibility study for the three identified use cases and the results of the assessment of the identified risks associated with the implementation of the MDS systems in two identified railway lines in Sweden and Italy.

The deliverable begins with a description of the operational scenarios, detailing the context, expected demand, and the high-level architecture of the system functions and elements considered in the study and identified in previous tasks.

Following this, the document describes the impact on the current alignment for the identified use cases. It should be noted that not all scenarios may impact the alignment. In fact, for those scenarios where an increase in capacity is expected without an increase in the maximum speed on the line, no major modifications have been foreseen. This does not mean that the analysed MDS technologies do not allow running at higher speeds.

The document also presents general aspects that are common to all scenarios, such as the signalling systems and the methodology for the magnetic analysis.

Finally, the document details the feasibility study for the three use cases and related scenarios.

The results of the feasibility study and operational scenarios will be the main input for Task 7.3 and WP8, where a cost-benefit analysis will be performed to evaluate the economic impact of the projects.

2. Abbreviations and acronyms

Abbreviation / Acronym	Description
5G	5^{th} Generation Technology
Airlev	Air Levitation
ATO	Automatic Train Operation
CBA	Cost-Benefit Analysis
CW	Continuous Wave
EDS	Electrodynamic systems
EDW	Electro-dynamic wheels
EMC	Electromagnetic Compatibility
EMS	Electromagnetic systems
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
EU-Rail	Europe's Rail
FRMCS	Future Railway Mobile Communication System
HSR	High-Speed Rail
IM	Infrastructure Manager
JU	Joint Undertaking
MaDe4Rail	Maglev-derived Systems for Rail
Maglev	Magnetic Levitation
MAWP	Multi-Annual Work Programme
MCA	Multi-Criteria Analysis
MDS	Maglev-derived Systems
N.A.	Not applicable or not available
O/D	Origin-Destination
NdFeB	Neodymium Iron Boron
OPEX	Operational Expenditures
PROMETHEE	Preference Ranking for Organisation Method for Enrichment Evaluation
RFI	Rete Ferroviaria Italiana

RU	Railway Undertaking
SWOT	Strengths, Weaknesses, Opportunities & Threats
TAZ	Transportation Analysis Zone
TCS	Train Control System
TMS	Traffic Management System
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
TRV	Trafikverket
WP	Work Package

3. Background

The present document constitutes the Deliverable D7.2 “Technical Feasibility Study” 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 chapter outlines the main objectives and aims of the feasibility study for three use cases identified during task 7.1 and reported in the related deliverable. The study aims to analyse and evaluate the technical feasibility for the three use cases, each one characterized by different system architecture with the goal of enhancing the railway infrastructure and promoting innovative transport system.

General objectives of this task are to identify the impacts on the performance and infrastructure resulting from the implementation of MDS systems. Particularly, the impact has been analysed with reference to:

- Civil Work (including track) and Excavation,
- Vehicle command control and command systems,
- Signalling systems and telecommunication,
- Energy and power supply systems,
- Rolling stock.

Specific objectives of the tasks are:

- Operational Scenario: define the operational scenario and expected flows for the selected use cases,
- Technical Feasibility Analysis: conduct a feasibility study of the technical characteristics of the proposed systems on the selected use cases assessing system architecture and impacts,
- Magnetic Analysis: develop magnetic analysis to estimate potential incompatibilities between levitation systems and other subsystems,
- Interface and interoperability: identify potential challenges related to interface and interoperability resulting from the implementation of MDS systems,
- Risk Analysis: identify specific risks applicable to the identified use cases.

5. Overview of results from D7.1

Deliverable D7.1 – Use Case Analysis presented an overview of the different generic use cases identified within WP6 and as well as the results of the use case workshops organised within WP7, which involved various experts and stakeholders in the field of transportation, both from passenger and freight sectors such as transport operators, infrastructure managers, and railway undertakings. From these outputs, three use cases have been selected, located, and thoroughly defined for passenger and freight applications, which should also present the different benefits that each use case may bring.

The use cases identified are the following:

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

To finalize task 7.1, workshops were performed for the identification of MDS applications in specific locations in Europe. The workshops involved over 40 participants from 8 countries, representing relevant stakeholders for rail transportation in Europe between Infrastructure Managers (IM), Railway Undertakings (RU), terminal operators, end customers (freight), technology companies, research and development institutions and regional transport administrators.

Implementing PROMETHEE method, the selection of the three use cases was carried out using the Multi-Criteria Analysis (MCA), which takes into consideration the criteria related to the operations and traffic control aspects, technology, interoperability, environmental sustainability, and implementation and economics.

6. Description of the 3 selected use cases

The following sections show and describe the 3 final use cases to be evaluated in the following tasks of the WP. This chapter describes the selected use cases and their main characteristics which will be explored and analysed in this Task 7.2.

The use cases identified are the following:

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

The use cases identified will be analysed considering two scenarios:

- Scenario A) maglev-derived systems with minimum requirements and impact on current infrastructure;
- Scenario B) maglev-derived systems with needed adaptations to fully exploit the maximum performance.

This version of Deliverable D7.2, adapted to exclude all sensitive information, does not include the analysis of the Hybrid MDS based on air levitation configuration due to confidentiality concerns.

In the following paragraphs, for each use case the characteristics associated with the different scenarios analysed will be explained.

6.1 Rail vehicle upgraded MDS configuration

One of the use cases is dedicated to studying the railway line that connects two cities in Sweden. The current railway consists of a major line that extends to other regional destinations. Connecting these cities is an existing single-track line with numerous curves and limitations in capacity, speed and travel time. The route serves one of Sweden's largest commuting areas and the current railway does not offer a competitive alternative to road traffic. Commuting along this route is mainly made by car or bus. The same applies to trips to and from the nearby airport, which currently lacks connections.

A new railway line between two cities in Sweden would provide faster train journeys, smoother work commuting and increased accessibility to nearby airport.

The technical scenario A represents the existing line between the two cities, which has a speed limitation that does make it not possible 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 various sections (Scenario A.1). As this corridor is a critical link in the national network, a High-Speed line (250km/h) has been proposed, and the planning phase ongoing (Scenario B.1). This new line would allow a significant increase of capacity by duplicating the number of tracks between the two Swedish cities, and by segregating traffic with different speeds where passenger services run mainly in the HS line. However, 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 for allowing heavy freight trains to maintain top speed even in challenging adhesion limit scenarios (Scenario A.2).

Cost-savings for new infrastructure

modify the design of the high-speed line by including higher gradients with incline pushers (Scenario B.2). 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.

These are 2 independent comparisons (A.1 vs A.2, and B.1 vs B.2), because the comparison between A.1 and B.1 has already been performed and the comparison of A.2 with B.1 and/or B.2 would not be suitable due to differences in costs and benefits expected in several orders of magnitude.

Scenario A	Description	Traffic in existing line	Traffic in existing line	Differential costs
TRV-A.1	Existing line	Freight trains 80km/h	Passenger trains 120km/h	-
TRV-A.2	Existing line with incline pushers	Freight trains 80km/h	Passenger trains 120km/h	Cost of incline pushers

Table *1*: Case studies on the existing lines

Scenario B	Description	Traffic in HS line	Differential costs
TRV-B.1	New line	High speed trains 250km/h and commuter trains at 200km/h	-
TRV-B.2	New line with incline pushers	High speed trains 250km/h and commuter trains at 200km/h (even 250 with boosters)	Reduced earthworks, cost of incline pushers

Table *2*: Case studies on the new line that is under planning

6.1.1 Context Analysis

6.1.1.1 Urban areas, population, and work- and study commute

This section includes information about the territorial context, demand side data and mobility offer data.

The corridor analysed is a single-track and electrified line that stretches all the way between two major cities, as well as other regional and local destinations . It is operated both long distances, regionally and locally. In the national plan for 2018-2029 period, the entire line is highlighted as deficient in terms of capacity, punctuality and robustness.

The route is one of the largest commuting routes in Sweden. The commute is made primarily by car and by bus, preferred over train as it takes a long time and has few departures. The extensive car and bus traffic causes congestion, both on the main roads and in the cities. The central area of one of the cities is so crowded that it is not possible to increase the number of buses in peak hours, which in the long run prevents the exchange of skills and labour in the region.

The characteristics of the existing line between two cities are as follows:

- Length (km): more than 50 km,
- Track standard: max. speed 120 km/h, varying. The main track and connections were built in 1990 and hold a good status (50 kg/m rails, concrete sleepers),
- Infrastructure: many bridges and few tunnels are located along the infrastructure. All tunnels are found to be tight and have a limited height for the catenary. The bridges are in relatively good condition,
- Rail traffic (trains per day): more than 10 round trip passenger trains, more than 5 single-trip freight trains (2021),
- Lane flow (million passengers per year / million net tonnes per year): 500,000 tonnes of goods, approx. 0.4 million arrivals per year).

There are five municipalities along the route: two major cities, along with three smaller towns. More than 800,000 people live in the municipalities in the stretch, and there are approximately 500,000 daytime-working population. The majority of the inhabitants live in one of the urban areas, where also the largest number of jobs are found.

More than 65,000 people commute for work or study along the route. Annually, approximately more than 9 million work trips take place annually. Including leisure trips, the number is significantly higher.

The majority of commuting journeys between the municipalities in the route takes place between the largest urban areas. The two largest cities can be seen as a common metropolitan area, their urban areas have grown into each other. The distance between the central stations of the two cities is approximately 10 kilometers.

6.1.1.2 Current traffic and infrastructure

The main infrastructure system along the route consists of a major highway and the coast-to-coast railway. Travel on this route is predominantly by car, with most drivers using the motorway that connects the two cities. Total travel time in the car can take up to more than an hour, depending on congestion conditions.. The road is an important connection in the west-east direction and has regional importance for work commuting. It is also of national importance for long-distance freight and passenger transport.

Long-distance freight transport is heavily concentrated on this route, with goods traveling to and from a major port via both the highway and the coast-to-coast railway. The railway includes transport for various industries, including automotive shipments, as well as container traffic between key locations. There were more than five one-way freight trains running daily on this section of the railway as of late September 2021.

The coast-to-coast line is served by regional trains on various routes. The trains run directly between the two major cities, while other makes stops at all intermediate stations. The coast-to-coast line is a single-track, electrified, and remote-block railway that stretches between several coastal and inland cities. It supports 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. Bus routes provide key connections between the cities, with frequent departures during peak hours. Primary bus service runs between the two cities with key stops along the way. Other bus services connect surrounding areas and offer direct or limited services to important locations, including a hospital. The frequency of bus and train services is high during rush hour, with several options available for commuters.

Public transport's share of total travel on the route is approximately 25% and buses account more than 90% of this. The bus journey from one city to another takes approximately 1 hour, with a key stop at a major interchange, where a large portion of travellers have nearby destinations. Bus services between the cities, as well as to nearby towns, operate with high frequency, departing approximately every five to ten minutes during peak traffic hours. In other areas, buses run once every half hour during peak traffic and once every hour during the rest of the day. For a short period in the morning, there is also a more frequent service to the major city. There are no direct public transport connections between some smaller towns and nearby cities. The main airport serving the region is an international hub. . The number of air travellers is approximately 7 million. It is also a large employer in the region with more than 3,000 employees. The airport is served by airport buses both from major cities as well as by public transport from a nearby travel centre, where buses to the airport run every 20 minutes. Many travellers also prefer to drive to the airport via the main highway.

It is worth noting that the majority of daily commuter traffic currently occurs between the largest city and nearby towns, extending to the airport and surrounding area.

6.1.2 Demand data and modal split model development

This section presents the demand and market share data for the route between two major cities, along with a methodological approach to develop and calibrate a modal split model (i.e., travel mode choice model).

6.1.2.1 Demand and market share data for the route

In June 2020, the Swedish Government requested updated and supplementary information regarding new High-Speed train routes for major corridors. According to the information collected, an annual average growth rate of 1.8% is assumed for the demand in the corridor with the same market shares for travel modes used to project demand values from earlier years to 2024, as detailed in the accompanying table.

Relation	Market share (%)		
	Rail	Bus	Car
Major corridors	10%	40%	50%

Table 3: Market share in major corridor

6.1.2.2 Modal split (travel mode choice) model development

A Multinomial Logit Model (MNL) structure is considered for modal split model development with rail, bus, and car as the alternatives, with the following service/traffic supply variables:

- **Rail and Bus:** travel time (TT), travel cost (TC), and service headway (H),
- **Car:** travel time (TT) and travel cost (TC).

Therefore, following the MNL formula, the utility function for travel alternative *i* (rail, bus, and car) is given in Equation (1):

$$U_i = V_i + \epsilon_i \tag{1}$$

Where, ε_i is a Gumble distributed random error and V_i is the systematic part of the utility functions for travel alternatives rail, bus, and car, as shown in Equations 2-4, respectively:

$$V_{\text{Rail}} = \text{ASC}_{\text{Rail}} + \beta_{TT,\text{Rail}} \cdot TT_{\text{Rail}} + \beta_{TC} \cdot TC_{\text{Rail}} + \beta_{H,\text{Rail}} \cdot H_{\text{Rail}} \tag{2}$$
$$V_{\text{Bus}} = \text{ASC}_{\text{Bus}} + \beta_{TT,\text{Bus}} \cdot TT_{\text{Bus}} + \beta_{TC} \cdot TC_{\text{Bus}} + \beta_{H,\text{Bus}} \cdot H_{\text{Bus}} \tag{3}$$
$$V_{\text{Car}} = \text{ASC}_{\text{Car}} + \beta_{TT,\text{Car}} \cdot TT_{\text{Car}} + \beta_{TC} \cdot TC_{\text{Car}} \tag{4}$$

Where, alternative-specific constants (ASC) represents alternative-specific constants for rail, bus, and car. β_{TT} represents mode-specific marginal utility of travel time for rail, bus, and car. β_{TC} represents the marginal utility of travel cost for rail, bus, and car while β_H represents the marginal utility of service headway for the rail and bus. Marginal utility values (β) are adopted from the Swedish transport CBA guidelines (ASEK 7.0).

Finally, the probability P_i of choosing the travel alternative *i* (i.e., market share of travel alternative *i*) is shown in Equation 5:

$$P_i = \frac{e^{V_i}}{\sum_{j \in \{\text{Rail,Bus,Car}\}} e^{V_j}} \quad (5)$$

6.1.2.3 Calibration of the developed modal split model

To ensure that the modal split demand model accurately estimates market shares, it is necessary to calibrate this model for the corridor under investigation based on the current demand/market and service/traffic supply variables. Therefore, the ASC shown in equations 2-4 will be iteratively calibrated to achieve the current user equilibrium, following the demand/market share values presented in Table 3. A rough sketch of the current traffic supply, used for the calibration of the developed model, is provided in Table 4.

	Rail	Bus	Car
Travel time (min)	Ca. 60	Ca. 55	Ca. 45

Table *4*: Assumed traffic supply variables in the major corridor in 2024

* From 4am to 24:00, 13 trains per day
** From 4am to 24:00, 101 buses per day
*** Single ticket Zone ABC 180 minutes Adult
**** Only fuel price is considered

Overall, the calibration is done through numerical optimization using Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm in which ASCs are the optimization variables and ASC for car is fixed to zero. The calibration results are presented in Table 5

	Rail	Bus	Car
Optimized ASC value	-1.249452	-0.4076532	0

Table *5*: optimized ASC values for the calibrated modal share model in major corridor (ASC for car is fixed to zero)

6.1.3 Operational Scenario

This use case is based on the fact that often, short but steep inclines affect the maximum load of a complete freight relation. Additional challenges may arise from difficult environmental conditions like ice, snow, and hail that can reduce conventional propulsion effectiveness as well as braking capacity. This can result in reduced loads/weight of the trains or will require additional locomotives, which causes additional operational costs. Often, additional locomotives are running from origin to destination, even when they are only needed in specific areas. MDS can be a punctual solution for additional traction. Even when the benefits in terms of capacity are not so big as that of a constructive and much more expensive solution like tunnels or bridges, a MDS based on upgraded traditional railway vehicles solves the problem with much lower costs using the existing infrastructure.

The current railway connecting two major cities in Sweden is a single-track, curvy and has limitations in capacity, speed and travel time. The route is part of one of Sweden's largest commuting areas and the existing railway is not a competitive alternative to road traffic. Commuting on that connection today is mainly made by car or bus. The same applies to trips to and from neabry airport, which currently has no railway connection today.

A new railway line between the two cities would provide faster train journeys, smoother daily commuting, and increased accessibility to the airport. The current route is also part of new network of trunk lines, the purpose of which is to:

- Add significant capacity to the Swedish railway system, enhancing punctual and robust journeys and transport for people and businesses,
- Provide significantly shorter travel times by train within Sweden and between Sweden and other countries in Europe,
- Through increased accessibility and new travel origins and destinations, such solution would boost conditions for strong labour market regions and regional development,
- Promote sustainable travel and transport.

The new planned line comprises more than 50 kilometres of new double-track railway for high-speed trains and fast regional trains. Along the proposed railway corridor, there are also several locations where it is necessary to build tunnels to overcome the conditions in the landscape. The proposed line has gradients up to around 25‰.

Freight service and also slower regional trains will still use the existing railway line. To increase the capacity and efficiency, with focus on freight services on this infrastructure, an MDS with upgraded rail vehicles and linear motors trackside could be used, a solution with low costs to the steep incline of the line providing the required operational parameters specifically where they are needed.

The main need to which an upgraded conventional vehicle with MDS technologies on wheels responds is to increase transportation efficiency – below are the assumptions for main characteristics of this system:

- For this use case upgraded wagons will always operate within trainsets controlled by locomotives and their drivers,
- MDS components will provide additional traction force in sections where the power of the traction unit in front of the train (one or more locomotives) is not sufficient,
- Tracks: track gauge – 1435 mm,
- Freight wagon dimensions do not change (upgrade of existing wagons without changes of wagon structure),
- Technology dedicated for passengers and cargo (two variants),
- Interoperable infrastructure for upgraded and conventional trains,
- Grid connection to the medium voltage network for MDS substations,
- Operating speed – up to 160 km/h (depending on infrastructural situation),

- Traction type: Linear Synchronous Motor with thrust force of up to 14 kN per equipped wagon,
- Dedicated onboard battery with voltage rating of 72 V,
- All MDS components in the track segment are only active, when the train is above them. Additionally, all devices which could cause danger by electrocution are covered and secured against environmental issues (e.g. flooding) or unauthorised contacts (e.g. passengers at stations)

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

Operational conditions are described as follows.

Speed and efficiency:

- Capable of increasing speed for freight trains on overall corridor,
- Capacity and flexibility: Designed to transport cargo, offering modular compartments that can be adjusted based on demand,
- Safety systems: Equipped with advanced safety features, including automated collision avoidance, emergency braking systems, and robust structural integrity for passenger protection,

Daily operations and example scenario are described as follows.

- Evening and night operations: Prioritizes cargo transportation. The modular design allows for easy conversion of passenger compartments to cargo spaces.

Integration with existing infrastructure is described as follows.

- Track compatibility: able to operate on existing rail tracks, which traditional design shall be subjected to a specific design integration assessment, also covering the maintenance aspects, allowing for a seamless transition from traditional rail systems,
- Station adaptations: no impact on current passenger station.

Future proofing and scalability are described as follows.

- Technology upgrades: built with the capability to integrate future technological advancements, ensuring long-term viability.
- Scalability: The system is designed to be scalable, working as traditional railway system in degraded scenario.

Based on the condition outlined above, the operational scenario for this scenario will not alter the current management of the line in terms of traffic control and safety. Furthermore, the rolling stock will remain unchanged, as the implementation of the booster can be viewed as an upgrade to the existing rolling stock.

How the technology is implemented in the rolling stock is discussed in section 6.1.4. System Functions and Elements.

6.1.3.1 Scenario A

This scenario involves the analysis that will evaluate the implementation of the existing line with Rail vehicle upgraded MDS technology.

This intervention will lead to evaluating the applicability of the new technology on the basis of the minimum achievable requirements.

6.1.3.2 Scenario B

This scenario involves the analysis that will evaluate the implementation of the same technology for the design and construction phases of new line.

This intervention will lead to evaluating which applications and needs are required to achieve maximum fulfilment, like the use of significantly higher slopes with inclined pushers for the optimisation of earthworks and track construction.

6.1.4 System Functions and Elements

MDS with upgraded rail vehicles and linear motors trackside is the preferred retrofit solution for existing rail infrastructure and vehicles. This system employs electromagnetic propulsion with a linear motor, enabling each wagon to move independently without a locomotive, while providing additional traction power to trainsets equipped with a dedicated number of wagons. Having the active part of the propulsion on the infrastructure side will have the advantage of an easier implementation in existing freight wagons, which today are usually not equipped with an energy system for propulsion purposes.

For this study in deliverables D7.2 and D7.3, the linear synchronous motor (LSM) system from NEVOMO will be the technological basis for the following estimations. This must not to be understood as a decision for later implementations but will help to estimate the technological needs and possibilities for one of the possible solutions.

Developed to enhance existing rail services for freight, the MDS offers benefits such as traffic automation and infrastructure electrification, along with greater flexibility, higher operational frequency, increased capacity, and improved dynamics. This technology can address challenges by adding additional traction force to sections with steep inclines for achieving higher speeds or handling larger loads for freight trains. Additionally, it can enhance speed and capacity by reducing travel times for passenger trains where additional traction power is required.

The vehicle subsystem consists of the main components listed below:

- Structure,
- Propulsion – vehicle part,
- Suspension,
- Guidance,
- Braking,

- Vehicle control system,
- Electrical system,
- Monitoring & safety.

The mechanical structure of a retrofitted vehicle integrates a classic freight wagon with a linear motor. Various types of freight platforms are suitable for MDS retrofitting. This component facilitates the transfer of internal (from payload) and external (track dynamic responses, wind) forces, ensuring their safe distribution to maintain the vehicle's integrity. Serving as the central component of the vehicle, the structure allows for the attachment of various other components, including onboard electronics, safety systems, suspension, and monitoring systems.

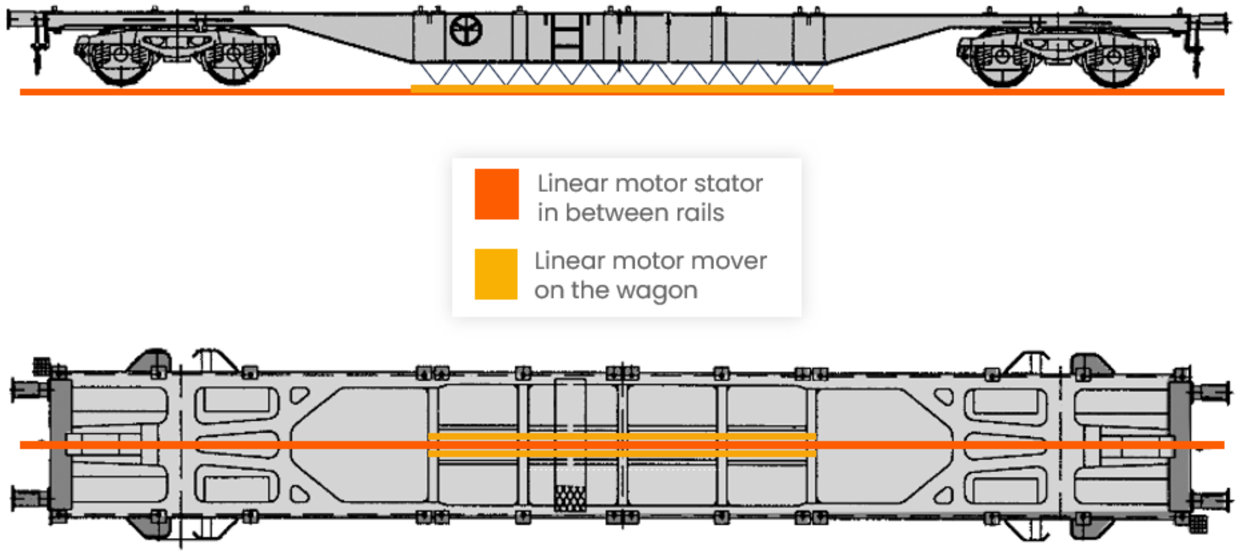


Figure 1: Principle of updated conventional freight wagon (source: NEVOMO)

The linear motor integrated into the upgraded conventional vehicle with MDS technologies on wheels is an LSM. This electric machine comprises the mover — a set of NdFeB magnets arranged in a Halbach array mounted on the vehicle — and the stator (active, powered part) — a 3-phase winding installed in the track. The permanent magnets installed beneath the wagon (as shown in Figure 1) are constituting the mover of the linear motor and are essential for creating the propulsion force for the vehicle.

The position of the magnets can be adjusted manually or automatically to ensure the proper width of the gap between the linear motor and the mover, depending on the specific configuration of the use case and the infrastructure situation. Stability during operation is maintained through a standard suspension system that utilizes existing railway wheels. These wheels not only provide stability but also ensure precise guidance along the track, facilitating controlled movement, even weight distribution, and the elimination of lateral swaying.

Figure 2: Example of mounted mover magnet on conventional intermodal rail wagon (source NEVOMO)

Linear motors play a dual role, serving both to propel the train forward and as a braking mechanism. During forward motion, the linear motor operates conventionally, providing traction. Conversely, when braking is required, the linear motor reverses its operation, converting the train's kinetic energy into electrical energy, which can then be fed back into the electrical grid. Linear motors offer versatility and can be employed for various braking scenarios, including service braking, fast braking and regenerative braking. In the conventional vehicle, emergency braking is implemented with an independent system. Considering the high safety integrity requested to emergency braking, common cause failure with the normal braking should not be present. Even if the linear motor can archive the performance for normal and emergency braking, it may not be used for both applications. Therefore, in addition to the electromagnetic braking, the system incorporates friction-based braking, utilizing the conventional brakes that directly engage with the railway wheels. This comprehensive braking strategy ensures redundancy and operational safety, enabling the vehicle to halt promptly and efficiently in the event of electromagnetic braking system malfunctions.

In this setup, the vehicles will always be part of a trainset. Nevertheless, it is necessary to align the propulsion system with the position of the different equipped vehicles in the train. The vehicle control system operates uniquely in this setup, with additional vehicle propulsion given from the infrastructure side to the equipped wagons in the train. A sophisticated command, control, and monitoring system, organized into sections and segments of the linear motor stator, meticulously manages the vehicle's position on the track and the amount of additional propulsion force depending on the specific situation. The high-performance drive system enables rapid acceleration and deceleration, resulting in shorter spacing intervals. This capability is advantageous for advanced traffic control and ensures optimal throughput utilization.

Consequently, the vehicle itself is equipped with a minimal set of sensors and devices tailored specifically for infrastructure safety, control, and guidance systems. These sensors perform various functions, including position measurement through GPS, IMU, and odometry, as well as monitoring parameters such as pressure, voltage, currents, and vibrations.

The electrical system in this configuration consists of two primary components. Firstly, there's a dedicated on-board battery serving as the primary power source for essential electronic devices and communication systems on-board the vehicle. This ensures continuous operation throughout the journey, even in the event of power disruptions. Secondly, a comprehensive cable wiring network serves as the backbone of the electrical infrastructure. This network efficiently distributes power to various devices and sensors within the vehicle, facilitating proper functioning and effective communication between systems, thus contributing to the safe and efficient operation of the transportation system.

Safety is paramount in this system, both for the vehicle and its surroundings. A Self-diagnostic System within the vehicle, comprising an onboard CPU and various sensors, continuously monitors the vehicle's health by tracking parameters such as vibration, current, voltage, pressure, and temperature. In emergencies or upon detecting anomalies, the Self-diagnostic System promptly relays critical information to the central control system and engages emergency braking as necessary. This proactive monitoring and real-time reporting enhance safety measures and enable swift responses to potential issues, thereby bolstering the overall safety and reliability of the transportation system.

6.1.4.1 Main Subsystems

- Propulsion system: LSM,
- Guidance system: conventional rail-wheel contact,
- Vehicle: updated conventional vehicles.

6.1.4.2 Main Components

Propulsion system:

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

Guidance system:

- Conventional rail-wheel contact without any changes.

Vehicle:

- Conventional vehicles updated with a mover magnet as part of the propulsion system,
- Sensors on the vehicle: IMU, GPS, and other Self-diagnostic System within the vehicle, consisting of a main CPU board for monitoring parameters such as pressure, voltage, currents, and vibrations,

- On-board electronics: a dedicated on-board battery, which serves as the main power source, and an electrical wiring network enabling proper functioning and effective communication between systems,
- Anti-collision system with radar sensor: facilitates safe braking at lower speeds and minimizes damage at higher speeds in case of collision.

6.2 Hybrid MDS based on magnetic levitation configuration

The use case is proposed on the line connecting major cities, with the implementation of a hybrid MDS based on maglev for the regional line. The definition of the use case reflects RFI's need to evaluate the performance of a hybrid MDS on secondary regional lines, as an alternative to constructing new HSR lines.

It is clear that MDS on secondary lines will not allow to reach top speeds (up to >500 kph) that could be expected on Hybrid MDS introduced on HSR lines. However, subject of the upcoming feasibility study is to verify technical conditions (e.g., speed, travel times, capacity) on regional lines.

The entire route from the origin to the destination has a length of less than 600 km. The route cuts across the country, passing through scenic mountain ranges. Many trains make stops at a strategic Italian station along the route. On faster services, no change of trains is required. However, traveling on a slower and less expensive regional train, may require transferring from one train to another.

6.2.1 Context Analysis

The cities at both ends of the route share several characteristics that significantly influence transportation demand and its characteristics. Both cities are major tourist destinations, attracting the highest number of visitors. One of the cities is considered as a major economic hub, leading to a heterogeneous transportation demand. Therefore, the infrastructural network must be adaptable to the complexity of transportation demand in these cities.

The transportation links between the cities are varied, including highways, railways and plane connections. For private transport, the highway network plays a crucial role, with key routes connecting the cities. The primary highways run along the North-South corridor, and others provide vital links in the East-West Direction. The average travel time by car between the cities using these highways is approximately 6 hours.

For public transport, several options are available: trains, buses, and flights. When considering air travel, the travel time between the cities is more than 1 hour. Rail represents a solution with a low environmental impact and high competitiveness. The railway line connecting the two Italian cities serves as a vital link in national rail network, facilitating around 40 trains on an average weekday. Major cities along the route serve as important nodes for high-speed services, offering convenient connections to other destinations across the country and beyond.

The route is serviced by intercity trains, providing direct connections between major cities and regional hubs. These trains make stops at intermediate local stations enhancing connectivity and accessibility within the region.

Regional trains complement the service offerings on the line, serving smaller communities and providing essential links for local commuters and long-distance travellers. With frequent stops at intermediate stations, regional trains play a crucial role in facilitating travel within the region.

Overall, the railway line serves as a crucial transportation artery, facilitating seamless connectivity between major urban centres and regional hubs. With different types of services, the line offers passengers a diverse range of transportation options, ensuring efficient and reliable travel between the two hubs.

In order to complete the technical and socioeconomic feasibility analysis, a transportation service with an MDS vehicle based on magnetic levitation has been projected for some of the intermediate stops along the historic route based on similar services that already exist. This type of service guarantees greater coverage than a high-speed rail, with the trade-off of a lower speed. However, it would benefit from the increased performance with higher speed when traveling through the different regions over long distances. Additionally, the system will take advantage of improved vehicle dynamics provided by MDS during deceleration and acceleration phases at stops, enhancing performance and making this service more attractive by combining high coverage with efficient operations. The theorized service would serve 16 stops, listed below.

6.2.2 Demand Analysis

To estimate the demand for the Hybrid MDS based on magnetic levitation use case, a comprehensive railway trip matrix for a year was constructed using displacement data obtained from mobile phone tracking for the municipalities along the line. This data is stored in a database where trips are measured as the unit of analysis.

Every trip contained in the database includes information regarding the origin, destination, transport mode used for the trip, weekday, time, regularity, and duration. To identify and geolocate the origin and the destination of the trip, the database is equipped with a cartography in which the Italian peninsula is divided in almost 3000 Transportation Analysis Zones (TAZs).

The database used to perform this analysis allows to identify all the trips in a selected month, including non-systematic ones. This characteristic represents a strength, also considering the line under analysis which links cities with high tourist flows. In this way, it’s possible to consider also the trips motivated by tourism or leisure.

6.2.2.1 Methodological framework

The first step to estimate the demand, is to define the possible stops of a MDS service along a specific long-distance route. This step is necessary to identify which municipalities could be influenced by the hypothesised service. To define the catchment area in which the journeys originate or terminate, it was necessary to set two different variables: the first was the centroid, coinciding with the station at which the train is scheduled to stop, and the second was the isochronous time interval or the estimated time interval in which users would be attracted to the station to start or finish their trip with an intermodal first/last mile phase.

Considering the type of service, which is similar to an intercity, the isochronous time interval has been set at a maximum of 30 minutes and is variable for each of the selected stops. Depending on the characteristics of the municipalities and the accessibility to the stations, the isochrone has been calculated assuming that, for small municipalities with a low population density, the user makes the journey to the station by private transportation means, while for big cities with high population density and with an extensive public transport system, the user accesses the station through collective transport means.

Another assumption regarding the definition of the catchment area has been that for cities with two stations, a single catchment area was considered, resulting from the aggregation of the catchment areas of each station. (i.e. for a major city: the catchment area is the aggregation of the catchment area for all of its stations). Given this last approximation, fifteen catchment areas have been identified for the long distance route.

The final step to estimate the demand consisted in associating the catchment area of each station with the corresponding TAZs of the demand database through a geo-analysis. For every single municipality assigned to the catchment area of a station, one or more TAZs from the database were associated, considering the degree of overlapping of the two layers. The result of this process is an assignment of one or more TAZs for each station in which the service is hypothesised.

Once the TAZs were assigned to a station in the hypothesised service over the specific historic route, it was possible to estimate the number of trips which originated or terminated in each station during the analysis period contained in the database. A monthly trip matrix was first defined as a base to derive a yearly matrix. Considering the availability of the data, November was selected as a typical month for the analysis, as other months contain more holidays and seasonal variations.

Since the available data only refer to one month, an approximation was necessary to estimate the total annual demand. This approximation involved calculating a daily demand by dividing the monthly data by 26 (a factor defined to account for fact that daily demand varies, especially on weekends) and then multiplying this last value by 300. The factor of 300 approximates the number of active travel days in a year, excluding weekends and holidays. This procedure allows for a good approximation of the annual demand based on the monthly data.

Finally, the demand matrix was symmetrized by incorporating its transpose. Each O/D pair in the matrix was adjusted by adding its corresponding pair from the transposed matrix and then dividing it by two. This process ensures symmetry in the matrix reflecting equal demand between O/D pairs in each direction, while excluding intrazonal trips.

6.2.2.2 Travel demand for the railway mode

The estimation of the demand used for the analysis refers to a time interval of one year for only the railway mode, as specified in the previous chapter.

Comparing the generation and the destination of each zone, it results that a central city along the route is the main pole within the line. This is explainable by the characteristics of the city, since it is not only interested by an influx of tourists but also by home-work journeys due the proximity to other urban centres. The main point of interchange is with another significant city, which is the very populous city in the region and one of the area's industrial poles.

The same observation could be made for the demand between two points in another region: one major city and a nearby urban area. In fact, the main component of demand between the above-mentioned cities is accounted for by systematic travel, which represents more than

55% of the total demand.

6.2.3 Operational Scenario

The MDS Express is a high-speed transportation line based on the implementation of a hybrid MDS based on maglev on the historical regional line connecting several major cities

The definition of the use case reflects RFI's need to evaluate the performance of a hybrid MDS on secondary regional lines, as an alternative to constructing new HSR lines. At the time of MDS system implementation, the line will be equipped with the ERTMS L2 signalling system.

The entire route has a length of less than 600km.

The trains on this route cut across the country. This operational scenario provides an overview of how an MDS line operates, using capsules connected by means of virtual coupling forming a convoy as rolling stock and employing a mixed operation of MDS and traditional train technology, with capsule movements governed by GoA 4 (Grade of Automation 4) at maximum speed of 300 km/h with an acceleration of at least 1.5 m/s^2, an operational deceleration of 1.5 m/s^2, and no limit on emergency deceleration capabilities. The circulation is managed automatically by the control centre, according to the planned timetable which regulates the spacing of the capsules considering also the movements of traditional trains on the line. Additionally, the control centre could adjust the speed of the capsule if needed during perturbed regimes, by setting limitations and configuring different performance levels. A single pod can have up to more than 70 passenger seats.

Prior to the scheduled departure time, automatic checks ensure that the capsules are ready for the journey. Comprehensive technical checks are conducted to ensure that all systems, including magnetic levitation and propulsion, are functioning properly. To guarantee that the timetable planning for new vehicles is compatible with timetabling for traditional trains, these automatic checks must be carried out in a time not exceeding the timetabling resolution i.e., their duration cannot exceed 10 seconds.

Passenger embarking and disembarking is carried out autonomously, without any aid or check from staff. Luggage is allowed within passenger's responsibility as in existing rail vehicles. Circulation of passengers inside the vehicle can have place in any travel moment within the same safety level nowadays available on traditional rail vehicles. Use of seatbelts is excluded.

Once all safety checks are completed, the capsule begins moving along the track, gradually accelerating to cruising speed.

Throughout the journey, the possibility shall be guaranteed for onboard staff to provide assistance to passengers, offering beverages, snacks, and information about the journey and upcoming stops.

In case of emergency, the on-board staff will proceed to assist the passengers, coordinated by the traffic control centre.

The capsule reaches the destination station promptly, strictly following the predetermined schedule. Upon arrival, the capsule comes to a gradual stop, and passengers can disembark autonomously. Passengers retrieve their luggage and exit the capsule to proceed to their final destinations, while ground staff prepares for the next journey.

After each journey, the capsule undergoes preventive automatic checks to ensure that all systems are in optimal condition for the next journey.

Ground staff can perform thorough cleaning operations inside the capsule, ensuring that it is clean and ready to welcome passengers on the next journey.

6.2.3.1 Scenario A

This scenario involves the analysis that will evaluate the implementation of the existing line with Magnetic levitation technology, without any technological or infrastructural upgrade intervention.

This intervention will lead to evaluating the applicability of the new technology on the basis of the minimum achievable requirements:

- Propulsion: LSM,
- Levitation: U-shaped sliders on existing rails,
- New M4R-pods,
- Existing line alignment.

Both scenarios involve the use of newly designed lightweight pods capable of carrying 70 people and achieving speeds up to 220 km/h. Two different propulsion systems are possible from the partners of the project consortium: LSM and linear induction motor (LIM). The first version of the propulsion system uses a linear synchronous motor (LSM), where a part of the vehicle's propulsion system is energetically passive and consists of a set of neodymium-iron-boron permanent magnets arranged on a steel core. The vehicle begins to move when electric power of precisely selected parameters is supplied to the linear motor stator. Then, the electromagnetic force starts to act on the movable element and moves the vehicle.

The second version involves using the MDS propulsion subsystem based on an LIM embedded in the vehicle. The inductor windings surround the magnetic core of the motor, and the U-shaped armature covers the assembly. The U-shaped armature is composed of a first internal part in copper or aluminium for the circulation of the induced currents, intimately associated with a part in magnetic material for channelling the magnetic field. On the open side of the U-shaped armature, the inductor is capped with an electromagnetic screen which blocks the leakage electromagnetic field.

For this study in work package 7.2 and 7.3, the LSM system from NEVOMO will be the technological basis for the following estimations. This must not to be understood as a decision for later implementations but will help to estimate the technological needs and possibilities for one of the possible solutions.

In this scenario, the levitation and guidance system are based on the principle of magnetic induction between materials with different permeabilities, through the interaction of a U-shaped slider with a ferromagnetic rail. The existing standard rail will be used and no additional equipment will be needed from trackside. The movable part is made of appropriately arranged permanent magnets in a U-shaped ferromagnetic profile. The rail is made of a material with high magnetic permeability, such as iron. The interaction between the slider and the rail generates a vertical force that suspends the load. This levitation principle is called "ferromagnetic levitation."

The newly designed pods will operate within the existing line alignment. This means that all physical characteristics of the track, such as curvature, gradient, as well as other elements like bridges or tunnels, will be preserved.

6.2.3.2 Scenario B

This scenario involves the analysis that will evaluate the implementation of the existing line with magnetic levitation technology, with all the technological and/or infrastructural upgrade interventions necessary for the system to function optimally and with the maximum attainable performance.

this intervention will lead to evaluating which applications and needs are required to achieve maximum fulfilment.

- Propulsion: LSM,
- Levitation: sliders on additional levitation beams,
- New M4R-pods,
- Changing line alignment to prevent “speed drops”.

This scenario also involves the use of newly designed lightweight pods capable of carrying 70 people and achieving speeds of up to 250 km/h. Two different propulsion systems are possible for use: LSM and LIM. The first version of the propulsion system uses a linear synchronous motor (LSM), where a part of the vehicle's propulsion system is energetically passive and consists of a set of neodymium-iron-boron permanent magnets arranged on a steel core. The vehicle begins to move when electric power of precisely selected parameters is supplied to the linear motor stator. Then, the electromagnetic force starts to act on the movable element and moves the vehicle.

The second version involves using the MDS propulsion subsystem based on a linear induction motor (LIM) embedded in the vehicle. The inductor windings surround the magnetic core of the motor, and the U-shaped armature covers the assembly. The U-shaped armature is composed of a first internal part in copper or aluminium for the circulation of the induced currents, intimately associated with a part in magnetic material for channelling the magnetic field. On the open side of the U-shaped armature, the inductor is capped with an electromagnetic screen which blocks the leakage electromagnetic field.

In this scenario, the levitation and guidance system are based on the sliders on additional levitation beams attached outside the rails fixed to the sleepers or slab tracks.

For this solution, the newly designed capsule will operate on an adapted and customized line alignment. This entails modification work to adapt the curvature and gradient of the track to minimize speed drops as much as possible.

6.2.4 System Functions and Elements

Interoperability of infrastructure stands as a paramount requirement. While conventional Full Maglev systems such as Transrapid and proposed hyperloop routes demand purpose-built infrastructure, hybrid Maglev solutions offer the flexibility for mixed operations of conventional railway rolling stock alongside Maglev pods.

This system entails the deployment of a hybrid MDS based on maglev technology on existing railway lines. In this scenario, MDS vehicles/pods will utilize the existing infrastructure and coexist with conventional trains on the same lines. Magnetic systems will handle propulsion, guidance, and levitation.

The fundamental unit of Maglev rolling stock will be a single pod (vehicle) similar in size to a standard wagon, capable of accommodating approximately 70 passengers. These single pods can be combined into "platoons," comprising two or more virtually coupled consists, without mechanical connections. Depending on capacity demands, pods can also be designed with physical couplings. Cabin crew in these pods will solely focus on passenger care.

The pods will consist of main components listed below:

- Structure,
- Propulsion,
- Suspension,
- Guidance,
- Braking system,
- Vehicle control and monitoring system.

The mechanical structure of the vehicle ensures the safe installation of propulsion systems, suspension, stabilization, and other necessary subsystems, guaranteeing the safe transport of passengers and their luggage.

The vehicle's propulsion system (mover) is energetically passive, consisting of NdFeB (Neodymium Iron Boron) permanent magnets arranged on a steel core. Electric power with precisely selected parameters activates the linear motor stator, initiating movement by exerting electromagnetic force on the mover. The linear motor must both provide propulsion force and enable braking. Automation level will be GoA 4, allowing fully automated and unattended operation on prepared infrastructure.

The pods suspension and guidance rely on MDS systems, necessitating permanent magnet arrangements onboard the sliders. Interaction between traditional railways or additional guideways and levitation sliders generate appropriate levitation and stabilization forces. The sliders are segmented and connected to the vehicle structure to ensure that they follow the profile of the tracks while the vehicle is progressing alongside them. While Maglev pods can operate on wheels like conventional trains, they start levitating slightly over rails on maglev corridors. Specialized auxiliary systems or finishes are needed to prevent wheel damage during engagement operations. The bogies are also similar to that known from traditional railway vehicles and have to secure the same functionalities, when pods are running without levitation or along non-equipped lines. In those cases, running stability and all static and dynamic loads are handled by the wheel-rail contact and the components of the bogie. To reduce the weight of the pods the bogies are made of lightweight materials e.g., aluminium alloys or composites.

To ensure lateral confinement and centering, lateral stabilization systems are essential, in addition to magnetic levitation systems. These systems are active only when the train operates in levitation mode and are integrated onboard the levitation sliders, interacting with the ferromagnetic rails to ensure centering and stabilization.

A crucial aspect of operating Maglev vehicles on existing infrastructure in case of possible infrastructure upgrade is the need for additional cant to achieve higher velocities while ensuring interoperability with traditional trains on the same tracks. The TSI 1299/2014 describes the allowed cant which is set to a maximum of 160 mm (or 180 mm for tracks only used by passenger services). If higher cants than the built-in are needed to reach higher speeds, MDS components can be installed in a way that they only affect those vehicles in high speed levitation mode as it is shown at last stage in the Figure below. With such a solution, the built-in cant stays the same for all vehicles operating on wheels and standard rails, but vehicles in levitation mode can use the advantages of a higher cant built by the additional levitation beams outside the standard rails (see also Figure *41*). In any case, the solution chosen depends on the specific operational (e.g. mix of trains using the tracks, reachable speeds) and technical (e.g. existing cant, curve radius, gauge) requirements.

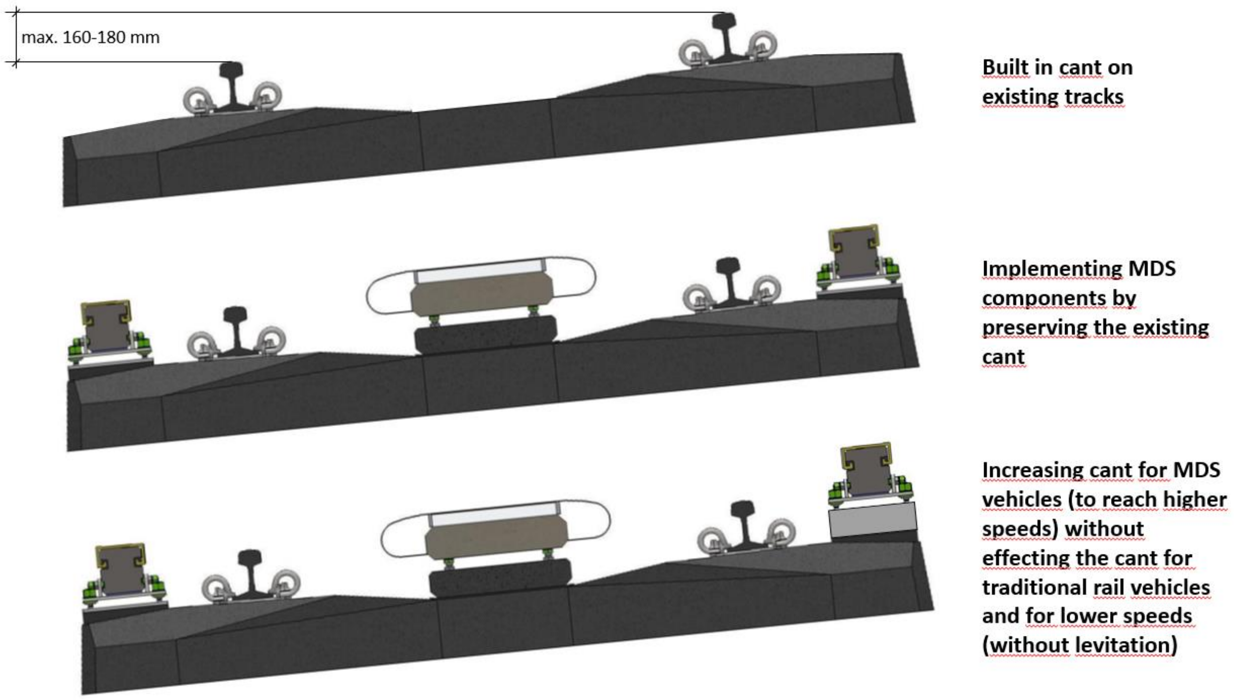


Figure 3: Implementing additional cant for MDS vehicles

The pods are equipped with an emergency braking system capable of bringing the vehicle to a complete stop at any location and time, irrespective of the functionality of the primary braking or propulsion system (which are combined into one system). This emergency brake system encompasses both infrastructure components and rolling stock components, integrated within a signalling and vehicle control system layer.

Adapting the infrastructure appropriately to meet the specific needs of the use case is crucial to harnessing the positive effects of the new system. Hence, it is always preferable to modify the infrastructure rather than utilizing it as is, which may result in diminished or negligible positive effects for the system. Consequently, the infrastructure comprises a conventional (existing) railway line supplemented with additional components: a linear motor (positioned between two conventional rails) and additional high-performance magnetic levitation guideways deployed on both outer sides of the rails on Maglev corridors. The deployment of this Maglev technology will be feasible on existing infrastructure and conventional rolling stock will be still able to operate on it. As a result, infrastructure equipped with such MDS components will be always interoperable with conventional vehicles, as it is shown in Figure 4, and will not create obstructions in conventional railway operations. The other way around, it is important to reduce the potential impact on the nearest environment if MDS equipped vehicles run on conventional lines. Therefore, adequate solutions must be part of the vehicle design e.g. lifting the magnets up.

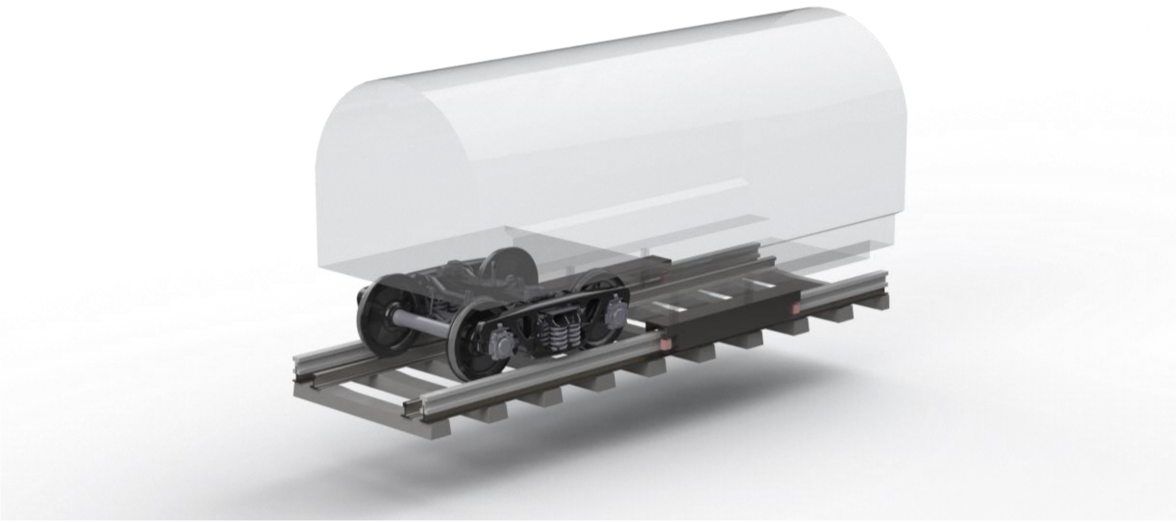


Figure *4*: Example of custom rails adopted in combination with traditional wheeled systems (source: IRONLEV)

Signalling and communication technology must facilitate the mixed operation of conventional trains and Maglev pods, enabling joint traffic control in compliance with both conventional train control systems and new ETCS systems, which communicate with GSM-R and future FRMCS. Given the importance of ensuring compatibility with existing railways, studies need to be conducted to establish the necessary requirements.

The Vehicle Control and Monitoring System comprises a set of measurement and control devices located on each Maglev Pod. This system serves as a central vehicle decision-making system, collecting data from subsystems, communicating with Maglev management systems, and controlling subsystems when necessary. It also incorporates the anti-collision system and

Juridical Recording Unit. The control centre is an integral part of the infrastructure. The existing version of CCS will not be utilized, necessitating new development.

Vehicle movement is controlled from the linear motor side. An electric power command and control system, based on sections and segments of the linear motor stator, enables precise vehicle position control on the track with an accuracy of up to 5 cm. The high efficiency of the propulsion system ensures very fast acceleration and deceleration, allowing for shorter separation times beneficial for high-level traffic control and optimal capacity usage.

In exceptional cases, such as major disruptions or blocked lines, as well as for bridging services using conventional railway lines not equipped with Maglev technology, the rolling stock dedicated to MDS operations can operate outside of a MDS line. Under specific conditions to be defined, the vehicle remains compatible and can operate on its wheels.

6.2.4.1 Main Subsystems

- Propulsion system: LSM,
- Levitation and guidance system: passive ferromagnetic levitation on conventional rails (scenario A) or additional levitation beams (scenario B),
- Vehicle: new designed MDS pods.

6.2.4.2 Main Components

Propulsion system:

- stator installed in between the existing rails fixed to the sleepers or slab track,
- mover equipped with permanent magnets attached to the vehicles,
- control centre to command the linear motor,
- inverter stations to deliver needed power to the linear motor.

Levitation and guidance system:

- Sliders with permanent magnets and lateral stability system attached to the vehicle,
- levitation directly applied to standard existing tracks (scenario A) or ferromagnetic levitation beam attached outside the rails fixed to the sleepers or slab track (scenario B).

Vehicle:

- New designed lightweight pods to carry 70 people and archive speeds up to 250 km/h,
- Interoperable with existing infrastructure.

7. Context analysis of the current reference state

7.1 Selected use case "Rail vehicle upgraded MDS configuration" – Verification of the existing vertical and horizontal route alignment

As the project team delves into the analysis of the proposed use case, one aspect emerges: the railway alignment requires no modifications. Contrary to initial concerns, the operational scenario does not necessitate significant increasing to the existing infrastructure.

The use case under examination revolves around the heavy freight and passenger transport boosting the speed and the load in the uphill direction.

Despite no specific alignment and track modifications being required, for Scenario B potential track and alignment changes represent a future opportunity. In fact, during the development of the study in Tasks 7.2 and 7.3, the possibility of modifying the proposed alignment will be explored to reduce costs related to tunnels and excavations. The quantification of this scenario is not included in this document but will be detailed in Task 7.3.

7.2 Selected use case "Hybrid MDS based on magnetic levitation configuration" - Verification of the existing vertical and horizontal route alignment

As the project team delves into the analysis of the proposed use case, an aspect emerges: the railway alignment requires no significant modifications. Therefore, two different scenarios for implementing MDS technology on the existing track have been developed.

In the first scenario, there will be no changes to the vertical and horizontal route alignment. Levitation and guidance will be achieved on the existing rails, and any potential speed increase will adhere to existing regulations. Improved propulsion performance and the introduction of new vehicles with tilting technology will enhance train dynamics, resulting in improved velocities and travel times.

The second scenario incorporates additional possibilities of MDS technologies and potential minor adjustments to the infrastructure to maximize effects on speed increase and travel time. Additional levitation (and guidance) beams will separate the new high-speed pods from the traditional rail vehicles. Consequently, speeds in curves can be increased for MDS vehicles without altering the existing route alignment or affecting existing railway traffic. Furthermore, this study will identify individual speed vulnerabilities that could significantly impact overall line capacity and quality of service if these points would be improved in their horizontal alignment, e.g. with slightly bigger curve radii where possible.

For both scenarios, the goal is to have none or at least only a minimum of needed upgrades to the alignment to achieve maximum effects.

8. General technical aspects for MDS systems

8.1 Signalling System

The purpose of this chapter is to highlight, regardless of the specific MDS technology used, which areas of the on-board signalling system could have side effects due to the use of MDS vehicles. It is a transversal chapter which contains all the aspects, linked to current signalling systems, which can also be influenced using MDS vehicles.

Following this analysis, which highlights the potential open points, it will be possible to analyse the impact of each point and any solutions designed to resolve them. This second step will be done during the description of each use case and the solutions applied in it

The assumption followed in this chapter's analysis is that the MDS vehicle together with traditional vehicles travel along lines equipped with signalling systems based on ERTMS/ETCS. So, if the signalling system is based on ERTMS/ETCS, some ETCS subsystem that can be affected by the operations of the MDS. These are:

- BTM-BALISE,
- Radio Communication System,
- On-board Train Interface,
- Train Detection System,
- Interface with other Trains,
- On-Board Localization System (this point is reported for future application, not yet in current TSI),
- ATO G0A4 (this point is reported for autonomous train, not yet in the current TSI).

For all these points, the potential issues highlighted during the activities in Made4Rail WP7 are reported.

8.1.1 Balise Transmission system

The standards in use describe the mechanical and electrical constraints that must be satisfied for the use of EUROBALISE.

In general, the origin of co-ordinates is in the plane of the top of rails, and in the middle of the track.

Constraint	Value	Comment
The maximum lateral deviation between the Z reference marks of the Balise and the centre axis of the track (see note below)	±15 mm	Tolerance for general applications.
Provided that the track curve radius is ^{3}1000 m and the Maximum Permitted Speed	±40 mm	Tolerance to be used only when the layout of the track does not allow

is 180 km/h, the lateral deviation from the centre axis 33 of the track may be:		for the general application tolerance.
Provided that the track curve radius is ^{3}1000 m, the Maximum Permitted Speed is 180 km/h and the Balise is installed 40 mm higher than otherwise allowed, the lateral deviation from the centre axis 33 of the track may be:	±80 mm	Tolerance to be used only when the layout of the track does not allow for the general application tolerance.
Allowed tilting of the Balise (Tb), related to the Y-axis:	±2°	
Allowed pitching of the Balise, related to the X-axis:	±5°	
Allowed yawing of the Balise, related to the X-axis:	±10°	

Table *6*: Eurobalise Mechanical Installation Constraints

Note: The central axis of the track is located half the distance between the webs of the rails. The value of the lateral tolerance does not include the influence from lateral rail wear (this shall instead be considered in the dynamic displacement of the Antenna Unit).

The Table 10 shows the tolerances for installing the EUROBALISE in the centre of the track.

For the EMC issues, it is necessary to verify that the new vehicle does not introduce spurious frequencies around the frequency of 27 MHz for the EUROBALISE energization functions. For CW Tele-powering signal. The magnetic field shall be produced at a frequency of 27.095 MHz with a tolerance of ±5 kHz. The signal shall be a continuous wave (CW). The carrier noise shall be < -110 dBc/Hz at frequency offsets ^{3} 10 kHz.

The field strength from the Antenna Unit shall be defined as magnetic flux linked to the specific current values.

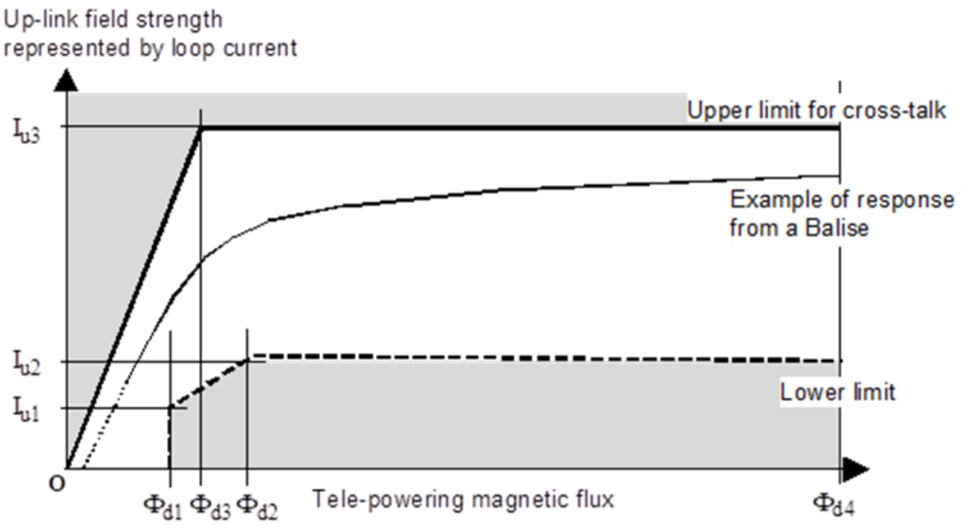


Figure 5: Input-to-output characteristics for a Balise

Characteristics for a Standard Size Balise:

Standard balise				
I_{u1} = 23 mA	I_{u2} = 37 mA	I_{u3} = 116 mA	I_{u3} = 116 mA	Non-permanent damage
Φ_{d1} = 7.7 nVs	Φ_{d2} = 12.2 nVs	Φ_{d3} = 9.2 nVs	Φ_{d4} = 200 nVs	Φ_{d5} = 300 nVs

Table 7: currents and flows for Standard Eurobalises

Characteristics for a Reduced Size Balise:

Reduced size balise				
I_{u1} = 37 mA	I_{u2} = 59 mA	I_{u3} = 186 mA	I_{u3} = 186 mA	Non-permanent damage
Φ_{d1}= 4.9 nVs	Φ_{d2} = 7.7 nVs	Φ_{d3} = 5.8 nVs	Φ_{d4} = 130 nVs	Φ_{d5} = 250 nVs

Table 8: currents and flows for Reduce Eurobalises

What is reported here is suitable for a preliminary investigation about the compatibility between the MDS vehicles and the current specification of the EUROBALISE.

For having a complete assessment, it is necessary to perform all the tests reported in the UNISIG 085 Subset, that guarantee the compatibility at the UNISIG Subset 036.

All these types of interoperability tests should be included in the activities carried out for MDS vehicles. This procedure must be carried on, if the signalling is ETCS, for each type of line on which the MDS vehicle circulates in all its operating conditions; this means that the tests must be carried out in such a way as to cover all cases of vehicle operation.

If the vehicle is fully compliant with the use of Eurobalises, there are no further requirements to consider. If this does not happen, the MDS vehicle is not able to read the Eurobalises or introduces disturbances that could cause malfunctions in nearby trains. In this case it is necessary to operate on the MDS vehicle and, depending on the side effect produced also on the other trains, in an operating mode that also requires visual circulation, and this would be extremely intrusive and unacceptable, also due to the repercussions on circulation of all trains involved.

Therefore, for a mix traffic the MDS vehicle must comply with the Eurobalises, as indicated above.

8.1.2 Radio Communication System

The communications associated with signalling in the ERTMS/ETCS area are currently based on GSM-R for circuit communications and GPRS for packet communications. The FRMCS specifications will be adopted in the future when they are consolidated.

In this context, the new MDS vehicles fit into and must comply with the TSI and the tests that must be conducted to verify compliance with this communication system.

In principle, there are no additional constraints applicable to MDS vehicles other than those that are already present. Compatibility in all service conditions must be certified. The applicable standards are:

1) ETSI EN 301 515 Global System for Mobile communication (GSM); Requirements for GSM operation on railways V3.0.0 (2018-07),
2) ETSI TS 102 281 Rail Telecommunications (RT); Global System for Mobile communications (GSM); Detailed requirements for GSM operation on Railways V3.1.1 (2019-01),
3) ETSI TS 102 610 Railways Telecommunications (RT); Global System for Mobile communications (GSM); Usage of the User-to-User Information Element for GSM Operation on Railways V1.3.0 (2013-01),
4) FFFS for presentation of functional numbers to called and calling parties fis for confirmation of high priority calls, reference F 12 T 6002 5.0,
5) FFFS for presentation of functional numbers to called and calling parties, fffs for presentation of functional numbers to called and calling parties, reference F 10 T 6003 4.

Similarly, as regards FRMCS, the specifications currently in use determine the following communication bands and the transmission medium used.

Currently, these are the main requirements to refer to verify the compatibility of the vehicle:

1) FRMCS Shall use radio spectrum (900 MHz,1900 MHz) for Railway Mobile Radio (RMR),
2) FRMCS shall support the use of 3GPP 5G NR technology for the paired frequency bands of: (M) a. 874.4-880.0 MHz, uplink b. 919.4-925.0 MHz,

3) FRMCS shall support the use of 3GPP 5G NR technology for the unpaired frequency band of: (M) a. 1900-1910 MHz 45 / 109 46 / 109,
4) An FRMCS Operator shall implement the RMR 900 MHz frequency band or the RMR 1900 MHz frequency band or both frequency bands,
5) FRMCS is able to flexibly use up to the maximum extent of spectrum available for rail in a given area,
6) FRMCS Radio Modules used for FRMCS communication purposes should support frequency bands allocated to public MNOs in Europe.

8.1.3 On-board Train Interface

An important aspect covered in this paragraph concerns the compatibility of current ETCS signalling systems inserted in an MDS vehicle. This to check whether any developments dedicated to compatibility with these new vehicles are necessary.

There are two main areas to explore:

- Interface with other vehicle Systems/Components,
- Odometry of the signalling system.

8.1.3.1 Interface with other vehicle Systems/Components

For the ETCS world, this type of system includes the OBU (On-Board Unit) for train protection functions and ATO (Automatic Train Operation) for automation functions. Both systems interface with the vehicle and can be affected by side effects produced by the vehicle or even produce unexpected effects. In accordance with railway regulations, it is necessary to carry out all checks of the operating conditions and therefore of the applicable standards referred to in EN 50155. This involves a series of checks of the site where the systems are hosted and of the use of the MDS vehicle in all possible operational ways so that the checks are exhaustive.

The new electronic systems used for on-board equipment are developed according to European regulations, these are designed to be unaffected by a wide band of disturbances. In the railway sector, the disturbance mask was designed for the technologies adopted up to that point. With the introduction of the new MDS systems, it is necessary to check whether the masks are still valid. Could it be that the MDS vehicles introduce signals of an amplitude not permitted in the masks currently in force, so it is necessary to evaluate how to manage this aspect. Introducing shielding at specific points could be the solution if the signal were to exceed the expected threshold.

Therefore, as mentioned for the radio communication part, it is necessary to have a clear image of the signals emitted by the MDS vehicles to evaluate any areas of intervention.

Carrying out these investigations is however a step required by regulations, therefore a nominal path for vehicle certification. For now, no additional operations have been highlighted, but only exploratory ones.

8.1.3.2 Odometry of the signalling system

Odometry in a signalling system represents the reference on which to base all movement protection controls. This quantity in all signalling contexts has a very safety integrity level 4 which is considered high. For this reason, it is important to highlight this point as it is necessary to evaluate the current implementations.

ETCS signalling systems usually use:

- **Wheel odometry**: refers to odometry (i.e., estimating motion and position) using rotary encoders (i.e., sensors that attach to the axle of the wheels to measure rotation). The electronic pulse generators (incremental encoders) work on a variety of principles, e.g. optical fork light barriers and Hall sensors. All axle-mounted sensors can be supplied in multichannel units. The pulse numbers, phase relationships and output circuits can be adapted to a certain extent. For these encoders the wheel has to "run" in contact with the track. The optical are based on laser pulse, while the Hall is based on specific magnetic field between the pick-up and the wheel or what is linked to the wheel. For these sensors, it is important to evaluate the correct contact between the wheel and the track, and it is necessary to evaluate any impacts due to the presence of magnetic fields,
- **Doppler radar sensor**: A Doppler radar motion-sensing transceiver typically transmits a continuous wave signal, receives the reflection of this signal from a moving surface, and compares the phase of the signals to demodulate the motion information. This information can be affected by the surface where the continuous wave is sent, and in general it can be tested in the environment where it is installed. Doppler radar technology uses, depending on the case, different frequencies ranging approximately from 8 GHz up to 24GHz. It is necessary to verify that the flows of the fields used for traction and/or levitation do not produce side effects.
- **Inertial measurement unit**: There are different versions of an Inertial Measurement Unit. Depending on the supplier needs, the IMU has different configuration. The more complete is composed of 3 accelerometers and gyroscopes, and 3 magnetometers depending on the application and precision. Together, these sensors measure specific force, angular rate, and magnetic fields around the device, providing a comprehensive picture of its motion.

All sensors applied in the railway sector comply at least with EN50155 standards and those referred to therein.

Within On-Board Systems, these sensors are used to calculate distance travelled and speed of the train.

Nothing prevents other sensors from being used, if in the end the result obtained is certifiable and the malfunctions and possible errors of each sensor can therefore be recognised.

Regardless of the type of sensor used, the system must be certifiable as SIL4 and have availability to allow the execution of the mission. This means that depending on the solution implemented, a certification phase is required for the generic solution and the specific one for the type of rolling stock.

8.1.4 Train Detection System

The use of Train Detection Systems on the line depends on the type of signalling applied. If the signalling also uses TDS for the location of the train along the line, then it is essential to verify its compatibility with the MDS vehicles.

In the ERTMS/ETCS, Train Detection System (TDS) may or may not exist both depending on the ETCS level adopted and any backup actions chosen by the Infrastructure Manager. If the signalling system provided on the specific line uses TDS, then it is necessary to evaluate the coexistence of the MDS vehicles with the TDS systems adopted.

It must be ensured that the present TDS system is able to safely recognize the presence of the MDS vehicle, otherwise there will be serious impacts on the safety of the line.

There are two main families of TDS adopted: track circuits and axle counters. Both systems can in principle have non-detections and/or false detections in the presence of MDS vehicles operating in their full functionality and may not be operational when the system is levitating. This fact certainly has an impact on the sure determination of the presence of the rolling stock on the rail. This means that levitation cannot be implemented if this type of TDS the only one present on the line travelled.

If there is not a correct coupling between the wheels and the tracks, the systems currently in use could fail to recognize the vehicle, so further investigations must be made in this direction to guarantee interoperability between the TDS systems used and the MDS vehicles. It is also necessary to carry out cross tests between the different technologies adopted to develop the MDS vehicles and the TDS systems in use.

These series of checks are essential to allow the circulation of MDS vehicles in operational service on the lines also travelled by traditional vehicles.

A possible mitigation at the adoption of TDS is the use of localization systems that implement the safe localization of the train using other sensors, like for example on-board sensors that detects digitally encoded location flags on the guideway. The Train Localization is addressed in the following paragraphs.

This type of approach, however, requires that there is a signalling system that safely identifies the presence of the train without the use of traditional TDS. In this case we are talking about new field devices that are using new sensors connected to the Interlocking for train detection in the ETCS Level 2 scenario or adopting ETCS moving blocks without TDS.

8.1.5 Interface with other Trains

Only for the signalling aspects, it is important to point out that in this chapter the effects of an MDS vehicle on other conventional rolling stocks are considered for the areas concerning signalling. In this chapter the other aspects are not considered, for example those of traction etc.

The disturbance mask obtainable from EN 50155 and the standards referred to therein, must be respected by all vehicles and therefore also by MDS vehicles in all operating conditions.

Therefore, in this chapter we consider the effects that may exist in the areas already considered in the other chapters relating to signalling. Some conditions are listed, that must be respected depending on the type of signalling used.

If the balises are present, there must be no cross-border effects when an MDS vehicle travels along the parallel line where a conventional train is running at the same time.

if there are trains (one of these MDS) stopped at the station on parallel tracks, it must be ensured that there is no mutual interaction, or that one rolling stock could cause malfunctions to the adjacent one. This applies to both the train interfaces and the communication media used.

8.1.6 On-Board Localization System

The part regarding the safe location of the train along the line is not a function that belongs to the TSIs currently in use.

The reason why it is included in this chapter is linked to the fact that the Safe Train Localization will probably be introduced and therefore it is necessary to prepare the MDS vehicles consequently.

The localization for the conventional trains uses a GNSS receiver, kinematic sensors and digital information of the line (line map). This set of information, if properly used, can safely provide the position of the train along the line.

It is therefore necessary to evaluate whether the MDS vehicle is compatible with the use of satellite receivers, gyroscopes or inertial platforms. Especially for gyroscopes and inertial platforms, the magnetic aspects are used to determine train poisoning. This could be influenced by the magnetic field produced by the traction of the MDS vehicle. It is therefore necessary, depending on the technological solution of the MDS vehicle, to evaluate its compatibility or to provide alternative solutions that are inherent in the adoption of the type of system created.

8.1.7 ATO up to GoA4

In general, the TSI currently in use will be updated especially following the results from ongoing projects, for example for the introduction of the ATO GoA 3/4.

This evolution also involves the introduction of the "standardized" use of other sensors for which compatibility with MDS vehicles will have to be verified.

For the CCS field, it is therefore necessary to identify a roadmap for MDS vehicles and define in this process how to adhere to and interact with the ongoing evolution. This way it is possible to anticipate any problem and find solutions that eliminate it.

One point in favour of this evolutionary path concerns the simplification of the lines with the reduction of the installed elements, and the movement of most of the intelligence on-board the train. Once all aspects of EMC on-board the MDS vehicle have been analysed and resolved, the path should proceed quickly towards the use of combined vehicles on the same lines.

For all other functional aspects, no functional incompatibility problems emerged. MDS vehicles will have to be added as other possible circulating vehicles, and the braking curves, therefore the spacing between trains, will have to be considered. But this is part of how to configure the control system.

It is necessary to understand the effects of new technologies compared to what is specified for the management of conventional systems. The ATO functions that have already been taken over by the TSI (GoA2) have the objective of having an automation system capable of simplifying operations always with the presence of the driver, for the new functions (GoA4) then they come into play automatic driving and/or remote driving functions without the presence of the driver on board. To achieve this result, it is necessary to introduce a series of new sensors (for example cameras or lidars) for which it is necessary to evaluate whether the field produced for traction can interfere with these functions. Communication aspects are also fundamental to reach the maximum degree of automation, GoA4.

One of the advantages of using MDS vehicles is the spatial precision in identifying the position of the train along the line when using an MDS vehicle.

For each sensor applied, preparatory to ATO functions, a test campaign must be conducted to verify the interoperability between the line and the MDS vehicles.

This type of check must be conducted for all sensors used and in order that the Safety principles are maintained.

8.2 Magnetic Analysis

Magnetic analyses are based on a finite element model to estimate the main parameters of the levitation system, with the aim of:

- evaluating the static transfer of vertical loads between the levitation system and the track,
- evaluating the dynamic behaviour of the levitation system,
- evaluating the energy consumption due to the magnetic drag generated by the levitation system and the associated drag force during relative motion between the levitation system and the track and based on the motion speed,
- analyse the spatial magnetic field around the levitation system to determine if there are magnetic interferences with other systems.

The analyses are performed with the aid of specialized Finite Element software to calculate the values of the parameters and outputs considered above.

The magnetic analyses performed started with a magnetostatic solution type and then progressed to a magneto-dynamic solution. The main steps involved in the analyses are the following:

- define the problem by outlining the system's geometry, material properties and external forces. It involves the representation of the system with a simplified geometry,
- create a detailed mesh to accurately represent the system's geometry and dynamics, ensuring precise field and force calculations,
- configure the FEA solver with appropriate boundary conditions and loadings to simulate magnetic field distribution and levitation forces,
- analyse simulation results to understand magnetic field strength, field distribution and optimize the design for efficient levitation performance.

The static and dynamic models were then evaluated and optimized in order to maximize the levitation performances. In the following chapters the main results are represented based on the specific case analysed.

9. Technical feasibility study and preliminary design of the maglev-derived system in the use cases selected

9.1 Selected use case "Rail vehicle upgraded MDS configuration"

9.1.1 Selected use case "Rail vehicle upgraded MDS configuration" – Scenario A

The Scenario A for evaluating the Rail vehicle upgraded MDS configuration corresponds to the existing railway line which links two cities. The existing line of this technical scenario has a speed limitation that makes it not possible to run high-speed trains in mixed traffic operation due to differences in maximum speed.

The main objective of this scenario is to evaluate whether it is possible to use goods trains where the introduction of MDS technology with Uphill Boosters / Incline Pushers can improve their performance, giving them a similar dynamic performance to the passenger trains with which they will share mixed traffic.

This Scenario involves the analysis that will evaluate the implementation of the existing line with Rail vehicle upgraded MDS technology, without any technological or infrastructural upgrade intervention. This intervention will lead to an evaluation of the applicability of the new technology on the basis of the minimum achievable requirements. This Scenario will be considered for freight traffic.

9.1.1.1 Evaluation of vehicle performance

This scenario could benefit from the introduction of Uphill Boosters / Incline Pushers, where additional power is introduced on uphill sections. This case study aims to achieve an increase in capacity of mixed traffic lines by upgrading the existing line with the introduction of uphill boosters, to allow heavy freight trains to maintain the maximum speed and travel time similar to those of passenger trains, even in difficult situations of adhesion limit.

9.1.1.1.1 Analysed configurations

To assess this Scenario, possible MDS vehicle configurations will be evaluated with respect to two basic configurations of conventional rail vehicles with the characteristics of the ones which are currently running on the line under study: a goods train and a passenger train. Table 9 shows the main characteristics and main parameters for the actual freight train:

Parameter	Value
Mass:	1.284 ton
Length:	484 m (locomotive + 30 wagons)
Power:	5.600 kW
Traction/brake maximum force:	+/- 320 kN

Table *9*: Actual freight train characteristics and main parameters

On the other hand, Table 10 includes the main characteristics of the passenger train (Regina) to be used, as a reference to compare with the freight train and try to have a similar dynamic behaviour in terms of reached maximum speed and travel time:

Parameter	Value
Mass:	161,2 ton
Length:	53,9 (2 coaches)
Power:	1.590 kW
Traction/brake maximum force:	+/- 107 kN

Table *10*: Passengers train (Regina) o be compared with the freight one

Figure 7 presents the traction curves and rolling resistances for both the passenger and freight trains. In this figure, it can be seen that for a railway line with the established gradients (17 ‰), the freight train is only able to reach 85 km/h while the passenger train can reach up to 140 km/h. These circumstances mean that, in this situation, it is not possible to make mixed passenger and freight traffic fully compatible, because of the differences in maximum speeds. The objective of this Scenario is to propose an MDS solution for the freight train that allows it to reach 140 km/h.

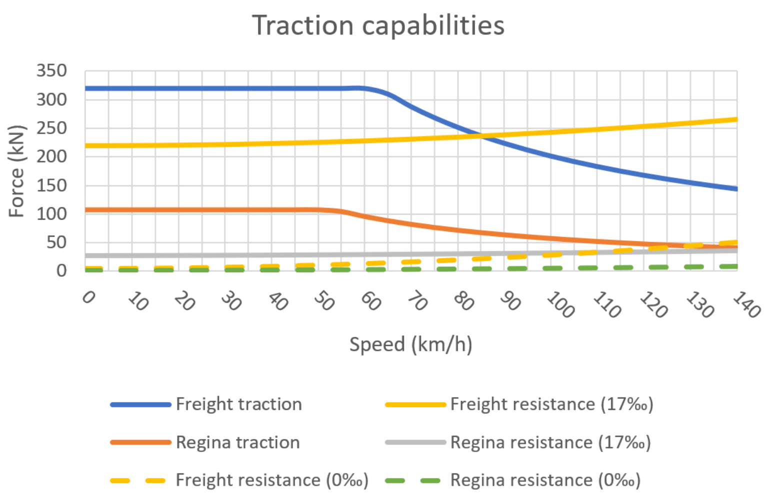


Figure *6*: Traction curves and rolling resistances for both the passenger and freight trains

In order to analyse different MDS configurations, two booster options have been considered to provide sufficient performance to achieve the desired speed and travel time:

- Option 1 (Regina imitation): booster that allows the freight train to imitate Regina's behaviour. The total traction capabilities of the freight train are modified to 850,6 kN and 12.407 kW,
- Option 2 (140 km/h limitation): booster that allows the freight train to imitate Regina's behaviour but taking into account the 140 km/h limit speed. The total traction capabilities of the freight train are modified to 850,6 kN and 10.805 kW.

These two options are shown below:

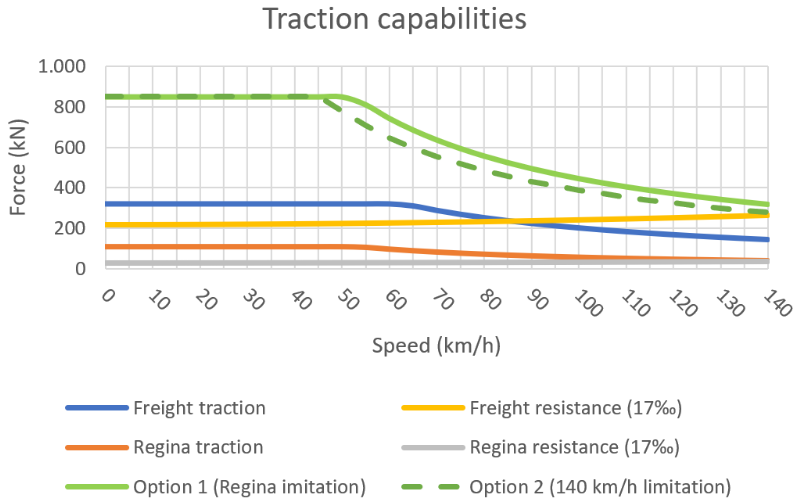


Figure 7: Different options considered for the booster in the freight train

9.1.1.1.2 Simulation model

The model defining the train motion of this work is based on the principles of longitudinal train dynamics (LTD). Hence, the train is considered as a point mass with one degree of freedom, where the traction/brake system, rolling resistances, air intake, aerodynamic drag, and slope and curve resistances are applied. The dynamic equations which are considered are as follows:

$$\dot{s} = v$$
$$M\dot{v} = -a - b\,v - cv^2 - F_e + F$$

where s (m) and v (m/s) denote the position and train speed, F (N) is the integrated driving/braking force, F_e (N) is the resistance force due to the track, M (kg) is the train's mass, a (N) is a term that includes the rolling resistance plus the bearing resistance, b (Ns/m) is a coefficient related to the air intake, and c (Ns^2/m^2) is the aerodynamic coefficient.

The resistance force F_e includes two components, F_g and F_R, which are defined as follows:

$$F_e = F_g + F_R$$
$$F_g = -Mg \times slope$$
$$F_R = -M \times 6/R$$

where F_g (N) is the component of the gravity force due to the slope of the track, the slope (m7m) is the slope of the track, g (m/s^2) is the acceleration of gravity, F_R (N) is the resistance in the curve, and R (m) is the radius of the curve.

The values of the *slope* and *R* depend on the line profile and the position *s* of the train on the line and are, therefore, known at each time.

9.1.1.1.3 Simulation results

The behaviour of the different vehicles on the line described in Figure *8* has been simulated using the model presented in the previous section. The following figures show the obtained results.

Figure *8* shows the travel time versus train position's diagram on the railway line. This type of diagram is typically used in line capacity analysis. In it, it can be seen how, for the same route and with the same stops, the current freight train today is much slower and needs more time to make the journey. In contrast, the proposals for upgraded vehicles with boosters achieve very similar performance to the passenger train considered as a reference, overlapping the curves.

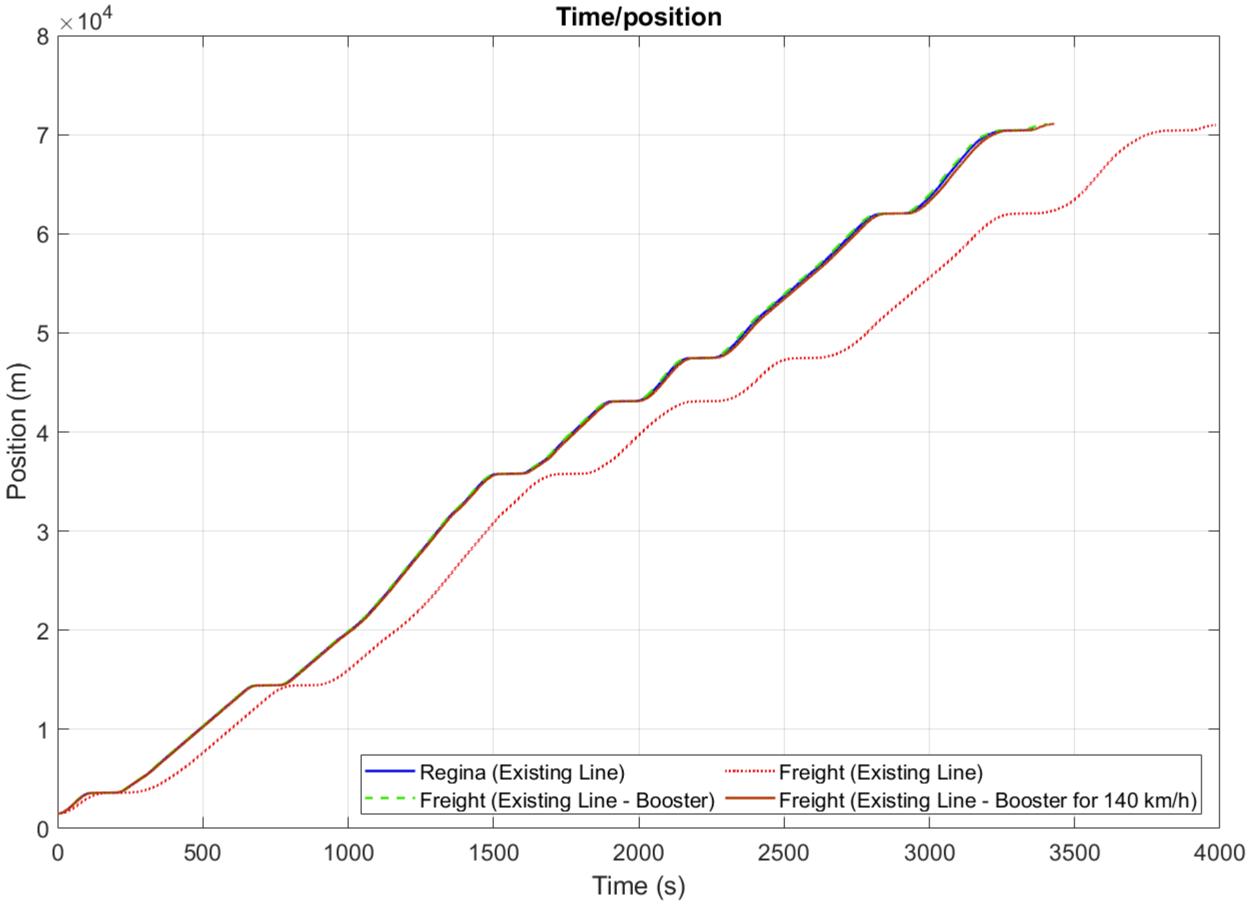


Figure 8: Time/position diagram for the different trains

Figure *9* shows the speed and longitudinal acceleration of individual railway vehicles at each point of the journey. On the left-hand side, it is shown as a function of journey time, and on the right-hand side, as a function of kilometre point.

In these plots, it can be seen again how the behaviour of the options with booster is very similar to that of the passenger train, while the current freight train needs longer travel time and has less traction/braking capacity and consequently lower traction and braking accelerations, which results in a considerably slower train in the end.

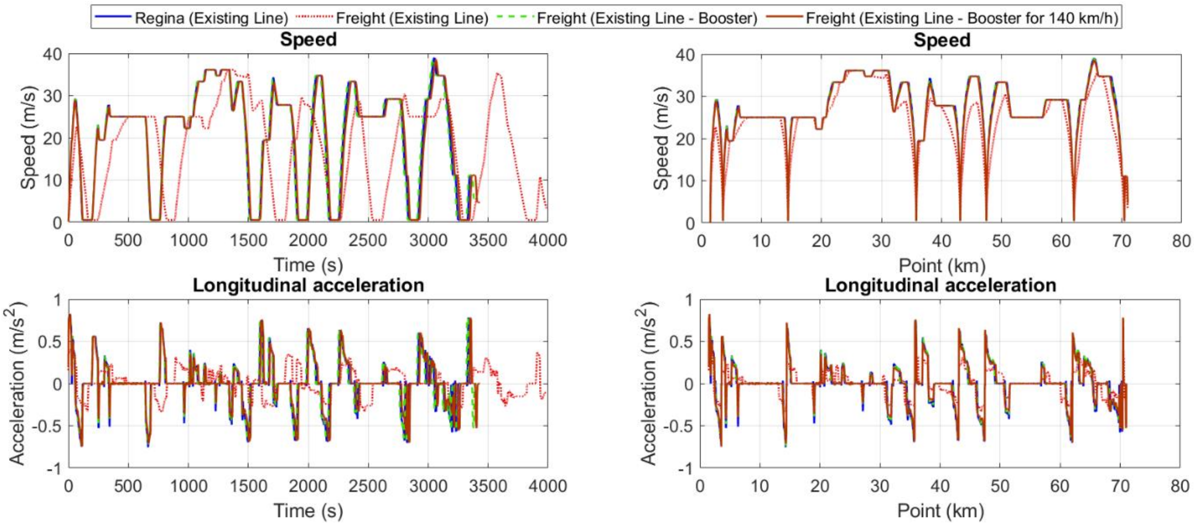


Figure 9: Speed and longitudinal acceleration for the different trains

Figure 10: shows the traction/braking requirements in terms of force and power for the different considered configurations. Here, the same trend can be seen again. As the current freight vehicle has less traction/braking capacity, it will need a longer travel time and will consume less energy than the two configurations considered for the booster.

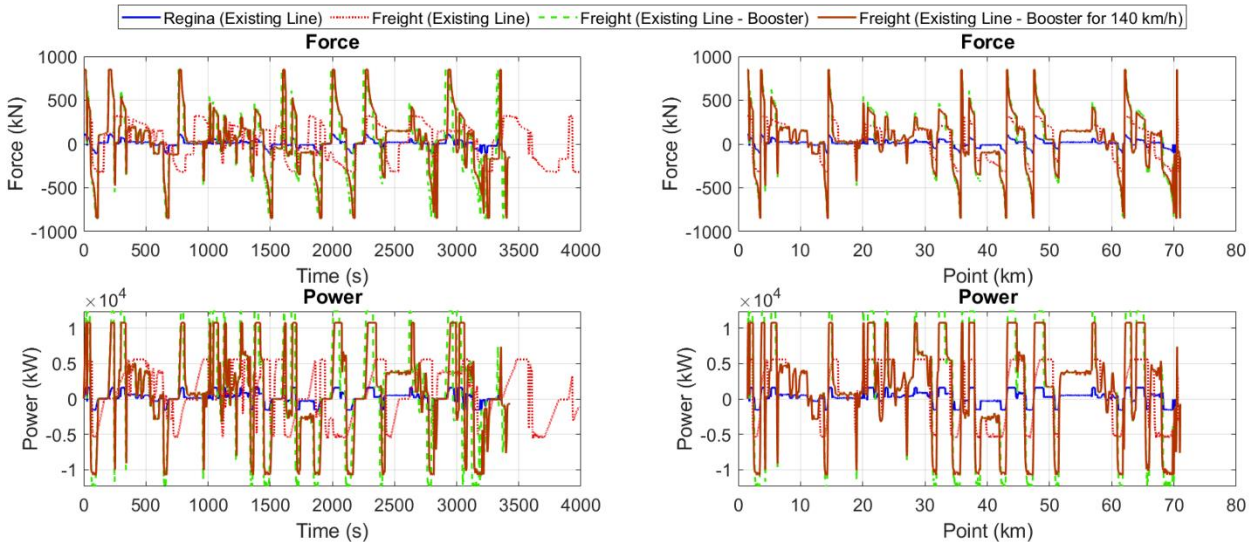


Figure *10*: Traction/braking force and power for the different trains

It should be noted that Figure 10: shows the total force required to move the train under the required conditions. This force includes both the traction/braking force provided by the conventional electric system of the train and the force provided by the booster, which is considered to assist in both traction and braking in this case.

It is interesting to segregate from this force the one provided by the booster. This force is represented in the following Figure:

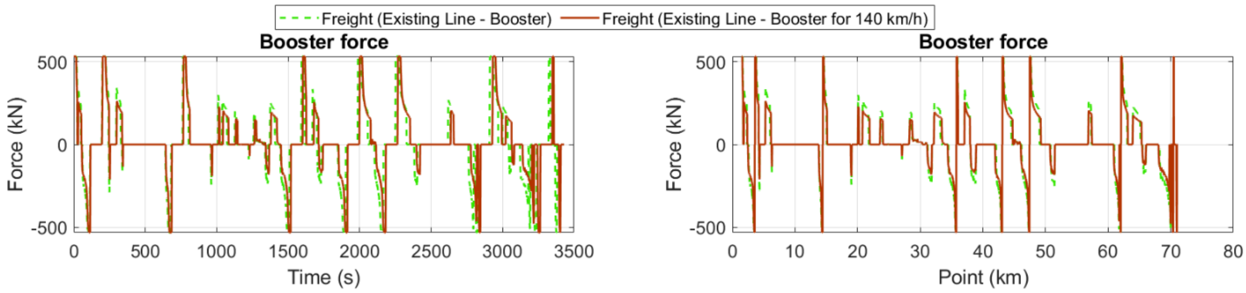


Figure *11*: Traction/braking force provided by the booster

In Figure 23, it can be seen how the booster only carries force at certain moments of the journey, when the conventional traction/braking is not sufficient. The peaks are related to the points where more acceleration and/or braking is demanded and coincide mostly with the entrances and exits of the stations. These circumstances occur mainly in acceleration or braking manoeuvres, and not when the vehicle maintains a more or less constant speed. This means that the booster can be limited to some sections of the line so as to optimize the practical implementation of the system.

In addition, if the 30 wagons of the freight train have a booster and the system needs to provide a maximum booster force of 500 kN for the entire convoy (approximately), each booster should provide 17 kN/booster (in case a booster is installed on each wagon). In any case, similar results in terms of behaviour and travel time can be obtained with shorter freight trains equipped with boosters, and therefore the total booster force required will be lower than the required in these results. This means that shorter trains can be used if total booster force is required to remain below a certain practical limit.

Finally, and in order to have elements to evaluate the use of this technology, Figure 12*:* is included, where the energy consumption during the whole journey is evaluated. Two values have been calculated, one for a system without regenerative braking, and the other with regenerative braking, considering an efficiency of 85%.

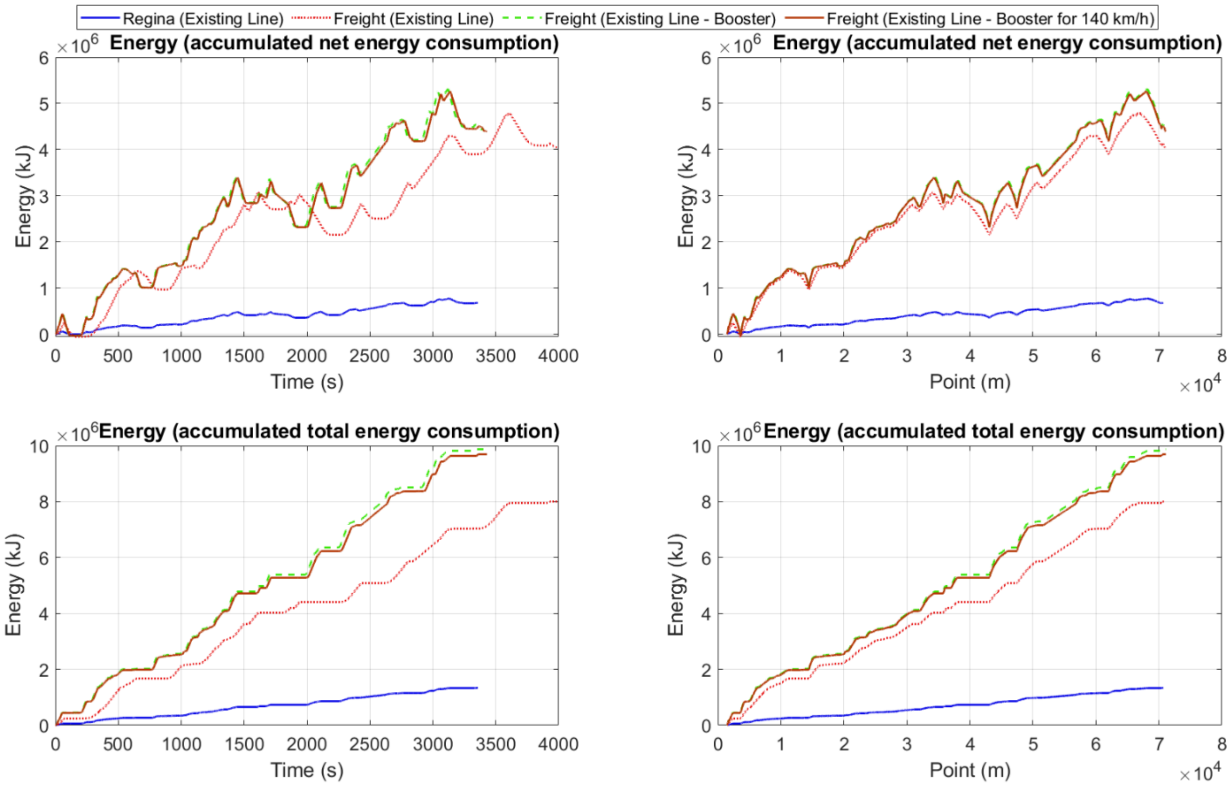


Figure 12: Energy consumption analysis

9.1.1.1.4 Conclusions

If we compare travel time and energy consumption, we can observe that, thanks to the booster, freight train can behave in a similar way to the Regina train (Option 1) and achieves a travel time of approximately 1 hour. Thus, travel time reduces nearly 15% with respect to the freight travel without booster. However, consumption increases 517,89 kWh (+23%) without energy recovery and only 111,10 kWh (+5%) with energy recovery.

When Option 1 is limited in power to take into account the maximum speed of the line (Option 2), travel time is close to 1 hour, but the energy consumption increases only up to 467,14 kWh (+21%), which saves 10% with respect to Option 1, and 83,34 kWh (+3,8%) with energy recovery. These results are summarized in Figure 13:.

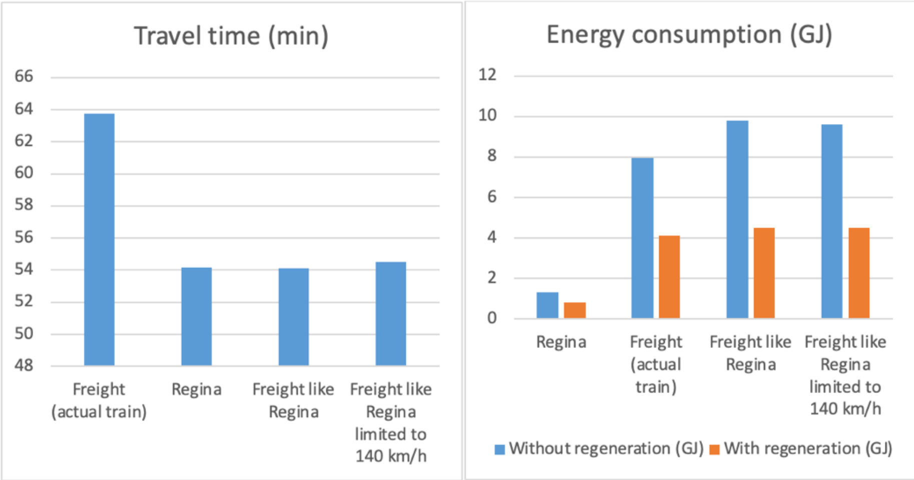


Figure *13*: Comparison between travel time and energy consumption

These results are very promising as a significant reduction in journey time is achieved for the freight train, bringing it on a par with the passenger train, with which it will be able to run in mixed traffic.

Regarding energy consumption, although it is higher than in the original freight train and the power is considerably higher, the total consumed energy is not relatively high because it is compensated by the potential increase in capacity and the shorter journey time compared with the original train.

Consequently, the results show that the considered proposals are of great interest and show potential for application.

9.1.1.2 Civil works

Railway track retrofitting

Some general measurements are needed to be done before the MDS components can be installed. Infrastructure must fit to the requirements of the used system. Preliminary works will be:

- Secure track quality regarding to the standard of this line for mixed traffic and speeds up to 140 kph,
- Sufficient track stability to dynamic loads of faster accelerating, running and braking freight trains.

To secure the needed quality, it might be necessary to maintain the tracks to a high-quality level, before starting the implementation of the new MDS technologies. These efforts are not only specific for the new traffic system and cannot be estimated for this study, as the condition of the route is unknown.

Track alignment

There are no specific technical requirements on minimum needed curve radius for this configuration of upgraded MDS coming from definitions in deliverable 4.2. Nevertheless, it should be checked if higher speeds, accelerations and decelerations of freight trains increase dynamic loads, especially in narrow curves. Therefore, all narrow curves with radii below 400 m along the existing line were analysed. The table below shows all relevant curve segments. Because of implausible data on the first section of the line, the analysis starts around 5 kilometres after the starting point. As train speeds will not be high within station area, this simplification is not crucial.

Element type	Length	PK	PK Final	Radius	Cant (mm)
Circular curve	66	6594	6660	-338	100
Circular curve	353	7020	7373	298	135
Circular curve	382	7497	7879	-297	135
Circular curve	37	7979	8015	-337	1
Circular curve	25	9659	9684	295	135
Circular curve	39	9843	9882	-295	125
Circular curve	150	11006	11156	295	125
Circular curve	277	12081	12358	345	105
Circular curve	160	12485	12645	-295	130
Circular curve	70	12695	12765	-350	120
Circular curve	202	12815	13017	-293	130
Circular curve	204	13135	13339	385	80
Circular curve	125	19214	19339	288	95
Circular curve	279	19434	19713	-299	85
Circular curve	27	19996	20023	-260	135
Circular curve	414	35705	36118	303	85
Circular curve	355	36232	36587	-299	125
Circular curve	315	36691	37007	326	90
Circular curve	42	39249	39291	-376	130
Circular curve	128	39856	39984	-383	135
Circular curve	235	40195	40430	357	140
Circular curve	349	42013	42362	-346	150
Circular curve	77	52211	52288	-291	130
Circular curve	219	52582	52801	302	120
Circular curve	63	53064	53127	-303	120
Circular curve	39	53976	54015	-359	105
Circular curve	100	54152	54252	293	130
Circular curve	289	54728	55017	-354	130
Circular curve	72	55235	55307	280	150
Circular curve	143	55317	55460	305	130
Circular curve	39	55578	55617	-300	130
Circular curve	134	56137	56271	-300	140

Element type	Length	PK	PK Final	Radius	Cant (mm)
Circular curve	108	56564	56672	300	140
Circular curve	140	58588	58728	395	150
Circular curve	122,9	61161	61284	-391	150
Circular curve	68	62411	62479	-355	130
Circular curve	188	62507	62695	-303	150
Circular curve	185,9	70877	71063	303	125
Circular curve	239,1	71078	71317	313	120
Circular curve	136,6	71431	71568	295	50
Circular curve	131,2	71590	71721	307	50

Table *11*: Curves with radii below 400 m

Altogether 41 curves below 400 m radius should be checked, if stability of the track is sufficient for faster running and accelerating freight trains. 15 of these curves (marked yellow in table above) have radii below 300 m and might need specific analyses or inspections.

MDS infrastructure integration

The sample implementation method of the MDS components on conventional infrastructure is shown in the following overview for the Scenario A configuration. The Scenario A configuration will use a linear motor in the middle of the rails.

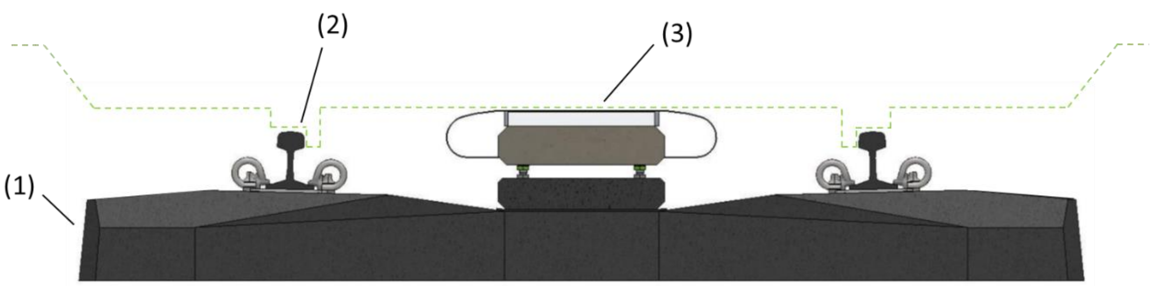


Figure *14*: symbolic picture of the MDS components

In the cross-section, to the conventional elements like sleepers (1) and rails (2) a linear motor (3) between the rails is installed. The configuration must be designed in such a manner that the UIC structure gauge is respected (green dashed line is the structure gauge).

MDS technology in this configuration will use conventional switches. In the switches, the stator will have a short gap which might not affect the propulsion of the train in a relevant way.

The new system needs additional components to provide the needed energy for the linear motor. Deployment of the power electronics subsystems contains especially grid and motor power converters, segment switches, cables for power and communications and the centre for motor control.

The line is a single-track line with bidirectional traffic. So, it is needed to implement the MDS linear motor everywhere along the line to guarantee the needed traction force for both directions. Between line kilometre 15,1 and 19,9 there is an almost flat section of 4,8 km length where no additional traction by linear motor might be needed. This also has been proved by the simulations. Additionally, some stations are equipped with an additional crossing track.

For this Scenario, the implementation of the linear motor in the station tracks is not necessary as the higher acceleration can only start when the last wagons passed the station switch. Therefore, no additional implementation on the passing and crossing tracks in stations will be considered. With a line length of ca. 70 km minus ca. 5 km of flat line section, as results from the simulations, this will lead to **ca. 65 km** of linear motor implementation altogether.

Existing superstructures

Adaptation of the existing railway superstructures to MDS needs will not be significant. For the bridges, there will be no construction changes planned as the weight and axle load are not changing. It has to be checked specifically if dynamic loads of faster freight trains can have negative effects. In those cases, speed will be limited to the maximum allowed limit given by maximum allowed dynamic load of the bridge. This is very specific and needs a detailed study on each bridge. For this study it is assumed that the stability of the existing bridges is strong enough. For the tunnels, there are no restrictions or major changes anticipated.

Single-level crossings can remain like they are. In these sections the stator will be lowered to the level of the rail heads. This will cause a less effective propulsion because of the bigger gap between the stator and the mover magnets, but street vehicles and pedestrians can pass the tracks safely.

9.1.1.3 Vehicle control and command systems

Compared to a traditional train, the TCMS must manage a different traction and a different brake control unit. In Any case, it must be checked the compliance with EN 50155.

9.1.1.4 Signalling systems

Considering what is indicated in the use case, the use of ETCS L2 is envisaged for signalling. The open points are:

a) To manage to install the Balises in the central position of the track,
b) Magnetic flux must not be intrusive in Balise On-Board Antenna communication.

It is necessary to evaluate the influence of the magnetic flux with respect to the TDS used (track circuits or axle counters). Since the wheel-rail contact does not change, if there are no side effects no change is required.

The biggest risk in this Scenario is not detecting the presence of a vehicle along the line. This could be due to the interference of an MDS vehicle with the adjacent line or of the MDS vehicle itself with respect to the line travelled. Instead, the aspects that compromise availability are:

- Not reading the encountered balise,
- Occupying a section unduly,

- Losing the radio connection,
- Interfering with the train traveling on the adjacent track.

9.1.1.5 Telecommunications

Considering the communication wayside on-board, these are the potential open points:

a) Verify that the new vehicle configuration complies with ERTMS standards included FRMCS,
b) No other potential open points are identified.

9.1.1.6 Energy and power systems

Considering the above trains and the above booster options, the simulation results for this Scenario were presented in the same previous section. The results from the simulation presented in the previous section of this chapter are summarized in the following Table 18, where an estimation of the mechanical energy consumption for each of the booster options is given. Reductions and increments are calculated with respect to the freight train in its normal travel without booster.

New Line	Description	Travel time (min)	Travel time reduction (%)	Travel time reduction (min)	Consumption (GJ)	Consumption increase (%)	Consumption increase (kWh)
Regina		54,17			1,33		
Freight		63,77			7,95		
Booster Option 1	Freight like Regina	54,10	15,2	9,7	9,82	23,4	517,89
Booster Option 2	Option 1 limited to 140 km/h	54,52	14,5	9,3	9,63	21,1	467,14

Table *12*: Scenario A simulation results

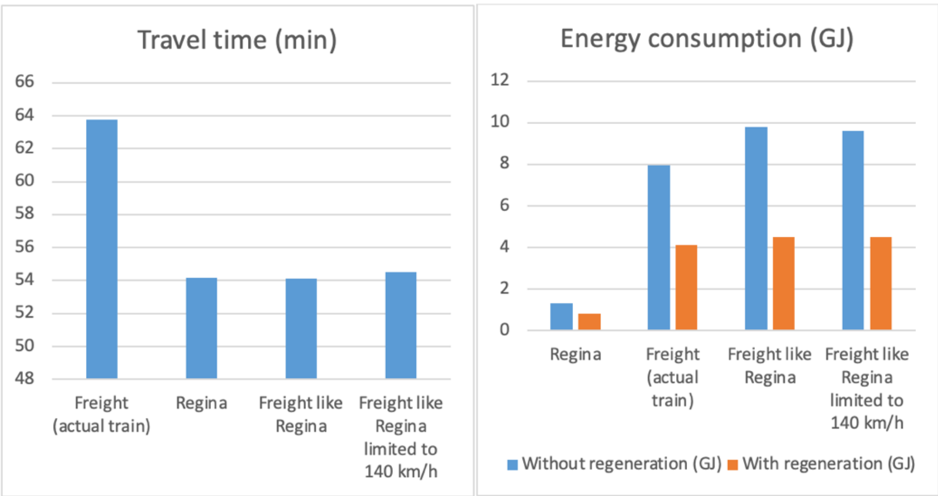


Figure *15*: Comparison between travel time and energy consumption

The MDS technology uses a linear synchronous motor and consists of two subsystems:

- Stationary system — the track infrastructure,
- Mobile system — the vehicle and its appliance.

The stationary part of the motor is a stator with a three-phase winding. The distributed type of winding is placed between rails in the track. The moving part of the motor, called the mover - which is the equivalent of the rotor in rotary motors - Is placed in the vehicle, and consists in surface-mounted permanent magnets in an N-S-N-S pattern placed on the flat steel yoke. The power electronic system is a part of the stationary infrastructure. From the drive system viewpoint, the vehicle is a passive component.

MDS propulsion system is based on a two-inverter configuration. Inverters operate interleaved, energy-supplying alternately the segments over which the vehicle is currently located. Each inverter can be connected to the stator by every two-segment using a segment switch. This configuration allows supplying all segments under the mover, even when the vehicle is moving from one segment to the next one.

To estimate the needed electrical power supply coming from the grid network, the system can be configured by the parameters of the infrastructure, the used vehicles and the operational concept. The needed traction force was calculated in the simulations. For the most promising booster (Option 2) the propulsion system needs to provide up to 530 kN of mechanical force and up to 6.800 kW of power.

In the next step, the configuration of the propulsion system can be estimated. This will be different for the different types of linear motor.

The NEVOMO system MagRail Booster uses a linear synchronous motor whilst the system of the project partner TACV-Lab produces the force by a U-shaped linear inductive motor. Both systems have advantages. It's important to note that all following calculations are based on the LSM setup, as there are significant differences between the two systems that should be considered.

To calculate and design the system, additional parameters are needed.

Freight vehicles (example of standard double bogie container wagon):

- Length of the wagons: 20 m,
- Length of the installed magnets per wagon: 7 m,
- Number of equipped wagons in the train: 20.

Infrastructure:

- Length of the sections: 6 km,
- Segmentation of the sections: 140 m.

By employing a six-turn winding configuration, the magnetic field generated by the stator is optimized for the desired traction performance. The inverters play a crucial role in regulating the current and voltage supplied to the windings, ensuring consistent and efficient operation. The specified current of 1,2 kA and voltage of 2,2 kV are chosen to achieve the necessary electromagnetic force for the MagRail Booster system.

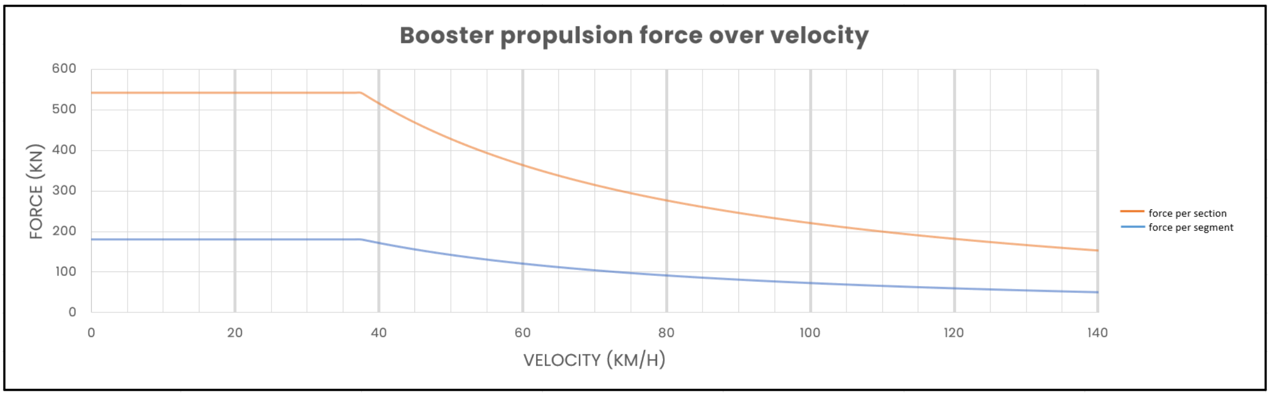


Figure *16*: force over velocity diagram

The resulting traction curve, illustrated in the diagram, reflects the relationship between the applied traction force and the velocity of the freight train. This curve is crucial for understanding the performance characteristics of the system. It demonstrates that the maximum traction force is provided up to ca. 40 km/h to ensure the acceleration when the freight trains come to a stop (e.g. in a crossing track). The orange line shows the force per section and the blue line the force per segment. This means, that the train will occupy three segments at every time.

After reaching this point, the provided traction force gradually decreases. At a speed of 120 km/h, the system can still deliver 180 kN of force what will be sufficient for the calculated needed forces of max. 158 kN coming from the simulations.

Splitting the – line into 12 sections, each section needs four inverters to guarantee a smooth movement of the pod, especially in the acceleration phase. Therefore, it can be guaranteed that always four segments in a row can be activated.

To enhance the overall efficiency of the system, each section of the track will be divided into 140 m long segments. This segmentation requires the installation of 43 segment switches per section along the line. These segment switches play a crucial role in managing and optimizing the flow of the system, allowing for precise control and increased performance.

At the stations, just the "main track" will be equipped, because the trains in the crossing tracks have to pass the turnouts with the restricted speed until the last wagon and can then be accelerated by linear motor on the "main track" with full needed propulsion force.

- Main line: 12 sections x 4 inverters = 48 inverters,
- Equipment of station tracks: no additional inverters,

This will lead to **48 inverters** all together.

- Main line: 12 sections x 43 segment switches = 516 segment switches,
- Equipment of station tracks: no additional segment switches.

This will lead to **516 segment switches** all together.

9.1.1.7 Interferences and interoperability

Magnetic interference with signalling system

In the context of this MDS use case, there is a potential interference observed between the linear motor mover and the ATC balises. The magnetic flux generated by the magnets attached to the vehicle might exceed the nominal values, for which the ATC balises are designed, by a factor of 300 to 500 times. This substantial increase in magnetic flux can induce a voltage in the ATC Balise Trackside Antenna (e.g., in ETCS Eurobalises it could have a ranging from 4 to 11V). Despite this relevant increase in magnetic flux, no physical damage is expected to be inflicted upon the ATC balise.

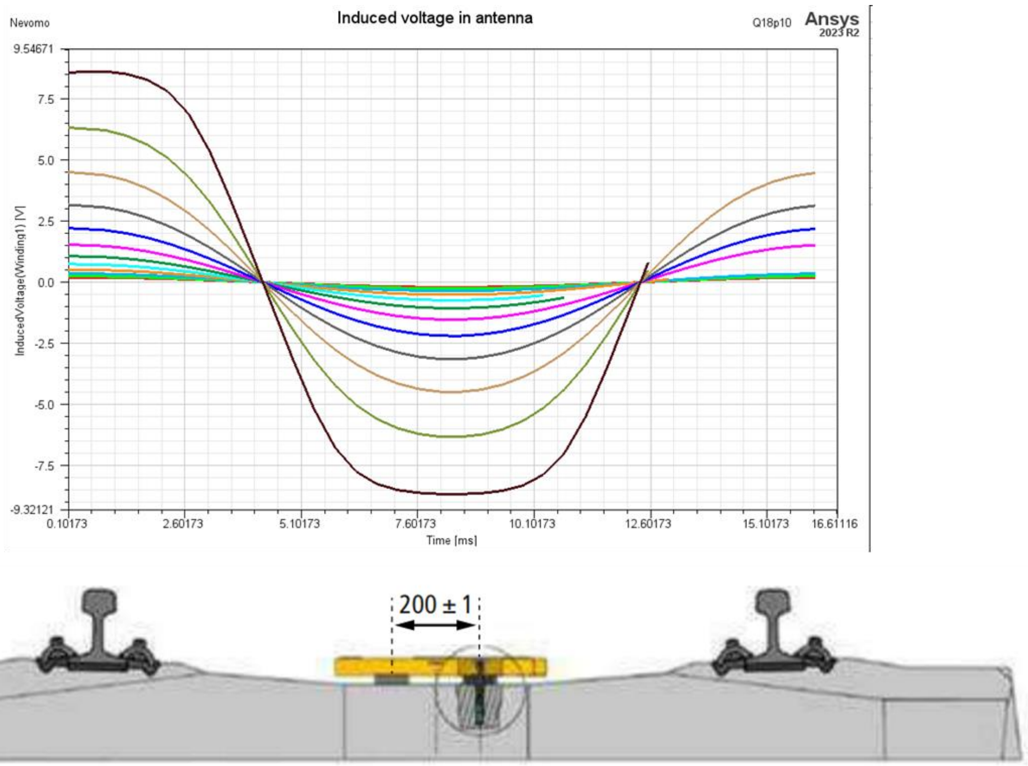


Figure 17: Induced voltage in antenna

Such interaction can impact system performance, potentially causing malfunctions in the CCS. To address this issue, further tests and validation are required. Additionally, operational adjustments can be implemented to ensure safe operation.

Structure gauge

The TSI INF specifies that the normative document to be considered when analysing the interoperable structure gauge is EN 15273-3:2013+A1:2016 (Railway applications – Gauges – Part 3: structure gauges). The structure gauge is divided into upper and lower parts. The upper part can be relatively freely selected according to the standard and local Infrastructure Manager (IM) requirements. The lower part, however, can be present in two variants: GI2, which is the general variant for the majority of lines, and GI1, which is used in cases where trackside rail brakes are installed.

As MDS components may interfere especially with the lower part of the structure gauge, it is essential to ensure compliance between the linear motor and levitation system with the GI2 (or GI1 in special cases) from the concept phase. This compliance must then be validated and verified during the V&V process to ensure safety.

9.1.1.8 Magnetic analysis

In the context of rail vehicle upgraded MDS, magnetic analyses, comprising electromagnetic analyses, magneto-mechanical analyses and dynamics, have the following main goals:

- Dimensioning of the traction system to be integrated on the vehicle, which includes both the stator components and the rotor. This process involves determining the optimal dimensions and technical characteristics required to ensure the efficiency and reliability of the traction system,
- Analyse the dynamic behaviour of the system in terms of power dissipation due to electromagnetic losses. This analysis is fundamental to understanding how electrical energy is converted into mechanical energy and to identifying any inefficiencies or critical points in the system,
- Evaluation of the magnetic effects on other systems or subsystems of the vehicle. It is essential to ensure that the traction system does not negatively interfere with other electronics or mechanical components of the vehicle, ensuring safe and reliable operation,
- Analysis of electromagnetic compatibility (EMC). This aspect is crucial to ensure that the traction system does not cause electromagnetic interference that could disturb other electronic devices on board or in the vicinity of the rail vehicle. Electromagnetic compatibility must be maintained to comply with regulations and ensure system safety,
- Assessment of magnetic or electromagnetic risks. This phase involves identifying and analysing potential risks associated with the magnetic and electromagnetic fields generated by the traction system. Various risk scenarios are considered, both for the safety of passengers and staff and for the integrity of the vehicle itself and the surrounding infrastructure.

9.1.1.9 Risk analysis

The discussion on risks is based on the identification of the hazards associated with the implementation of the incline pushers on the track, and the traffic conditions of the existing railway line between two cities.

The section will discuss possible accidents in the event of malfunction, external influences, human errors, etc., and their possible causes. The signalling system and the power control system have been separately discussed in the previous sections.

The railway line is single-track, electrified and curvy. The track uses wooden sleepers and has a high track gradient and relatively low operational speed (max. 120 km/h). many bridges and a few tunnels are located along the infrastructure. All the tunnels have tight infrastructure gauging and limited heights for catenaries.

Since Scenario A uses linear synchronous motors with minimum requirements, the trackside linear motor stators are only installed in the track sections with high track gradients to provide extra tractive force for freight trains, which can avoid using additional locomotives. Compared to the existing railway system on the route, besides the signalling system and power control system, there are two main changes on site: Upgraded wagons with permanent magnets beneath the wagons as the mover, and the 3-phase winding that needs to be installed in the track as the stator.

The accidents discussed in the section are grouped into the following four general categories:

Derailment

Derailment is a type of train wreck that occurs when some rail vehicles come off their rails. Although most derailments have low severity, all result in temporary disruption of the proper operation of the railway systems. They are a potentially serious hazard that can cause a big loss, e.g., hitting neighbouring trains, blocking tunnels and damaging infrastructure. If the derailment is very serious, some wagons can hit the neighbouring passenger train and even fall from the bridge, which could cause serious casualties.

Since the freight wagons still use pneumatic braking, there would be a lag to trigger the braking action of all the wagons. The braking effort of the entire train could not be well synchronized. Since there are many tight curves on the route, if the train driver applies severe emergency braking too hard, the wagons between the locomotive and the upgraded wagons with magnets can be pushed aside and climb up rails in tight curves, especially when the wagons are unloaded.

There are many tight curves on the route. When the upgraded wagons negotiate tight curves, the curving overthrow of the wagon can lead to lateral displacement and lateral force between the stator and the mover, weakening the running stability. When there is a crosswind (even within a normally acceptable range), the affected wagons can derail from the track.

Since there are many high vertical gradients and tight curves on the track, the incline pusher is used to replace additional locomotives, so the mechanical braking effort of the trains is weakened. The incline pusher is not totally a fail-safe solution or technology. Once the protection circuit immediately cuts off the circuit of the linear motor or the permanent magnet has been overheated, the incline will fail to brake. When the rail-wheel interface is slippery due to water and contaminated rail surface layers, the mechanical braking system of the trains cannot effectively lower the speed, especially when the train is passing a steep downhill gradient. The train would derail if it ran at an over recommended speed in tight curves.

The upgraded wagons with permanent magnets are supposed to operate not only on the defined route but also on any possible track route across the country. If there is any big piece of ferromagnetic metal not removed from the track by human error, the metal can be attracted by the magnet. If it drops onto the track, it can cause derailment.

Collision

A train collision is a type of train wreck that involves one or more trains. In this sense, the train collides with the neighbouring trains or infrastructure, which can be caused by miscommunication or serious derailment. Since the signalling and control systems were studied in the previous sections, only the collisions caused by derailment are discussed in this section.

When the derailment is serious, because of tight gauging in the tunnels, the derailed vehicle can hit the wall, which can cause serious injury.

The derailed vehicle can damage the infrastructure, e.g., signalling systems, catenary masts, and the stator of the linear motor. In most cases, the severity of this kind of collision is not very high. In the case that the trackside stator is damaged and thus shut off due to circuit protection, the emergency braking performance would be greatly decreased, which can result in more serious derailment.

Since the route is through a populated area, there are many railways over bridges. The worst case is that the derailed vehicle crashes into the pillar of a railway over bridge. Once the bridge structure collapses, the personnel on-board and the bypassing persons/vehicles on the bridge would get affected and even led to casualties.

Fire

Compared to the existing systems with high voltage catenaries, the incline pusher needs the installation of on-track windings, which makes the high voltage conductor relatively more accessible and vulnerable.

The insulation of the windings can be damaged by flying stones, falling objects, improper track maintenance, animals and even vandalism. Since the stator is not always energized unlike the catenary, the damage can be detected only when there is a train passing over. If the protection circuit is not properly triggered, the grounded or short-circuited conductor can generate heat or spark, which can ignite the wooden sleepers on the track. The old wooden sleepers contain some harmful chemicals, and while burning they can release harmful fumes, which are dangerous for the neighbouring residents.

When there is a collision, the flammable goods carried by wagons can drop onto the stator of the linear motor. If the damaged windings of the stator are not immediately shut off, the goods can catch fire and even explode, which can lead to casualties when it is close to a residential area.

Electrocution

Since the high-voltage windings are on the track, the insulation has a higher probability of being damaged by flying stones, falling objects, improper track maintenance, animals and even vandalism than the railway catenary. The exposed high-voltage conductor is more accessible to intruders, trackside workers, and evacuated passengers in an emergency than the railway catenary. Since the route is through a populated area, there is a higher chance of intruders getting into the track area.

If the damage is not detected and the protection circuit does not shut off the power in time, the persons in the track area can get electrocuted.

During track maintenance, repair or inspection, if the winding power supply is not shut off because of human errors, the personnel can get electrocuted.

Examples of risks identified in the analysis of the use case study and where to direct the attention are presented below. There are six kinds of malfunctions linked to the mover and stator, where actions may need to be considered. They are as follows:

- The linear motors and the locomotives are supposed to provide traction and braking force at the same time when the trains are negotiating steep gradients. However, the linear synchronous motors are controlled and powered by the trackside control centre and inverter stations while the locomotives are controlled by the train drivers. If the actions of the two parallel systems are not well synchronized, there would be some associated hazards,
- When the wagon negotiates a curve, the vehicle's centre line is still straight while the track's centre line is curved. Thus, there is a difference in the positions of the two lines, known as curving overthrow. Since the mover is located in the centre of the wagon and the stator is in the track centre, the lateral misalignment between the mover and the stator can cause some lateral forces, which can weaken the vehicle's running stability in curves,
- The permanent magnets beneath the upgraded wagons are supposed to run on both the defined track sections with stators and the other existing track sections all over the country. The permanent magnets can attract not only ferromagnetic dust but also large pieces of ferromagnetic metal, which can degrade the traction and braking performance and even challenge running safety,
- The permanent magnets are sensitive to temperature but exposed to the open air. When a magnet is exposed to the cold, its magnetic properties become stronger, while a higher temperature weakens a magnet's strength and magnetic field. The permanent loss of magnetic performance is experienced when a magnet is heated above its Curie temperature. The change to magnets is invisible, but the weakened magnetic field can decrease the traction and braking performance and even cause accidents,
- The stators which are energized in operation are installed on the track. The linear motor stators are more accessible for persons and animals than the overhead power lines. Since the stator windings are on the track, the insulation can be damaged by flying stones and other falling objects from passing trains or the steep and thus the energized conductor can be grounded, which can cause accidents in operation. Wooden sleepers may also catch fire,
- The incline pusher is used to replace additional locomotives to negotiate high-track gradients. Since there are fewer locomotives in use, once the incline pusher suddenly stops working the train braking performance would get much decreased, which would challenge the running safety.

9.1.1.10 Rolling Stock

As described in Chapters 6.1.3 and 9.1.1.6, this Scenario necessitates an upgrade of the existing freight wagons. Due to the unavailability of detailed information regarding the most frequently used wagon types on this particular line, this study assumed the use of a standard double-bogie container wagon, as illustrated in Figure 64. These wagons have a total length of nearly 20 meters, which should accommodate a 7-meter-long magnet pack. This specification is crucial for calculating the potential transferable propulsion force via the linear motor.

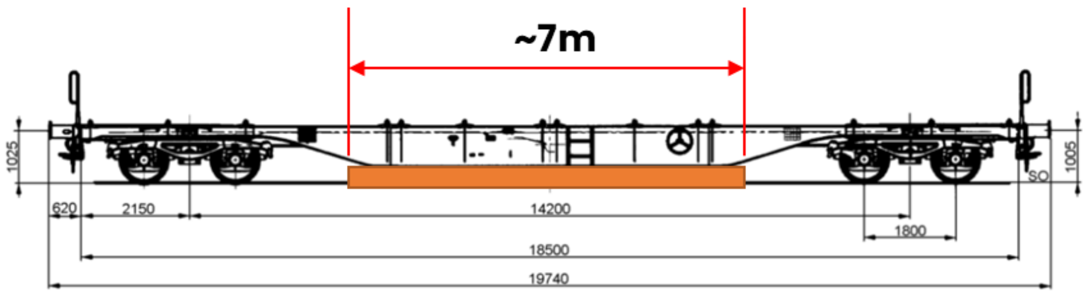


Figure *18*: example of magnet installation on standard intermodal waggon

The permissible train length on this line is 630 meters, which implies that a freight train composed of these types of wagons can include up to 30 freight wagons, plus a locomotive.

The need for upgrading these freight wagons is underlined by the linear motor's capacity to transfer propulsion force efficiently as presented in chapter 9.1.1.6. Given the standard length and configuration of the double-bogie container wagons, mounting a 7-meter magnet pack is both feasible and essential for optimal performance. The calculation indicates that in a train length of 630 meters, where up to 30 wagons are allowed, upgrading 20 wagons will enhance the train's propulsion significantly. This proportion, representing two-thirds of the train, ensures that the majority of the wagons are capable of leveraging the advanced propulsion system, thereby improving overall efficiency and performance on this specific line.

9.1.2 Selected use case "Rail vehicle upgraded MDS configuration" – Scenario B

The Scenario B for evaluating the Rail vehicle upgraded MDS configuration corresponds to a new railway line linking the two cities. As this corridor is a critical link in the Swedish network, a high-speed (250km/h) line has been proposed, the planning phase of which is currently underway. This new line would allow a significant increase in capacity by doubling the number of tracks between the two cities, and by segregating traffic with different speeds where passenger services would run mainly on the high-speed line whereas the freight services would remain in the existing line. The construction of a new high-speed line has very high investment costs, while having a significant impact on the capacity of the corridor.

The main objective of this use case is to evaluate if the trains that have been used until now (which have less performance than required for this line) can be used in a line of these characteristics, improved with a booster, compared with conventional electric trains of higher

power that can reach the necessary requirements of this new line.
The main characteristics of the line are shown in the following Table and Figure:

Parameter	Value
Number of stations	3
Length:	62 km
Maximum speed:	250 km/h
Max gradient:	22 ‰

Table *13*: Actual line characteristics and main parameters

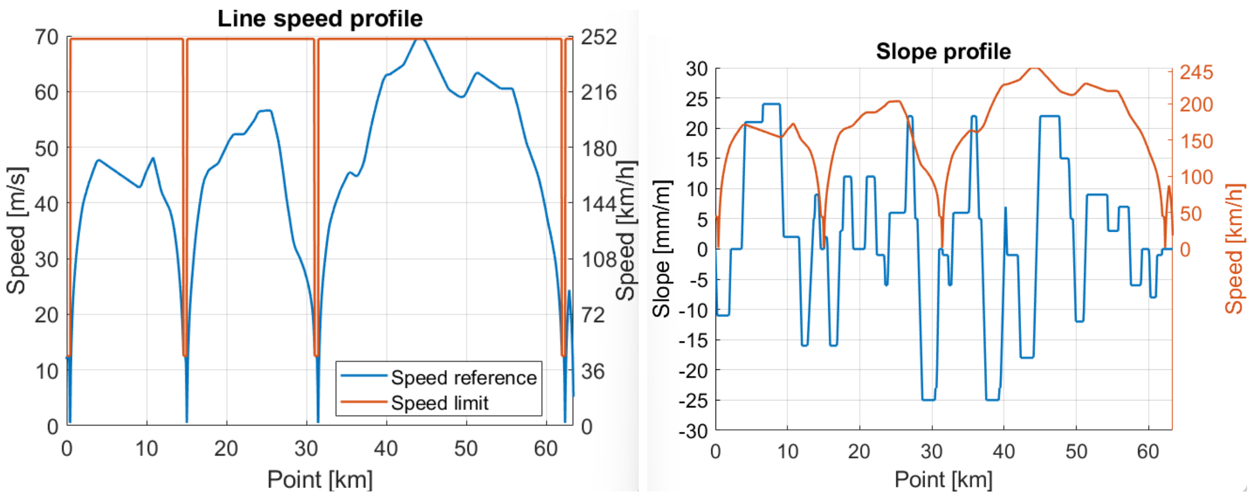


Figure *19*: Line characteristics and main parameters: Speed limitations and maximum speed able to be reached by the actual train (Regina) and Vertical alignment with slopes

The above Figure shows how the train running on the current line is not able to reach speeds of 250 km/h in areas with increasing gradients, reaching these speeds only in downhill areas with negative gradients. Therefore, the objective is to make the train capable of reaching speeds of 250 km/h over most of its route.

9.1.2.1 Evaluation of vehicle performance

This Scenario involves an analysis that will evaluate the implementation of the existing line with Rail vehicle upgraded MDS technology, with all the technological and/or infrastructural upgrade interventions necessary for the system to function optimally and with the maximum attainable performance.

This section pretends to evaluate which applications and needs are required to achieve maximum fulfilment. This Scenario will be considered for passenger traffic.

9.1.2.1.1 Analysed configurations

To assess this Scenario, possible MDS vehicle configurations will be evaluated, with two basic configurations of conventional passenger vehicles considered as references. The first reference vehicle corresponds to the passenger train with the characteristics of the one currently running on the line under study (Reference 1). These characteristics are as follows:

Parameter	Value
Train:	Regina
Mass:	161,2 ton
Length:	53,9 m (2 coaches)
Power:	1.590 kW
Traction/brake maximum force:	+/- 107 kN

Table *14*: Actual passenger train characteristics and main parameters

On the other hand, the second reference (Reference 2) includes the main characteristics of an electric passenger train capable of reaching speeds of 250 km/h over most of this route (Table 15)

Parameter	Value
Mass:	161,2 ton
Length:	53,9 (2 coaches)
Power:	4.157 kW
Traction/brake maximum force:	+/- 107 kN

Table *15*: Passenger train to be compared with the actual one (Regina)

Figure 20 presents the traction curves and rolling resistances of both trains. In this Figure, it can be seen that the current passenger train is only able to reach a speed of 120 km/h for increasing gradients of 25 ‰ and 140 km/h for gradients of 20 ‰. In order to reach speeds of 250 km/h with gradients of 20 ‰, a much more powerful electric train is needed, that is, a 4.157 kW electric train is necessary to achieve the desired performance. Therefore, the objective of this Scenario is to propose an MDS capable of reaching 250 km/h with the actual Regina trains and without using a 4.157 kW train throughout the line.

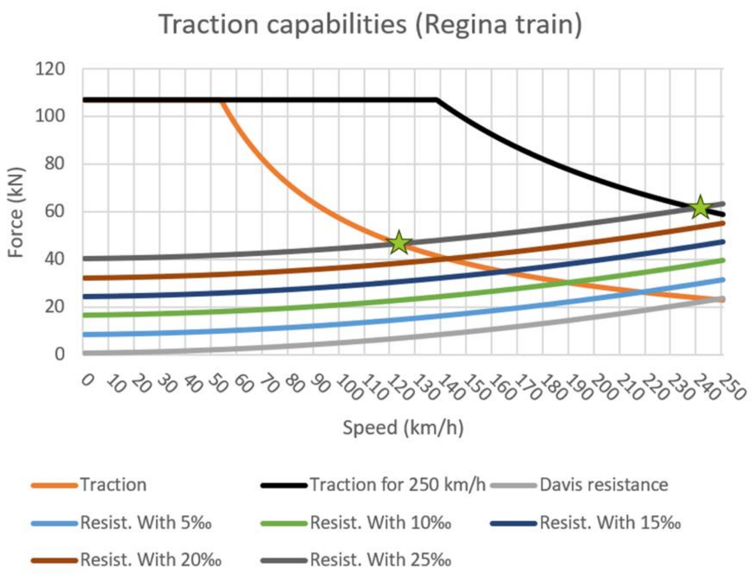


Figure *20*: Traction curves and rolling resistances for both of the passenger trains

For the subsequent analyses, the following assumptions are made:

- To reach 250 km/h with a gradient of 22 ‰,
- Regenerative braking performance: 85%,
- Booster is only applied for traction (NOT for braking),
- Max Acceleration: 0,8 m/s^2.

The objective is to combine the current train (1.590 kW) with a booster to achieve similar performance but with lower energy consumption than with a 4.157 kW conventional train.

In order to analyse different MDS configurations, several booster options have been considered to provide sufficient performance to achieve the desired speed and travel time.

- Option 1 (60 kN): booster that allows to reach 60 kN for speeds higher than 95 km/h,
- Option 2 ($P_{variable}$): booster that allows a variable power between the power of the Regina train and the power of 4.1 MW train,
- Option 3 (F_{max}): booster that allows the use of the maximum traction force (107 kN) for all speeds until 250 km/h,
- Option 4 (Accel): booster that allows an acceleration of 1,5 m/s^2 at low speeds,
- Option 5 (Accel + P_{max}): booster that allows a simultaneous application of option 4 with a booster that provides an equivalent power curve of 4.157 kW,
- Option 6 (Accel + F_{max}): booster that allows a simultaneous application of options 3 and 4.

Options 1 to 3 are shown in Figure 21

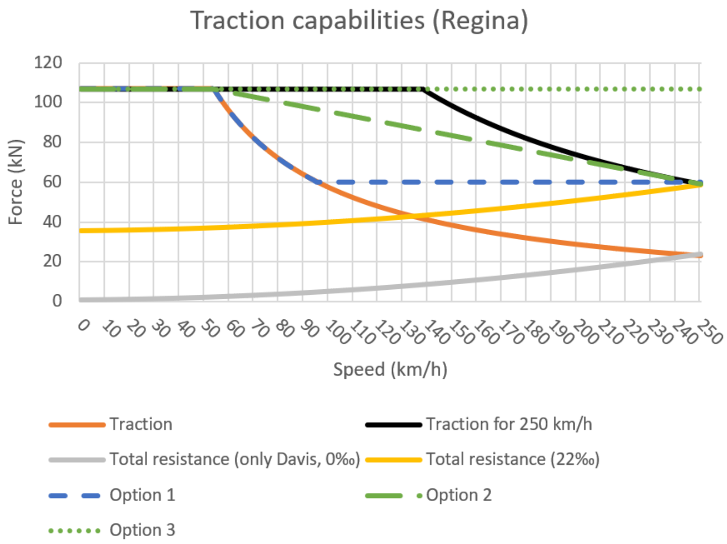


Figure *21*: Different options considered for the booster

9.1.2.1.2 Simulation results for the new line

The model defining the movement of the train in this work is the same as the one used in the previous freight case (see Scenario A) but adjusted with its corresponding parameters.

The six options defined in the previous section have been simulated but only results from Options 1 to 3 are presented.

Options 4 to 6 have given similar results to Options 1 and 3, showing improvement only when the train starts moving because this is when the traction force (and therefore, the acceleration) is higher. However, the speed and time at which it is applied are small, having no significant effect on travel time, while energy consumption increases. For these reasons, these solutions have been discarded.

Then, the behaviour of the different vehicles on the line described previously has been simulated using the model presented in the previous section. The following Figures show the obtained results.

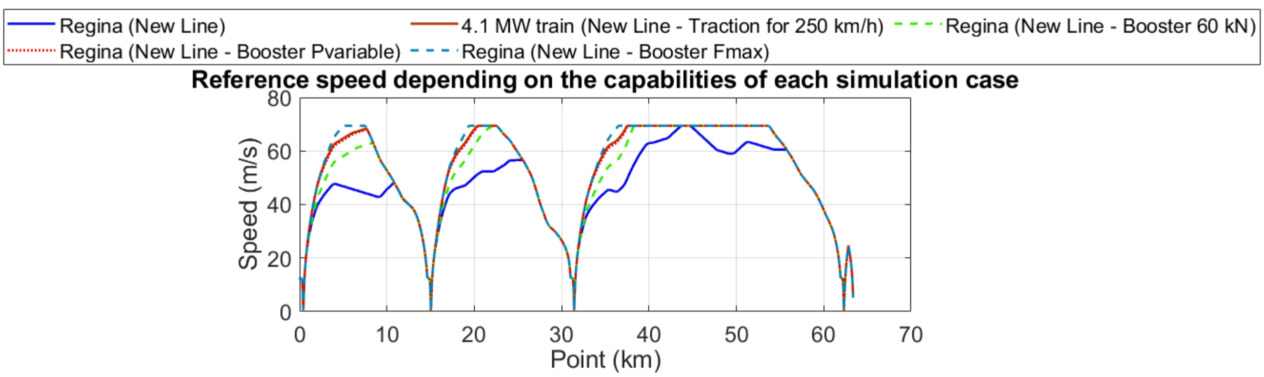


Figure *22*: Driving speed for each considered configuration

Figure 22: shows the driving speed for each analysed configuration. The two references considered for purely electric vehicles are shown in solid lines, while the dashed lines show the speeds achieved for each booster option. It can be clearly seen how the current train cannot reach the required speed, while the other options can reach it.

In addition, Figure 23: shows the travel time versus train position diagram on the railway line. It can be seen that, for the same route and with the same stops, the current train is significantly slower and takes longer to complete the journey. In contrast, the proposals for vehicles upgraded with boosters achieve a performance close to the passenger train considered as a second reference (i.e., they can travel at 250 km/h).

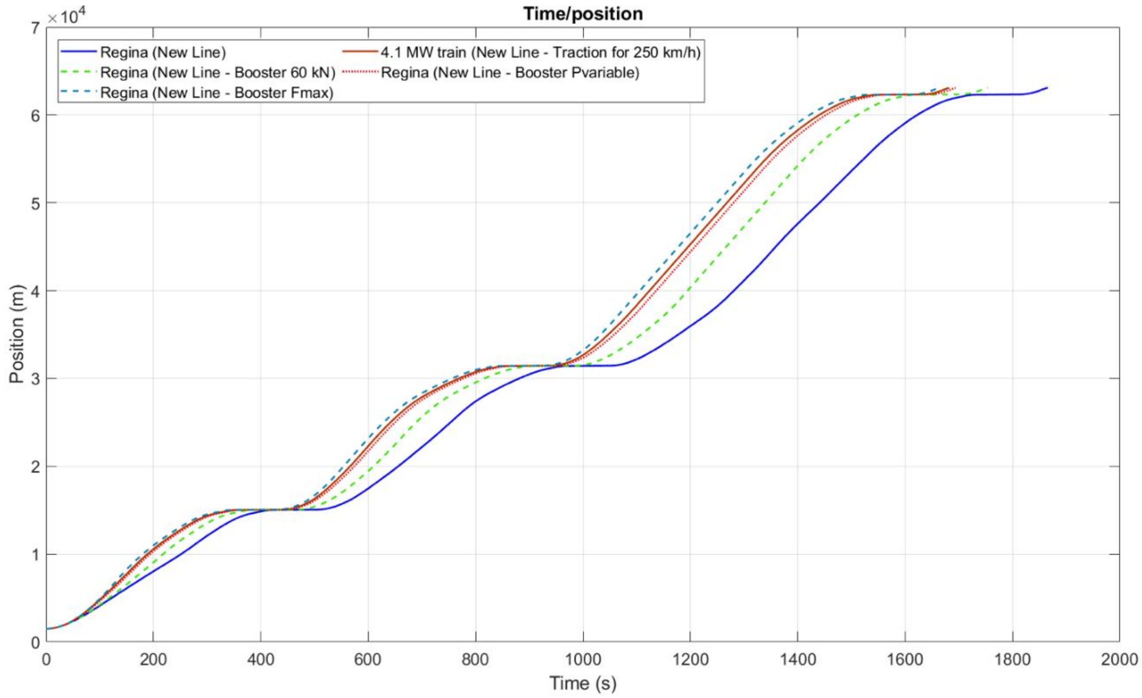


Figure *23*: Time/position diagram for the different trains

The speed and longitudinal acceleration at each point of the journey are shown in Figure 24:. On the left-hand side it is shown as a function of the journey time, and on the right-hand side as a function of the kilometre point.

In these plots, it can again be seen how the behaviour of the different booster options is close to that of the passenger train, substantially improving that of the current passenger train, which needs more travel time and has less traction/braking capacity, which in the end translates into a considerably slower train that is not able to ascend the gradients of the line at the required speed.

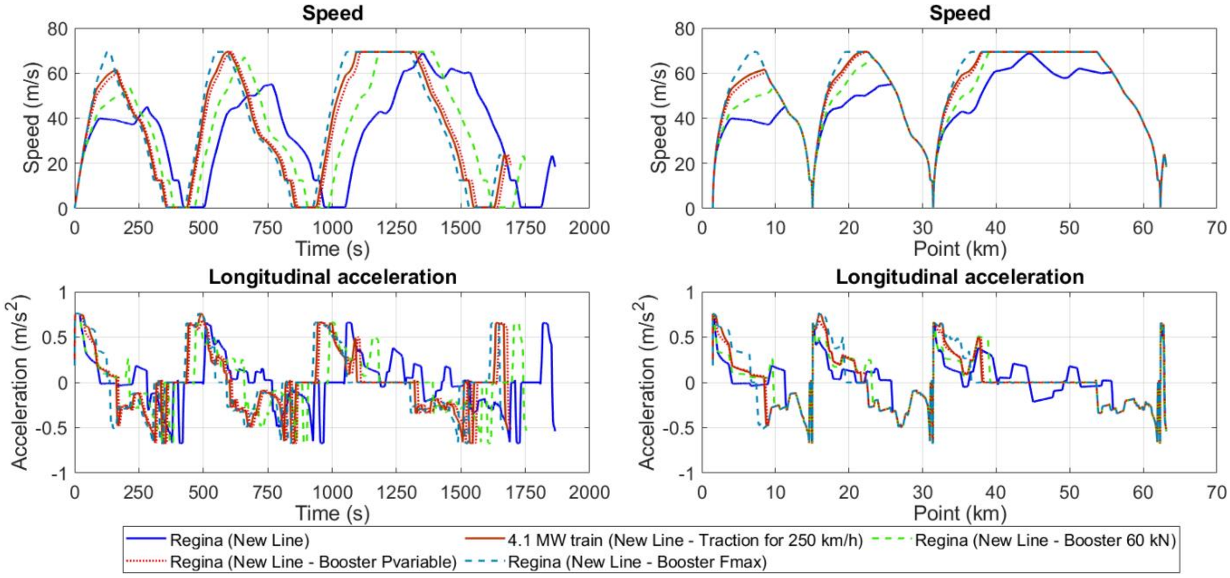


Figure *24*: Speed and longitudinal acceleration for the different trains

Figure 25: shows the traction/braking requirements in terms of force and power for the different considered configurations. Here, the same trend can be seen again. As the Regina train has less traction/braking capacity, it will need a longer travel time and will consume less energy than the configurations considered for the booster.

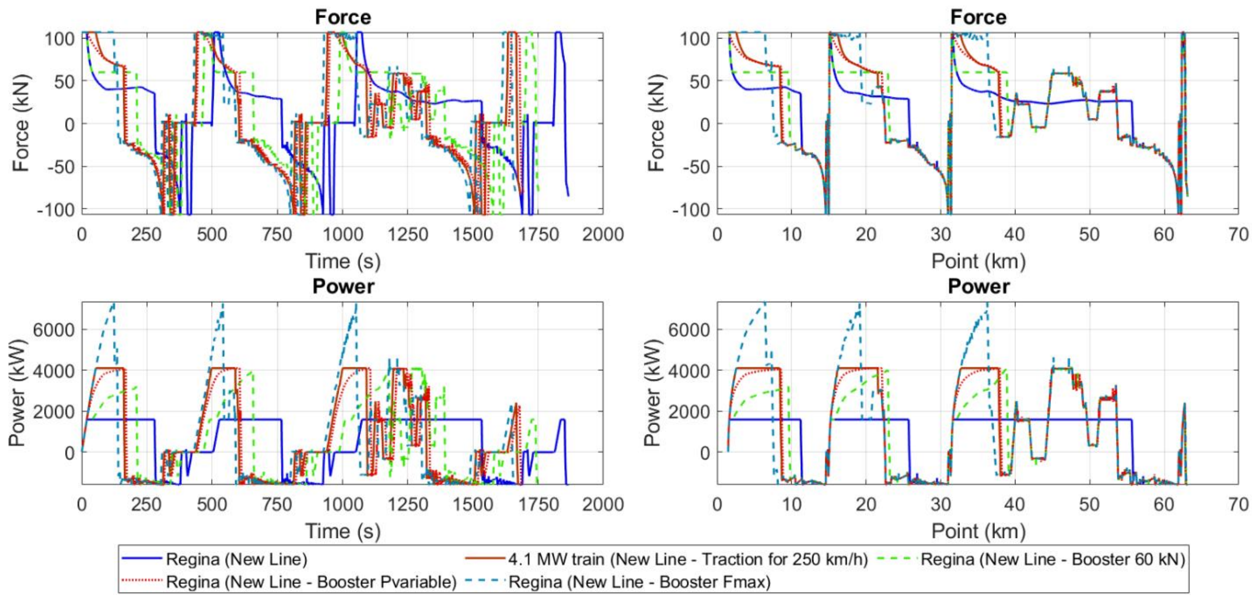


Figure *25*: Traction/braking force and power for the different trains

It should also be noted the total force required to move the train under the required conditions, as shown in Figure 25:. This force includes both the traction/braking force provided by the conventional electric system of the train and the force provided by the booster, which is considered to assist in traction but not in braking in this case.

If the force provided by the booster is segregated, the results can be seen in Figure 26::

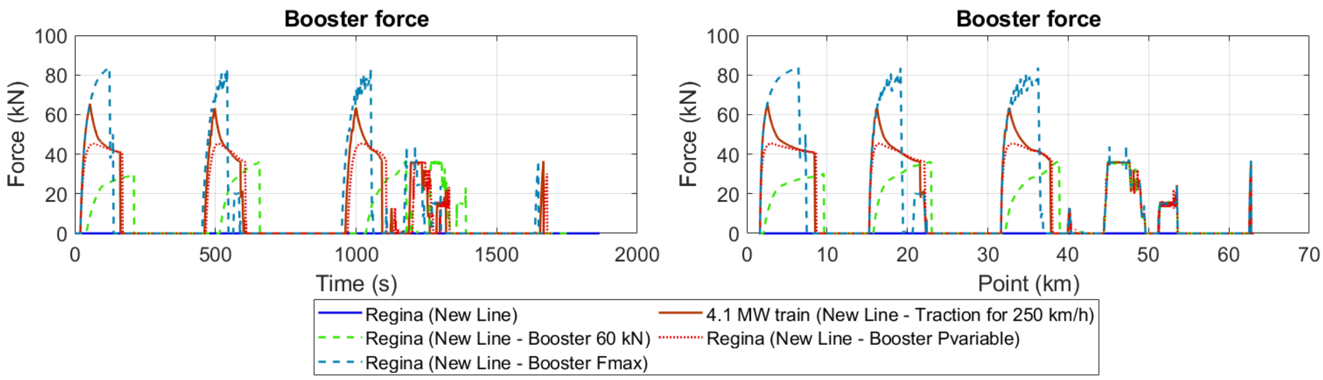


Figure *26*: Traction/braking force provided by the booster

This Figure 26: represents the total extra force that the booster has provided throughout simulations.

This booster force is applied when the traction capabilities of the train are not sufficient to track the reference speed. Therefore, this Figure represents the difference between the applied traction force in the traction/power Figure and the maximum traction capability, considering the speed.

This booster force is referred as a "total force" because it is the sum of all the boosters in the different coaches of the convoy that the system should globally provide.

If the two coaches of the Regina train have a booster and the system needs to provide a maximum booster force of 50 kN for the entire convoy, each booster should provide 25 kN/booster. Note that it is possible to restrict the booster application to specific sections of the line and that it is also possible to limit the maximum traction effort in some sections of the line. In both cases, the performance is expected to remain in an intermediate point between the Regina without booster and the presented simulation results.

Finally, and in order to have elements to evaluate the use of this technology, a similar study for energy consumption during the whole journey is included in Figure 27: , which also considers two different situations: a system without regenerative braking (at the bottom of the figure) and another system with a regenerative braking with an efficiency of 85% (at the top of the figure).

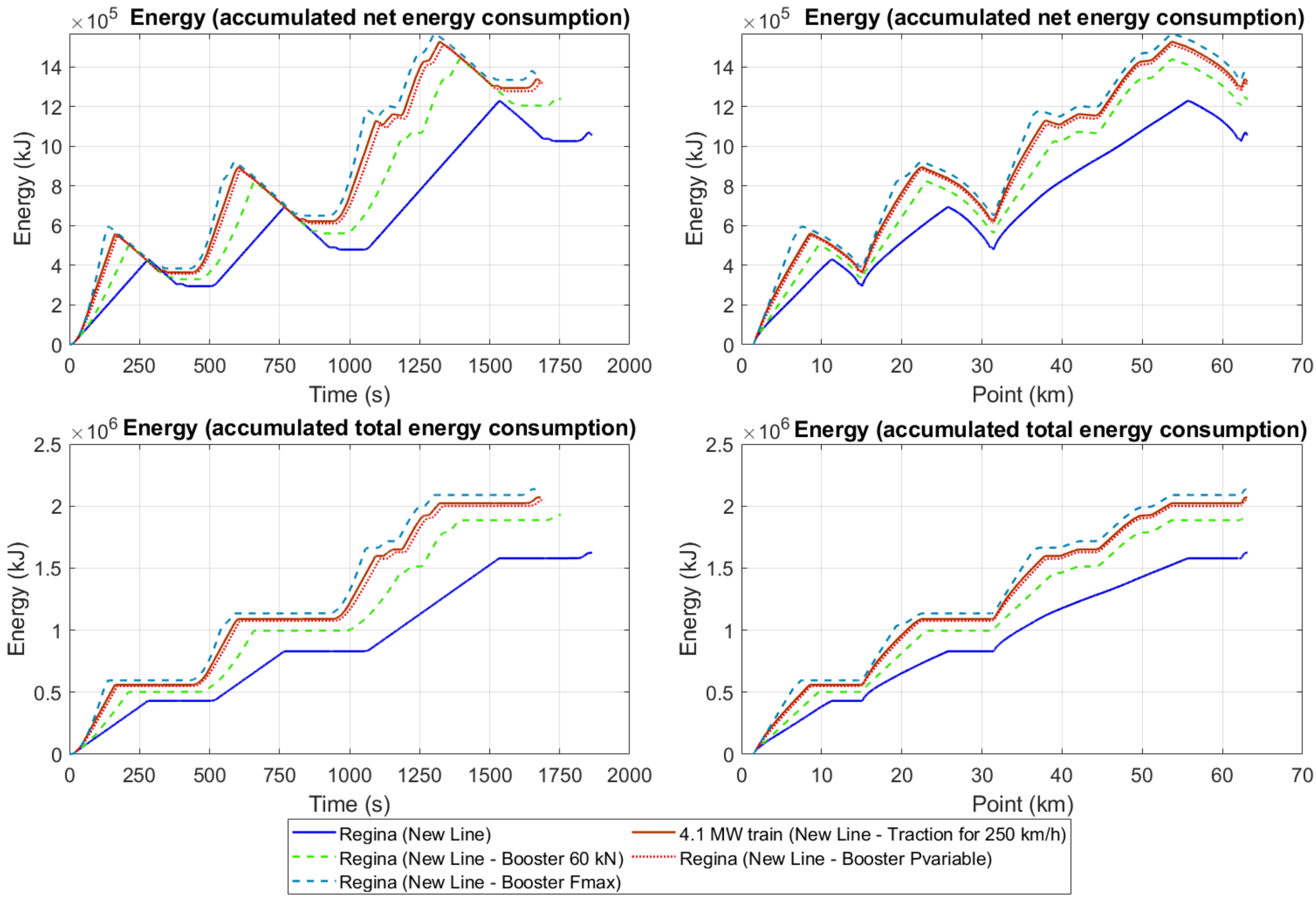


Figure 27: Energy consumption analysis

9.1.2.1.3 Simulation results for the new line with steeper gradients

As a variant of a railway line layout, another layout similar to the previous one, but with steeper gradients, has also been analysed. The objective of this layout is to see if such a route, which would require less civil works but with greater gradient requirements, could be operated by trains with the considered characteristics.

The objective is to consider a maximum gradient of 24 ‰ and to analyse the effect of using a booster applied to the Regina train in a hypothetical new line with less investment costs (less tunnels, higher slopes, etc.). Figure 28: shows the characteristic of this new line:

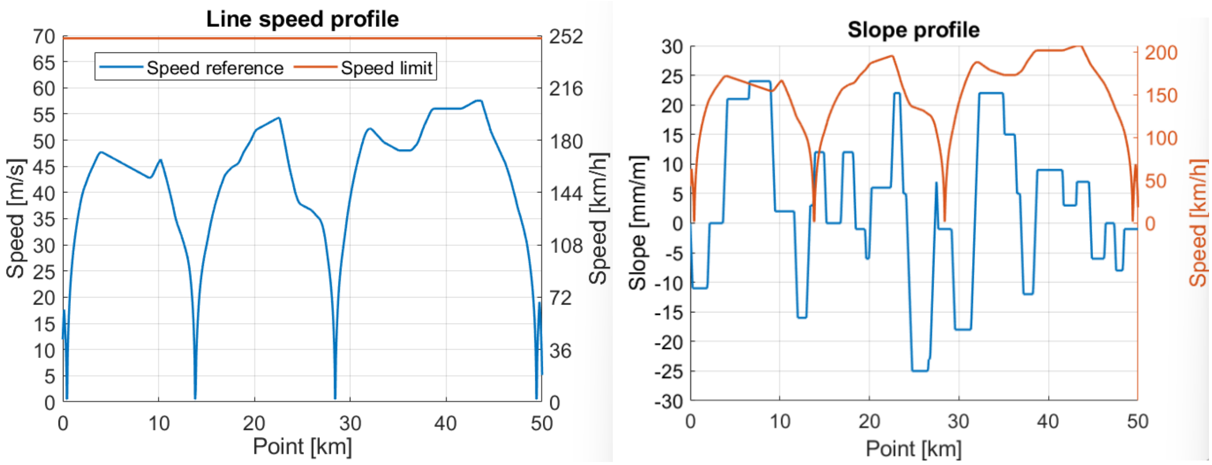


Figure *28*: Alternative line characteristics and main parameters. (a) Speed limitations and maximum speed able to be reached by the actual train (Regina). (b) Vertical alignment with slopes

Similar simulations have been performed for the different booster configurations. The results are shown in the next section.

9.1.2.1.4 Conclusions

As seen above, the current train is not able to meet the necessary speed requirements. For this reason, the results of the booster options have been compared with a conventional electric train of 4.157 kW which can reach the required speed. It should be noted that the simulations assume the installation of the linear motor along the entire line.

Conclusions for the new line

Comparing with the Regina train and with the normal running speed (250 km/h) in the line defined (new line), the following results are obtained:

- Option 1 reduces travel time of nearly -6,7% with an energy consumption increase of +19,4%. If a regeneration efficiency of 85% is considered, the energy consumption increase would be +17,4%,
- Option 2 reduces travel time of -10,1% with an energy consumption increase of +26,7%. If a regeneration efficiency of 85% is considered, the energy consumption increase would be +24,5%,
- Option 3 reduces travel time of -11,8% with an energy consumption increase of +32,3%. If a regeneration efficiency of 85% is considered, the energy consumption increase would be +30%,
- Option 4 presents similar results to the Normal travel case (Regina without booster),
- Option 5 reduces travel time of -14,2% with an energy consumption increase of +29,4%. If a regeneration efficiency of 85% is considered, the energy consumption increase would be +27,7%,

- Option 6 reduces travel time of 5 minutes (-17,3%) with an energy consumption increase of 158,5 kWh (+36,1%). If a regeneration efficiency of 85% is considered, the energy consumption increase would be 102,4 kWh (+35,9%).

These results are summarized in Figure 29::

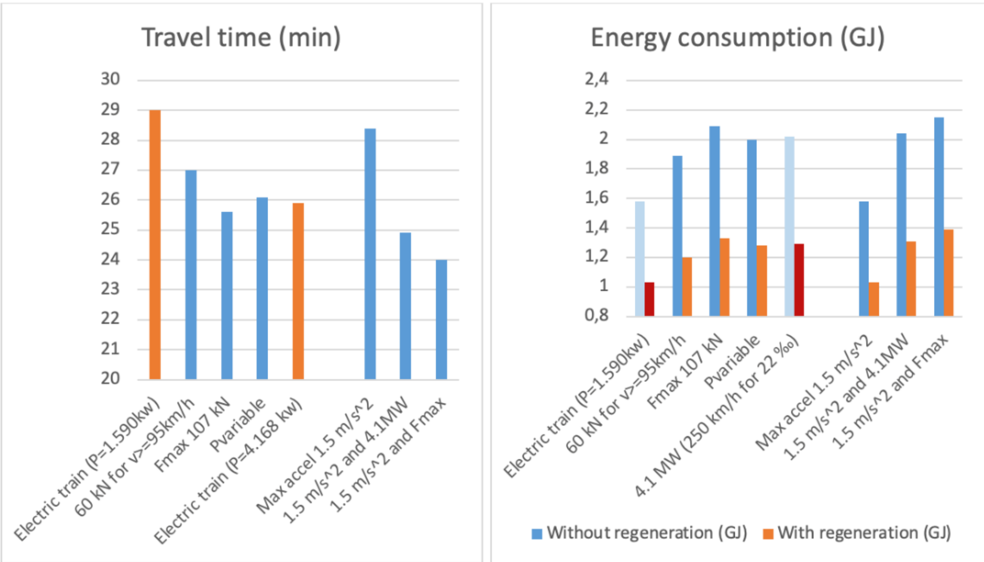


Figure *29*: Comparison between travel time and energy consumption

Comparing with respect to the 4.1 MW train (second Reference), the following options are more efficient than the 4.1 MW train:

- Option 1 increases travel time of 1,2 minutes (+4,6%), but saves 38 kWh (-6,8%). If a regeneration efficiency of 85% is considered, the energy consumption decrease would be 24,6 kWh (-6,8%),
- Option 2 presents similar results compared to the 4.1 MW train.

With respect to both references, even though the booster shows a great potential, note that there is not a completely clear preferable booster option over the others because other factors may influence in its practical application. In relative terms, all options presented an elasticity, which was defined as the time travel reduction with respect to the energy consumption increase) equal to 1 in all options. In absolute terms, an energy efficiency factor, based on the total energy consumption per minute of travel, showed that Option 1 seems to be the best choice among the analysed booster options. However, the final chosen Option should consider other additional factors such as the desired capacity of the line and the investment costs.

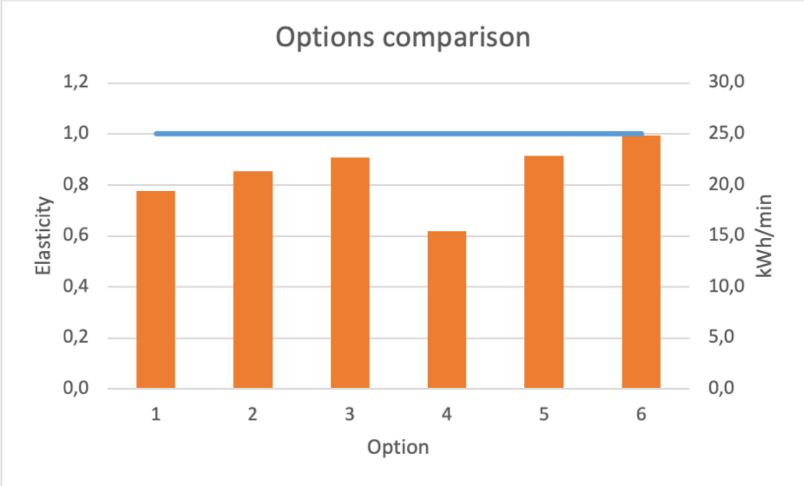


Figure *30*: Options comparison

Conclusions for the New line with steeper gradients

Comparing with the Regina train and with the desired running speed (250 km/h) in the line defined in Figure 28: (new line with steeper gradients), the following results are obtained:

- Option 1 reduces travel time of nearly 2 minutes (-6,9%) with an energy consumption increase of 75,6 kWh (+20,4%). If a regeneration efficiency of 85% is considered, the energy consumption increase would be 41,9 kWh (+18,6%),
- Option 2 reduces travel time of nearly 3 minutes (-10,8%) with an energy consumption increase of 105,1 kWh (+28,3%). If a regeneration efficiency of 85% is considered, the energy consumption increase would be 61,7 kWh (+27,4%).

These results are summarized below:

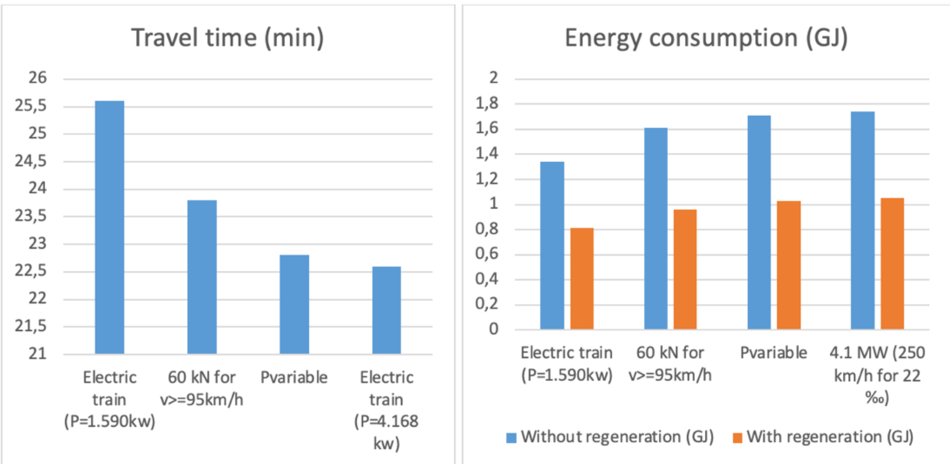


Figure *31*: Comparison between travel time and energy consumption

With respect to the 4.1 MW train, Option 1 needs 1,2 minutes more of travel time (+5,4%) with an energy consumption saving of 35,8 kWh (-7,4%). If a regeneration efficiency of 85% is considered, the energy consumption saving would be 24,3 kWh (-8,4%). Meanwhile, Option 2 presents similar results to the 4.1 MW train, because it presents a similar travel time (+0,2%) and an energy consumption saving of 6,2 kWh (-1,3%). If a regeneration efficiency of 85% is considered, the energy consumption saving would be 4,5 kWh (-1,6%). This also means that it is possible to achieve a similar behaviour to the 4.1 MW train with a Regina train equipped with a booster.

Moreover, increasing the inclinations of the line to save in investment costs reduces the line's length, and therefore, travel time from 29 minutes to 25 minutes, approximately. Simultaneously, the booster allows to achieve 250 km/h in a line in which the maximum speeds would have been reduced at certain points due to higher inclinations.

General conclusions

Therefore, the inclusion of a booster on the new line to reach 250 km/h makes it possible to use trains that would have less traction capacity without a booster. In this use case, this means that instead of using a train with a minimum of 4.1 MW, it would be possible to use a 1,590 kW train equipped with a booster. It should be noted that the simulations assume the installation of the linear motor along the entire line.

Depending on a cost-benefit analysis (especially, in the economic aspect) and the final implementation, the previous point could lead to different advantages:

- A reduction in the maintenance costs, as a result of using trains with less power,
- A reduction in the investment in traction systems for both, the Infrastructure Manager and the Railway Undertakings, if designed for trains with less traction capabilities,
- The opportunity to offer capacity to trains with less traction capabilities, always that they are equipped with a booster, which can increase the offer of trains in the line and/or improve the access of Railway Undertakings to the infrastructure.

In addition, results show that the inclusion of a booster in the new line to reach 250 km/h reduces energy consumption with respect to using a 4.1 MW train.

In any case, the results show that the proposals considered are of great interest and show potential for application.

9.1.2.2 Civil works

The use of incline pushers on a vertical railway profile offers significant benefits in terms of operational efficiency and cost savings. By enabling trains to tackle steep gradients more effectively, incline pushers reduce the need for extensive earthwork, such as soil and rock excavation and filling, which are typically required to create gentler slopes for conventional rail systems. This not only conserves natural landscapes and minimizes environmental disruption but also substantially lowers construction costs. Additionally, the reduced need for large-scale earthmoving decreases the project's carbon footprint, making it a more sustainable option. Overall, incline pushers facilitate more economical and environmentally friendly railway construction by optimizing the use of existing terrain.

In the case of Scenario B, for the proposed new branch line between two cities the track vertical layout has been modified so that it better follows the orography and avoids tunnelling or building bridges. These modifications address only the vertical profile of the track, and do not account for any other possible limitations except for a maximum track inclination of 5%. Different sections of this projected track are depicted in Figure 32 and Figure 33, where the planned line in the preliminary studies (blue line) is overlayed with the proposed modifications (orange line).

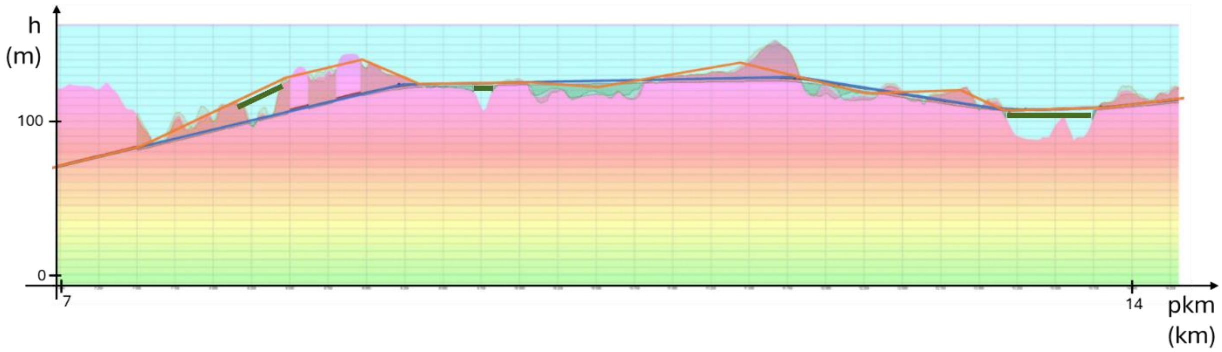


Figure *32*: Height profile for the proposed line between km points 7 and 14, including the proposed line (blue) and the modified one with higher track inclination (orange)

In the original project figure, shaded sections show excavation and filling, while red track sections are redesigned with bridges (green) and large track gradient to avoid tunnelling and reduce the work on excavation and filling.

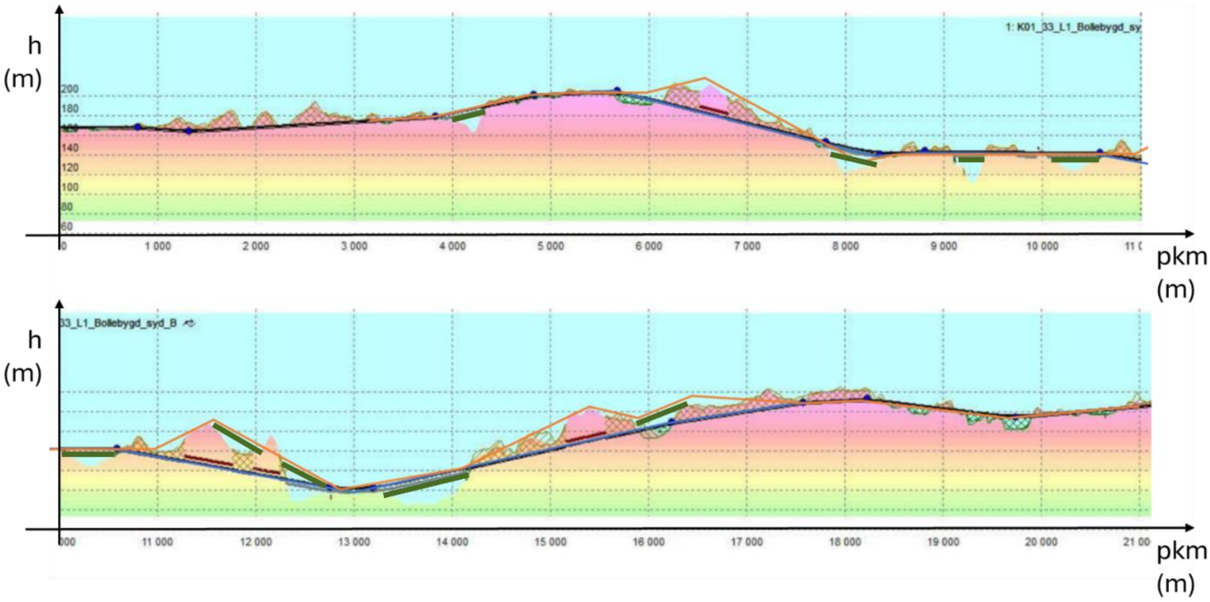


Figure *33*: Height profile for the proposed line between km points 22 and 36 (approx.), including the proposed line (blue) and the modified one with higher track inclination to avoid tunnelling and earthworks (orange)

In the original project figure, shaded sections represent excavation and filling, while red track sections are redesigned with bridges (green) and large track gradient to avoid tunnelling and reduce the work on excavation and filling.

The implementation of the incline pushers helps the trains to cope with higher track gradients, which can influence the track design by avoiding tunnelling and reducing earth work (excavation and filling). For the selected two track section shown in Figure 32 and Figure 33, by implementation of the incline pusher, the tunnelling is completely avoided, and the excavation is much reduced while the filling is increased a bit. For the selected section of the railway line, as mentioned above, the estimated earth work (including tunnelling, bridging, excavation and filling) of the original design and the new design with the incline pushers are compared in Table 16. For the rest part of the line, there is no change to the track design.

Name of earth work	***Original track design***	***New track design***
Length of tunnel (m)	17 300	15 500
Length of bridge (m)	3 900	6 100
Excavation (m^3) *	1 821 600	926 400
Filling (m^3) *	568 800	793 200
*** For simplification, a track width of 12 m is assumed.**		

Table *16*: Comparison of earth work and tunnelling / bridging of the original track design and the new track design with incline pusher installed

The evaluation of the difference in earth work between the two cases in Scenario B are graphically estimated based on the available track design on paper and thus limited to the vertical alignment in this report. The accuracy is dependent on approximation from the available track design on paper. The associated cost-related differences in earthworks, tunnelling and bridging, and the cost associated to these will be included with the Cost Benefit Analysis.

The sample implementation method of the MDS components on conventional infrastructure for this Scenario is identical to the Scenario A and is shown in the following overview. Also, the Scenario B configuration will use a linear motor in the middle of the rails.

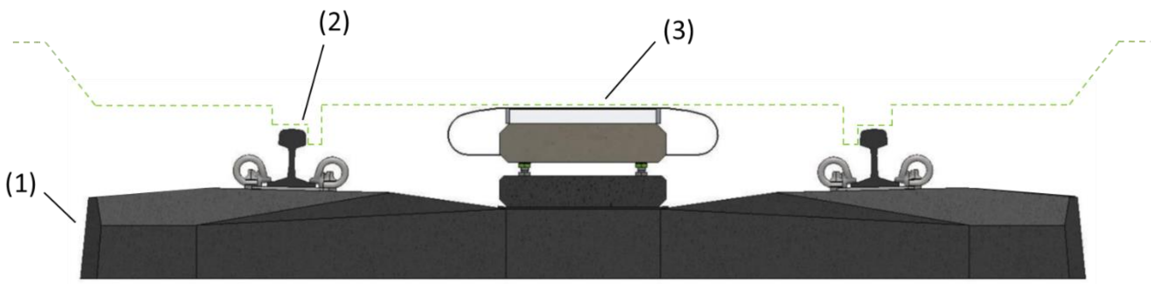


Figure *34*: symbolic picture of the MDS components

In the cross-section, to the conventional elements like sleepers (1) and rails (2) a linear motor (different configurations will be analysed in WP8) (3) between the rails is installed. The configuration must be designed in such a manner that the UIC structure gauge is respected (green dashed line is the structure gauge).

MDS technology in this configuration will use conventional switches. In the switches the stator will have a short gap which might not affect the propulsion of the train in a relevant way.

The new system needs additional components to provide the needed energy for the linear motor. Deployment of the power electronics subsystems contains especially grid and motor power converters, segment switches, cables for power and communications and the centre for motor control.

The new planned high-speed line between two cities is a double track line. So, it is needed to implement the MDS linear motor in all sections with high inclines (up to 25 ‰) and after the two planned station stops, where trains have to reaccelerate. This also has been proven by travel time simulations. As a result, from those simulations (chapter 9.1.2.2.2) the total length of the new optimized line is approximately 50 km from which 24,0 km must be equipped with linear motor in direction –from one city to the other and 15,0 km in the opposite direction. This leads to 39,0 km of linear motor all together.

Additional equipment of station tracks is not needed, because station tracks must be almost flat and the high-speed passenger trains will have the ability to adequately accelerate in station areas. Back on the main tracks, the linear motor will help to increase speed up to 250 km/h as fast as possible.

9.1.2.3 Vehicle control and command systems

Compared to a traditional train, the TCMS must manage a different traction and a different brake control unit. In any case, it must be checked the compliance with EN 50155.

9.1.2.4 Signalling systems

Considering what is indicated in the use case, the use of ETCS L2 is envisaged for signalling. The open points are:

a) To manage to install the Balises in the central position of the track,
b) Magnetic flux must not be intrusive in Balise On-Board Antenna communication,
c) Since there is no contact between the wheel and the track, the TDS may not work, thus safety problems for ETCS L2 systems.
d) It is also necessary to evaluate the influence of the magnetic flux produced by the wheels/train towards the TDS.

Also, in this Scenario the biggest risk is not detecting the presence of a vehicle along the line. This could be due to the interference of an MDS vehicle with the adjacent line or of the MDS vehicle itself with respect to the line travelled.

While the aspects that compromise availability are:

- Not reading the encountered balise,
- Occupying a section unduly,
- Losing the radio connection,
- Interfering with the train traveling on the adjacent track.

9.1.2.5 Telecommunications

Considering the communication wayside on-board, these are the potential open points:

- To verify that the new vehicle configuration complies with ERTMS standards included FRMCS,
- No other potential open points are identified.

9.1.2.6 Energy and power systems

In the Scenario B of the Rail vehicle upgraded MDS configuration, a Regina train has been used with the following characteristics (without the use of any booster):

- Mass: 161.2 ton,
- Power: 1590 kW,
- Maximum traction force: +/- 107 kN.

This Regina train presents the traction curves (labelled as 'Traction') shown in Figure 47. Note that the Regina train might have problems when it comes to reach 250 km/h in a line with 22 ‰ gradients. Therefore, a second train is also used as a second reference in the simulations (labelled as 'Traction for 250 km/h'). This second train is considered to have the same characteristics as the Regina train but for an increased power that allows it to reach the 250 km/h in a line with 22 ‰ gradients, that is, a train with a power of 4,157 kW.

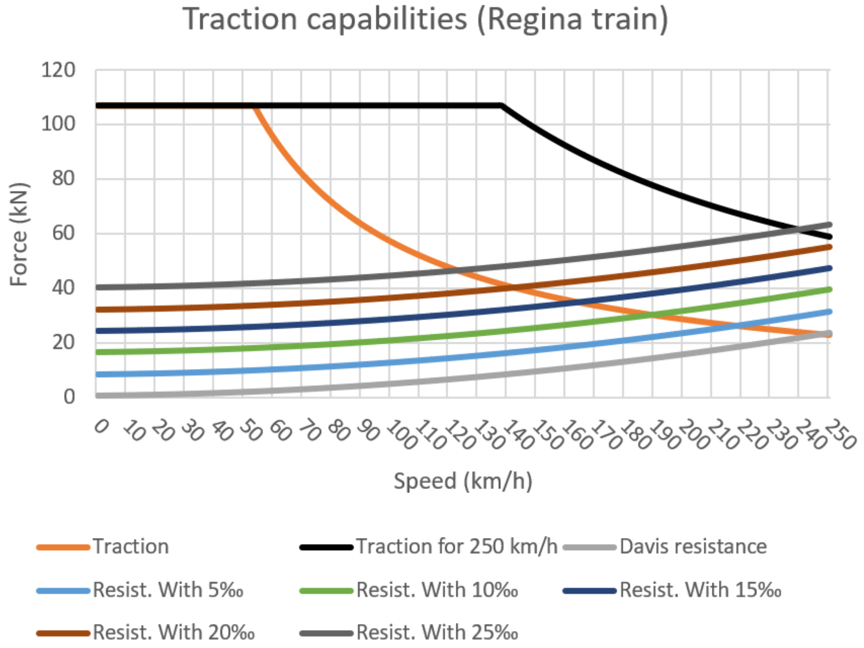


Figure 35: Traction curves

Considering the above trains, the following booster options have been studied:

- Option 1 (60 kN): booster that allows to reach 60 kN for speeds higher than 95 km/h,
- Option 2 ($P_{variable}$): booster that allows a variable power between the power of the Regina train (reference 1) and the power of the 4.1 MW train (reference 2),
- Option 3 (F_{max}): booster that allows the use of the maximum traction force (107 kN) for all speeds until 250 km/h,
- Option 4 (Accel): booster that allows an acceleration of 1,5 m/s^2 at low speeds,
- Option 5 (Accel + P_{max}): booster that allows a simultaneous application of option 4 together with a 4.1 MW traction curve,
- Option 6 (Accel + F_{max}): booster that allows a simultaneous application of options 3 and 4.

In the following figure, Options 1, 2 and 3 are shown with respect to both references.

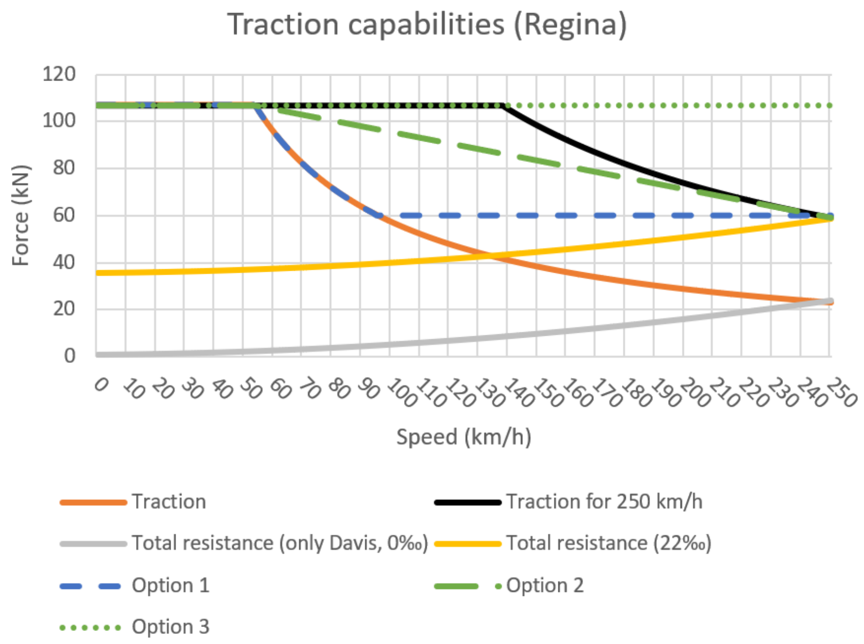


Figure *36*: Traction options

Considering the above trains and the above booster options, the simulation results for the Scenario B were presented in the previous section 'evaluation of vehicle performance'. These results are summarized in the following Tables, where an estimation of the mechanical energy consumption for each of the booster options is made. It is also important to note that an 85 % regenerative braking performance has been considered for the 'consumption with regeneration' Table. The summarizing Tables relating to the new line will be firstly shown, whereas the tables relating to the new line with steeper gradients will be secondly shown.

Summarizing results for the new line

New Line	Description	With respect to Regina Travel time reduction (%)	With respect to 4.1 MW train Travel time increase (%)
Regina			12,1
Regina (200 km/h)		-2,1	14,4
Train with 4.1 MW	250 km/h for 22 ‰	10,8	
Booster Option 1	60 kN for v>=95km/h	6,7	4,6
Booster Option 2	Pvariable	10,1	0,8
Booster Option 3	Fmax 107 kN	11,8	-1,2
Booster Option 4	Max accel 1.5 m/s^2	1,9	10,0
Booster Option 5	1.5 m/s^2 and 4.1MW	14,2	-3,8
Booster Option 6	1.5 m/s^2 and Fmax	17,3	-7,3

New Line	Description	With respect to Regina Consumption increase (%)	With respect to 4.1 MW train Consumption reduction (%)
Regina			21,9
Regina (200 km/h)		-3,1	24,4
Train with 4.1 MW	250 km/h for 22 ‰	28,1	
Booster Option 1	60 kN for v>=95km/h	19,4	6,8
Booster Option 2	Pvariable	26,7	1,1
Booster Option 3	Fmax 107 kN	32,3	-3,3
Booster Option 4	Max accel 1.5 m/s^2	0,0	21,9
Booster Option 5	1.5 m/s^2 and 4.1MW	29,4	-1,0
Booster Option 6	1.5 m/s^2 and Fmax	36,1	-6,3

Consumption with 85 % regeneration		With respect to Regina	With respect to 4.1 MW train
New Line	Description	Consumption increase (%)	Consumption reduction (%)
Regina			20,7
Regina (200 km/h)		-6,7	26,0
Train with 4.1 MW	250 km/h for 22 ‰	26,1	
Booster Option 1	60 kN for v>=95km/h	17,4	6,9
Booster Option 2	Pvariable	24,5	1,2
Booster Option 3	Fmax 107 kN	30,0	-3,2
Booster Option 4	Max accel 1.5 m/s^2	0,0	20,7
Booster Option 5	1.5 m/s^2 and 4.1MW	27,7	-1,3
Booster Option 6	1.5 m/s^2 and Fmax	35,9	-7,8

Table *17*: Summarizing results for the new line

Summarizing results for the new line with high inclinations

New Line (High Slopes)	Description	With respect to Regina Travel time reduction (%)	With respect to 4.1 MW train Travel time increase (%)
Regina	Reference speed 250 km/h		13,1
Regina (200 km/h)	Reference speed 200 km/h	0,0	13,1
Train with 4.1 MW	250 km/h for 22 ‰	11,6	
Booster Option 1	60 kN for v>=95km/h	6,9	5,4
Booster Option 2	Pvariable	10,8	0,9

New Line (High Slopes)	Description	With respect to Regina Consumption increase (%)	With respect to 4.1 MW train Consumption reduction (%)
Regina	Reference speed 250 km/h		23,1
Regina (200 km/h)	Reference speed 200 km/h	0,0	23,1
Train with 4.1 MW	250 km/h for 22 ‰	30,0	
Booster Option 1	60 kN for v>=95km/h	20,4	7,4
Booster Option 2	Pvariable	28,3	1,3

Consumptions with 85 % of regeneration New Line (High Slopes)	Description	With respect to Regina Consumption increase (%)	With respect to 4.1 MW train Consumption reduction (%)
Regina	Reference speed 250 km/h		22,8
Regina (200 km/h)	Reference speed 200 km/h	0,0	22,8
Train with 4.1 MW	250 km/h for 22 ‰	29,5	
Booster Option 1	60 kN for v>=95km/h	18,6	8,4
Booster Option 2	Pvariable	27,4	1,6

Table *18*: Summarizing results for the new line with high inclinations

To estimate the needed electrical power supply coming from the grid network, the system can be configured by the parameters of the infrastructure, the used vehicles and the operational concept. The needed traction force was calculated in the simulations. For the most promising booster Option 1, with additional traction force that allows to reach 60 kN for speeds higher than 95 km/h, the propulsion system needs to provide up to 36 kN of mechanical force and up to 2.500 kW of power.

In the next step the configuration of the propulsion system can be estimated. This will be different for the different types of linear motor.

The NEVOMO system MagRail Booster uses a linear synchronous motor whilst the system of the project partner TACV-Lab produces the force by a U-shaped linear inductive motor. Both systems have advantages. For this study in deliverables D7.2 and D7.3 the LSM system from NEVOMO will be the technological basis for the following estimations. This must not to be understood as a decision for later implementations but will help to estimate the technological needs and possibilities for one of the possible solutions.

To calculate and design the system, additional parameters are needed.

High speed trains (assumed for operation on the new line):

- Length of the train: 54 m,
- Length of the installed magnets per waggon: 15 m,
- Number of equipped waggons in the train: 2.

Infrastructure:

- Length of the sections: 5 km,
- Segmentation of the sections: 60 m.

By employing a three-turn winding configuration, the magnetic field generated by the stator is optimized for the desired traction performance even at high speeds. The inverters play a crucial role in regulating the current and voltage supplied to the windings, ensuring consistent and efficient operations. The specified current of 800 A and voltage of 1,2 kV are chosen to achieve the necessary electromagnetic force for the MagRail Booster system.

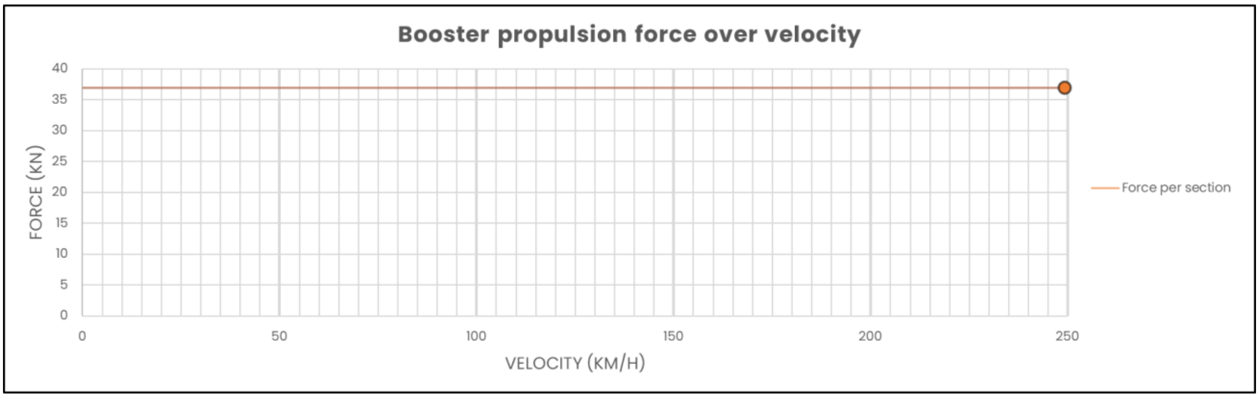


Figure *37*: force over velocity diagram

The resulting traction curve, illustrated in the diagram, reflects the relationship between the applied traction force and the velocity of the freight train. It demonstrates that the maximum needed traction force of 36 kN is provided up to 250 kph to ensure the maximum speed even in sections with very high inclinations.

Splitting the new line between two cities into 10 sections, each section needs two inverters to guarantee a smooth movement of the pod, especially at the acceleration phase.

To enhance the overall efficiency of the system, each section of the track will be divided into 60 m long segments. This segmentation requires the installation of 84 segment switches per section along the line. These segment switches play a crucial role in managing and optimizing the flow of the system, allowing for precise control and increased performance.

Additional equipment of station tracks is not needed as already mentioned in chapter 9.1.2.2.

- Main line: 10 sections x 2 inverters = 20 inverters
- Equipment of station tracks: none

This will lead to 20 inverters all together.

- Main line: 10 sections x 84 segment switches = 840 segment switches
- Equipment of station tracks: none

This will lead to 840 segment switches all together.

9.1.2.7 Interferences and interoperability

The new railway line between two cities is set to improve regional travel, delivering faster train journeys, smoother commuting, and enhanced accessibility to and from nearby airport . This planned line spans approximately 60 kilometres and features a double-track railway designed to accommodate both high-speed trains and fast regional services. This project can also set an emphasis on interoperability, with the line being planned from the start for the implementation of MDS technology.

By prioritizing interoperability from the beginning, the project ensures that all technologies used along the new railway line will be compatible and seamlessly integrated. This approach facilitates the smooth operation of high-speed and regional trains, as all components and systems will be designed to work together harmoniously. The careful consideration of interoperability means that the railway infrastructure, signalling systems, and train operations will be fully synchronized, minimizing potential disruptions and enhancing overall efficiency.

9.1.2.8 Magnetic analysis

No specific magnetic analysis is required for the identified Scenario.

9.1.2.9 Risk analysis

The discussion on risks is based on identifying the hazards associated with the implementation of the incline pushers on the track and the traffic conditions of the new planned railway line between two cities.

This section will discuss possible accidents in the event of malfunctions, external influences, human errors, etc., and their possible causes. The signalling system and the power control system have been separately discussed in the previous sections.

The railway line is ca. 60 km-long, double-track, electrified, ballast track and with maximum operational speed of 250 km/h, so the track area is closed and supervised. The maximum line gradient is proposed to be 25‰. There are several locations where it is necessary to build tunnels. There is no tight curve in the new line and the cross-sections of the tunnels are big enough to ensure safety operations of high-speed trains.

Since Scenario B uses linear synchronous motors with a maximum attainable performance, the trackside linear motor stators are installed wherever it is needed to provide extra tractive force to let the trains cope with much higher track gradient (higher than the originally proposed gradient 25‰, up to 45‰). The railway line can, therefore, be redesigned to minimize the costly tunnelling and earth works in construction. Compared with the original design of the railway line, besides the signalling system and power control system, there are two main changes on site: upgraded vehicles with permanent magnets beneath the vehicles as the mover, and the 3-phase winding installed in the track as the stator.

The accidents discussed in the section are grouped into the following four general categories:

Derailment

As mentioned previously, most derailments have low severity, which results in temporary disruption of the regular operation of the railway systems. For the passengers' high-speed trains, the braking actions of different cars are well synchronized and there are no tight curves on the route. Large track distance between the two tracks and low track irregularity can significantly lower the frequency and severity of derailments.

Collision

In contrast to the derailment, its high operational speed, double-track design, and passenger-dedicated line make the severity of the collision high. The train can collide with the neighbouring trains or infrastructure at relatively high speed, which can cause the death of a large number of passengers.

Once the linear power is suddenly shut off, the train running downhill cannot receive sufficient braking force, so the braking distance would get much longer, especially when rail-wheel adhesion is poor in bad weather. Therefore, it is hard to stop the train in time to be free from colliding on-track obstacles and the emergently stopped train on the same track. Since the train can be full of passengers, once a collision happens the severity is very high.

Fire

Compared to the catenary system, the incline pusher needs the installation of on-track windings, which makes the high voltage conductor relatively more accessible and vulnerable. However, only when the windings are improperly grounded and the protection does not shut off the power supply in time, there might be the hazard of catching fire.

Electrocution

Since the high-voltage windings are on the track, the winding insulation has a higher probability of being damaged by flying stones, falling objects, improper track maintenance, and even vandalism when compared with the railway catenary. The exposed high-voltage conductor is more accessible to intruders, trackside workers, and evacuated passengers in an emergency than the railway catenary. Even though the route may be passing through a populated area, a well-fenced and supervised track area can keep most of the intruders away from the railway line.

If the damage of insultation is not detected and the protection circuit does not shut off the power in time, the persons in the track area can get electrocuted, especially during evacuation.

During track maintenance, repair or inspection, if the winding power supply is not shut off by human errors, the personnel can get electrocuted.

Examples of identified risks during the analysis of the use case study, which is essential to pay attention to, are presented here. There are two kinds of malfunctions of the mover and stator, where actions may need to be considered. They are as follows:

- When the train runs a steep downhill section and the weather conditions are bad, if the linear motor stops working due to an emergency, the braking force is not sufficient to stop the train. There is higher risk of head-on collision, which can cause a big casualty of passengers onboard,
- The stators which are energized in operation are installed on the track. The linear motor stators are more accessible for personnel during track maintenance and passengers under evacuation than catenary. Since the stator windings are on the track, the insulation can be damaged by flying stones, human errors during track maintenance and other falling objects. Electrocution is an issue that needs to be adequately considered.

9.2 Selected use case "Hybrid MDS based on magnetic levitation configuration"

This use case compares the running of a conventional train, operating on the current line (the ETR 421 model train, with four cars), with a set of the same number of pods based on a Hybrid MDS configuration, running in virtual coupling mode. For this configuration, the pods will run on the same railway line, but with an increase in speeds in the curves – allowed by additional cant in these sections – developed by tilting the new vehicle to increase passenger comfort, allowing the pods to run at higher speeds by reducing the cant deficiency. The objective is to compare the travel time and energy consumed by the train currently providing the service with an equivalent configuration in terms of transport capacity, using the advantages of the new MDS technology.

We consider that the 4 pods operate as a convoy with virtual coupling when, in normal operation, all four pods are able to arrive at the station at the same time without any delays between them.

So, the reason for choosing 4 pods in the simulations is that, when in a station, the 4 pods occupy the same space on a platform as the conventional ETR 421 train with which they are being compared, since the limiting parameter is the size of the platform.

9.2.1 Evaluation of performance

This scenario could benefit from the introduction of hybrid MDS based on magnetic levitation, where a group of pods is used in a virtual coupling configuration. In this way, this case study aims to achieve an increase in the capacity of the traffic line by significantly reducing the travel time while maintaining a similar energy consumption to that of the current conventional trains operating on this line.

The reduction in travel time is achieved by the increase in speed that comes from the additional cant in curves, obtained by the tilting of the new vehicle which is made possible by magnetic levitation technology.

Maintaining similar energy consumption by increasing the speed of travel is achieved by optimising the aerodynamic drag of the capsules, which is improved when using virtual coupling. As will be discussed in the following sub-chapters, virtual coupling allows the pods to ride closer together, and the slipstream effect and airflow between the pods results in a reduction of the aerodynamic drag of the pods, which ultimately translates into a reduction of energy consumption.

9.2.1.1 Curve speeds

Technical data related to MDS performance has been developed and provided by the MaDe4Rail project. Within the project a framework was developed on how to calculate max. available MDS speed, in relation to max. speed of underlaying railway infrastructure for the different configurations.

It is assumed that max. top speed of MDS deployed at HSR infrastructure (designed for 300-350 km/h conventional HSR operations) will be able to reach over 500 km/h. However, in regional and curvy lines the speed gains will be lower, but still substantial. In the following paragraphs the possible additional curve speeds are estimated. The new allowed speeds will be valid for both scenarios.

It is assumed, that maximum speed for MDS operations will be higher than the one for conventional train operations. The increase comes from the nature of the specific magnetic suspension used in the system, allowing to achieve higher values of cant for either the magnetic track on the same curve radius and possible tilting systems in the new MDS vehicles to increase passenger comfort.

For the estimation of potential speed increase in curves, the complete line between the two cities was investigated. The data base provided by RFI shows about 600 curves with variations of radii between less than 300 m up to more than 10 km. Many of the curves are multicentric, with changing radius within the curve.

To calculate the possible increase of curve speed, a simplification is needed: for every one of the 600 curves, only the narrowest radius will be used for the calculation. This will underestimate some concrete values, but all together will give a valid estimation of the possible effect.

For the calculation of possible higher curve speeds a stepwise approach starting from status quo is chosen. First the possible speeds based on the existing build in cant and the allowed cant deficiency are calculated, to have an overview of the today's possibilities.

The second step is the calculation of possible speed increase in curves, for Scenario A. Therefore, the build in cant will stay the same, as the levitation system will use the existing rails. And additional cant in curves will be developed by tilting the new vehicle to increase passenger comfort. The maximum tilting angle for this case will be set to 6°, as the tilting technology helps increase the curve speeds, but also has negative effects on passenger's well-being if the tilting angle is too large. Experience of the Pendolino at RFI has shown, that tilting angles over 6° were not accepted by the people.

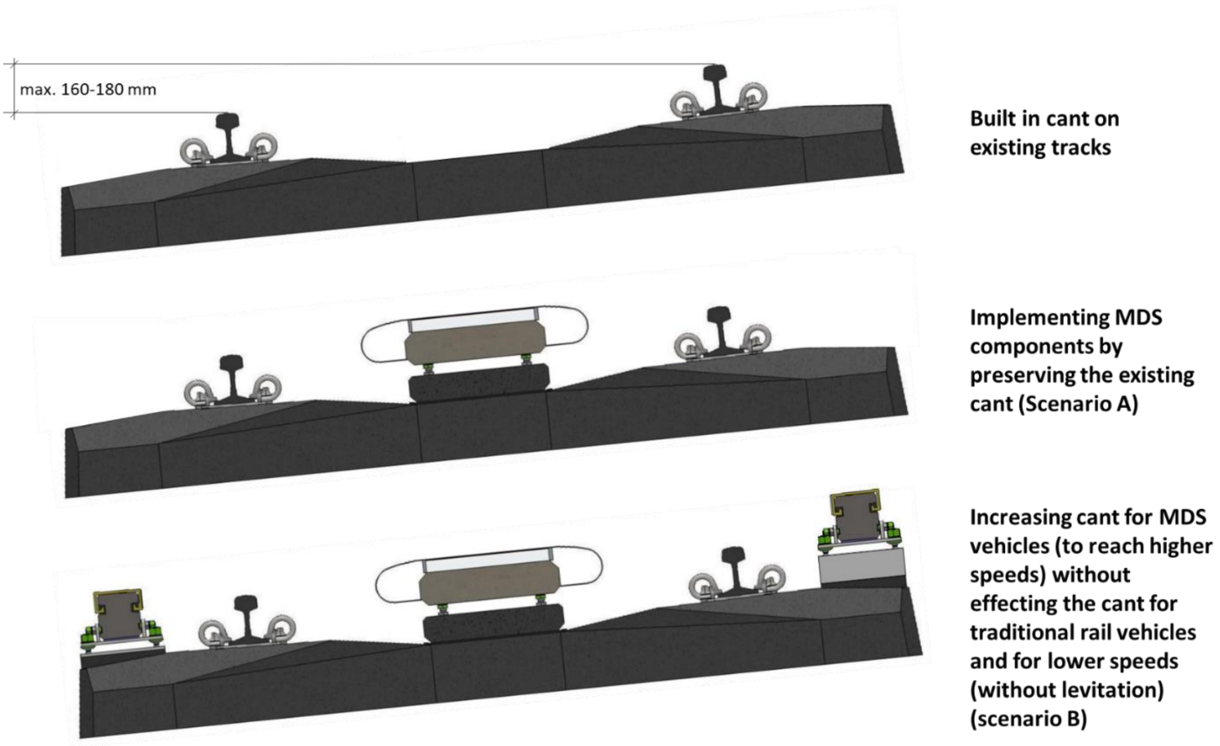


Figure 38: Various scenarios applied on the existing cant

The use of the existing rail entails the big advantage of lower investment costs but brings a higher restriction on possible higher speeds in curves, as it is only dependent from the passenger acceptance of tilting technology in the vehicles. In comparison, the Scenario B with additional beams for the levitation system needs higher investments but has therefore the advantage to increase the built-in cant for the fast (levitating) trains without effecting the slower trains still rolling on wheels and rims with a cant optimized for lower speeds (see Figure above).

The calculation of velocities for Scenario B was made in two steps. In a first step, the possible additional built-in cant of the levitation system was restricted by the valid regulations of maximum built-in cant, allowed cant deficiency and the allowed grade of cant change at the transition curves. In a second step, oriented on other traffic systems, new values were proposed to show the potential of the system.

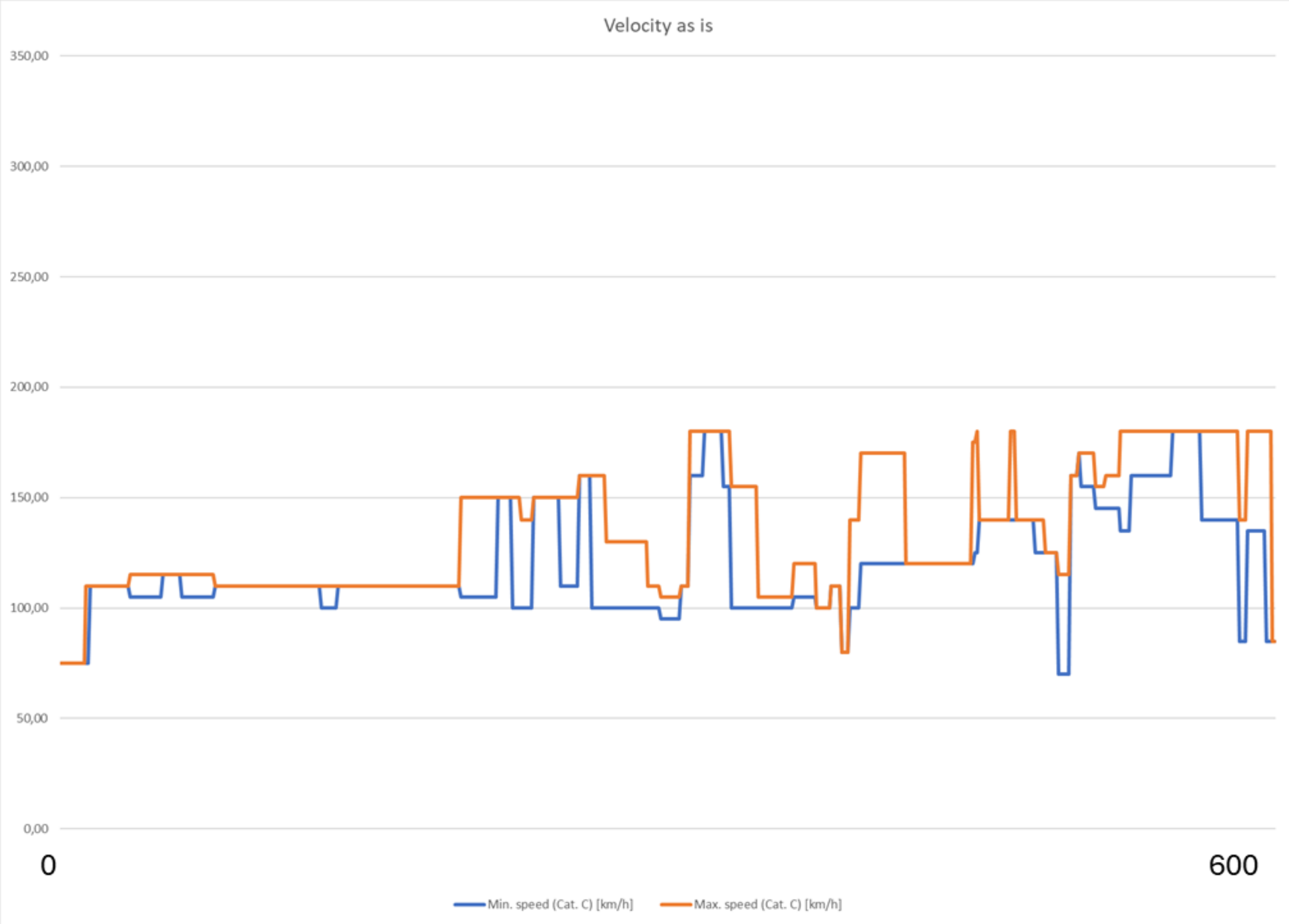


Figure 39: Allowed speeds on the line between two major cities for passenger trains

For every one of the about 600 curves, the maximum speed was calculated if the maximum allowed cant deficiency would be used on the given infrastructure with the built-in cant. As the values are theoretically getting very high on curves with big radius, the velocities are cut at 299 km/h.

The speed is calculated with the simplified formula which results from the interrelations of the lateral acceleration in elevated circular arc:

$$v_{allowed} = \sqrt{\frac{r}{11{,}8}(u + max.\,u_{def})}$$

- $V_{allowed}$: maximum allowed speed,
- r: curve radius,
- u: built-in cant,
- u_{def}: cant deficiency (here 153 mm from TSI INF chapter 4.2.4.3).

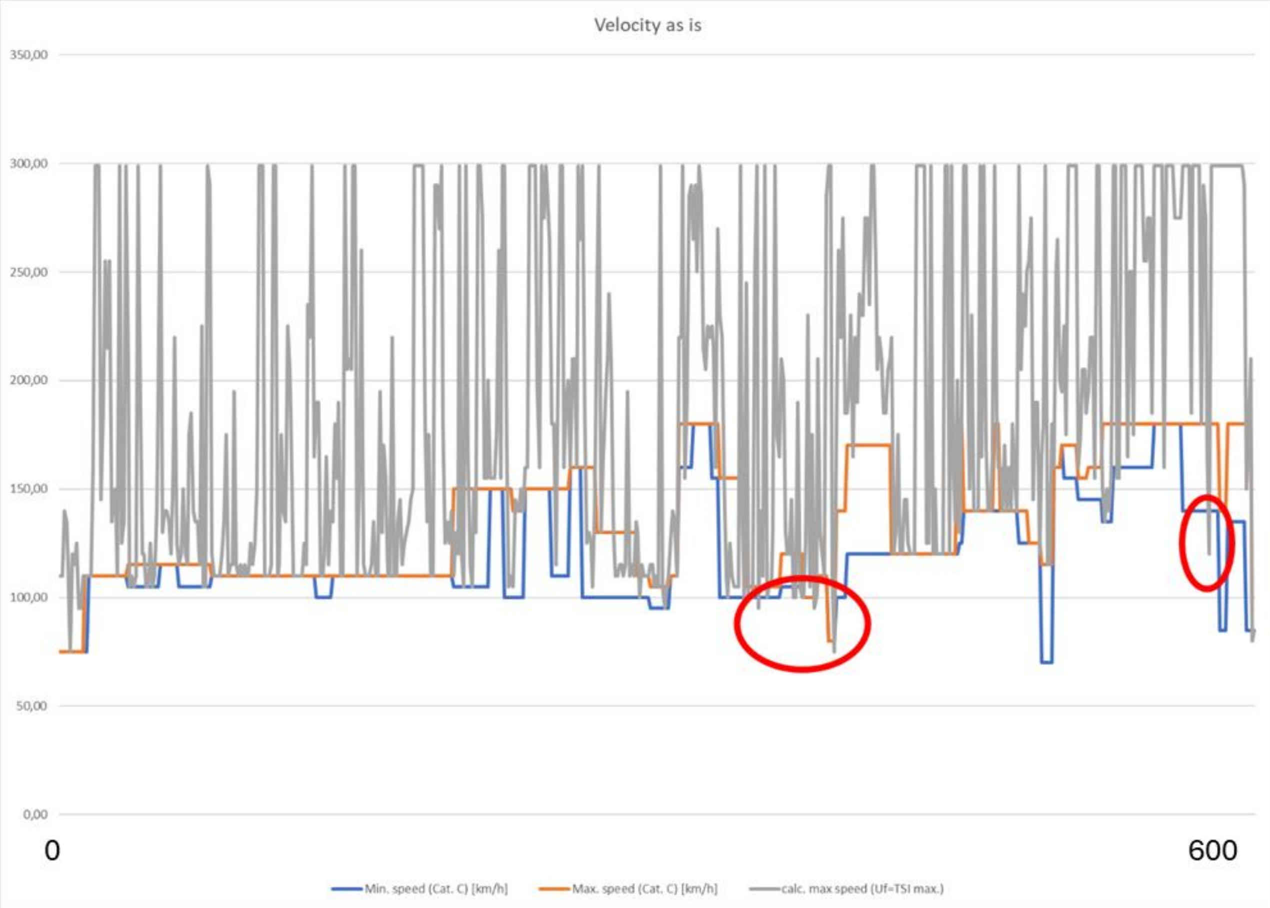


Figure 40: possible speeds with using maximum allowed cant deficiency (153mm)

Calculating the speeds with the maximum allowed cant deficiency justifies the existing speed restrictions along approximately 600 km connection between two major cities. However, there are two sections where the values seem implausible. Between km 290 and km 310 (am intermediate node), some calculated maximum allowed speeds are even lower than the actual allowed speed, which might indicate a section with special permissions. Additionally, the end of the line, there may be a minor data error in the combination of allowed speed limits and calculated values.

After finishing the calculations for the status quo, the possible speeds were estimated for the two different scenarios. In the first Scenario, the levitation system will use the existing rails as a basis and therefore built-in cant will remain the same as before. To increase speed there will be the possibility to use a tilting mechanism of the new MDS pods to lower the cant deficiency for the passengers. From former experiences with tilting trains, the amplitude vehicles tilting should be not too high due to passenger comfort: if the tilting angle is too big, passengers often tend to getting sick in the trains. Therefore, the calculations will be done for a tilting angle of 6° so the additional allowed cant deficiency, which will be compensated from the tilting system, would be:

$$u_{tilt} = \tan(6°) \cdot 1500mm \cong 157mm$$

Using additional 157 mm of allowed “virtual cant” the maximum possible speed will be increased:

$$v_{allowed} = \sqrt{\frac{r}{11{,}8}(u + max.u_{def} + u_{tilt})}$$

- $V_{allowed}$: maximum allowed speed,
- r: curve radius [m],
- u: built-in cant [mm],
- u_{def}: cant deficiency (here 153 mm from TSI INF Chapter 4.2.4.3),
- u_{tilt}: additional virtual cant compensated by tilting system of the pod (157mm at 6°).

For the second Scenario, there will be additional beams used for the levitation system, offering the advantage of different possible cants for regular trains (built-in cant of the standard rails) and high-speed levitating trains (built-in cant of the levitation beams). Therefore, the possible cant for levitating trains can theoretically be increased as high as it is needed and can be realized technologically. For the second Scenario, the maximum MDS cant will be a combination from actual build-in cant of the levitation beams and a very light tilting of the vehicle by 1°.

Because of the restrictions of the clearing gauge, which must be secured for interoperability of the system, the difference in height between the heads of the levitation beams cannot be higher than 220 mm. This distance must be normalized to the track gauge, to use it for calculations. This leads to a built-in MDS cant of 145 mm. Additionally, the pod will tilt by about 1° which brings another 26 mm.

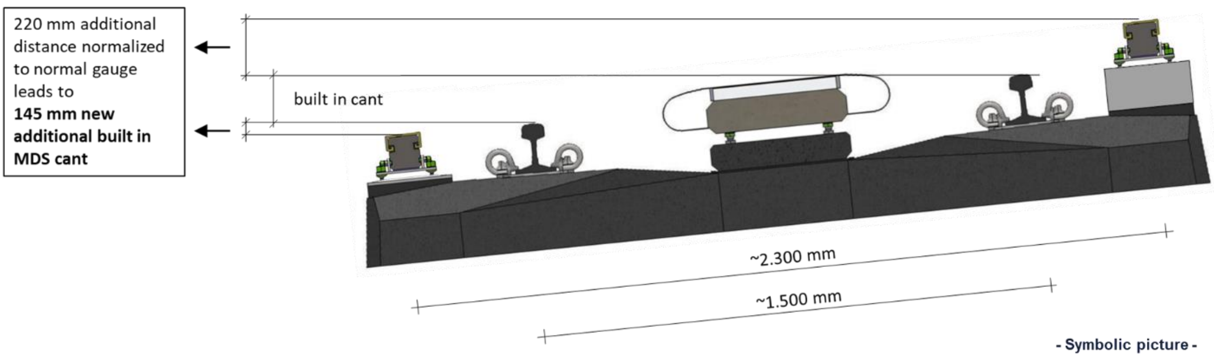


Figure 41: The additional distance between the levitation beams

$$u_{lev.beam} = 145mm + 26mm = 171\ mm$$

$$v_{allowed} = \sqrt{\frac{r}{11{,}8}(u + max.u_{def} + u_{lev.beam})}$$

- $V_{allowed}$: maximum allowed speed,
- r: curve radius [m],
- u: built-in cant [mm],
- u_{def}: cant deficiency (here 153 mm from TSI INF Chapter 4.2.4.3),
- $u_{lev.beam}$: additional built in cant only for levitating pods (171mm).

In both scenarios, railway operations have additional restrictions which must be taken into account. Today the built-in cant and cant deficiency are restricted. This also concern the jerk, which results from the change of the cant during the transition curve when the radius is changing from straight line to curve. This grade of increasing the cant along the transition curve is restricted.

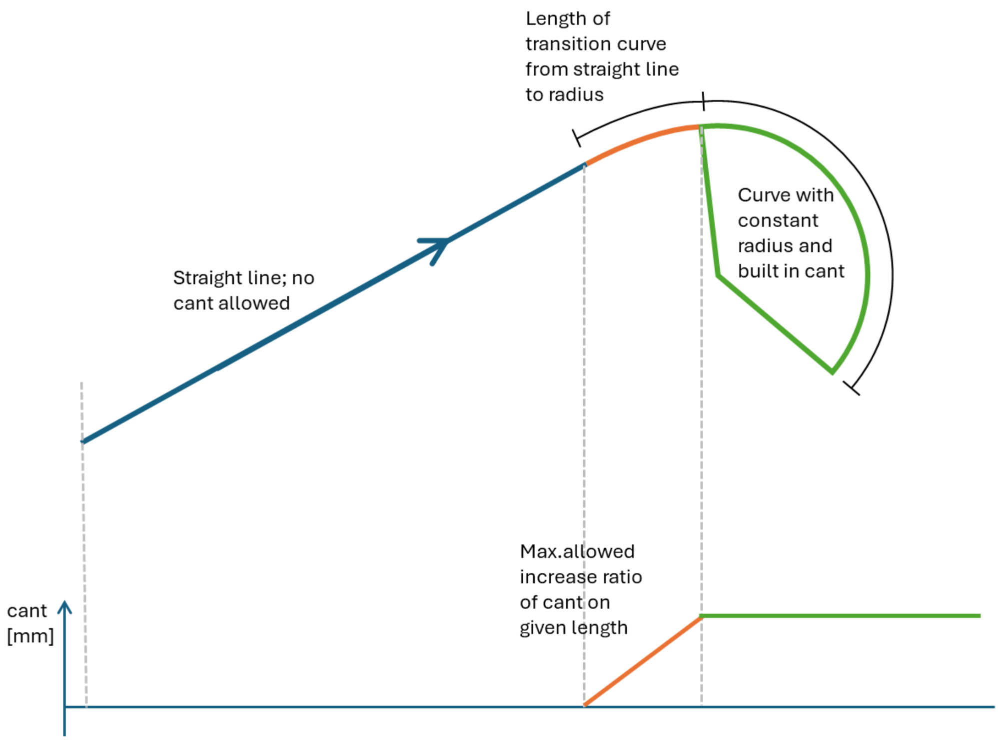


Figure 42: Cant geometrical restrictions

As there are restrictions existing, the first calculation of allowed speeds will be done with respect to the common regulations. Therefore, the maximum allowed cant is set to 180mm (TSI INF, Chapter 4.2.4.2.), the maximum allowed cant deficiency is set to 153 mm and the allowed grade of cant increase within transition curves of 1:400, which means 1mm of cant increase every 400 mm of track length.

For multicentric curves this will be very difficult to calculate, which is not necessary for the first estimation. Therefore, the most restrictive (smallest) curve radius will be relevant for the complete multicentric curve. To calculate the possible speed increase, the maximum possible increase of cant within the first transition curve length is calculated and compared to the technical maximum of the two scenarios (Scenario A: 157 mm, Scenario B: 171 mm). The smaller of these two values will be taken for calculation as Δu (see following figure), which is the additional possible cant u_{tilt} or $u_{lev.beam}$.

One last restriction from existing rules will be the maximum allowed built-in cant of 180 mm.

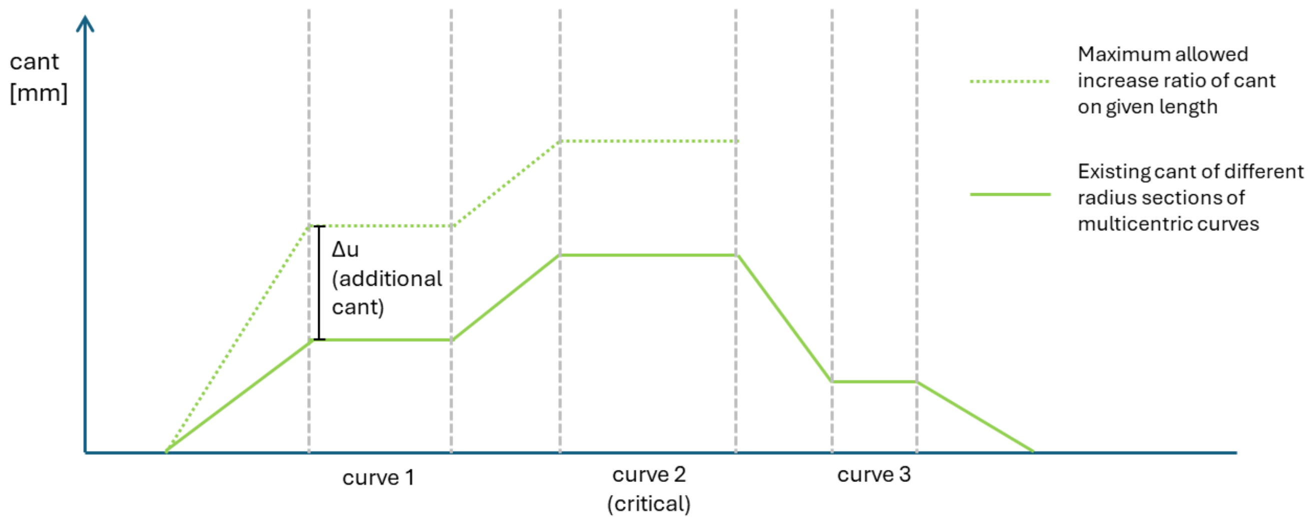


Figure *43*: Possible additional allowed cant in multicentric curves

Taking all these circumstances into account, the new possible speeds in curves can be calculated as shown in the following Figure for the two scenarios. The results show only a very small positive effect on the maximum allowed speeds because of the very restrictive existing rules, which do not allow for the specific possibilities of new MDS technologies. In most sections of the line, the speed can be increased by 5-20 km/h. Additionally, it shows that the TSI and national's rules have a strong restrictive effect on both scenarios, so there is no difference between the two.

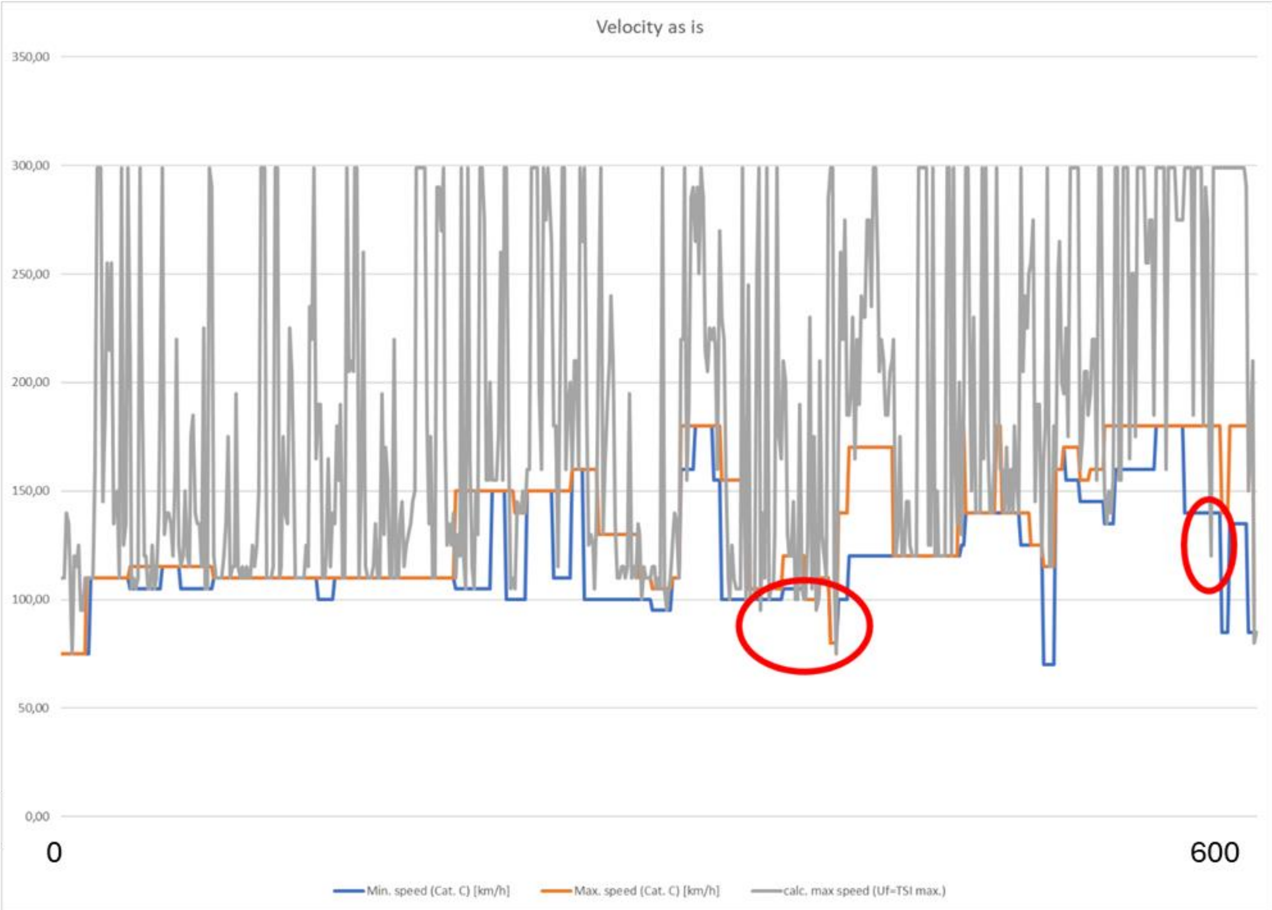


Figure *44*: Calculation of new speed in curves for scenario A

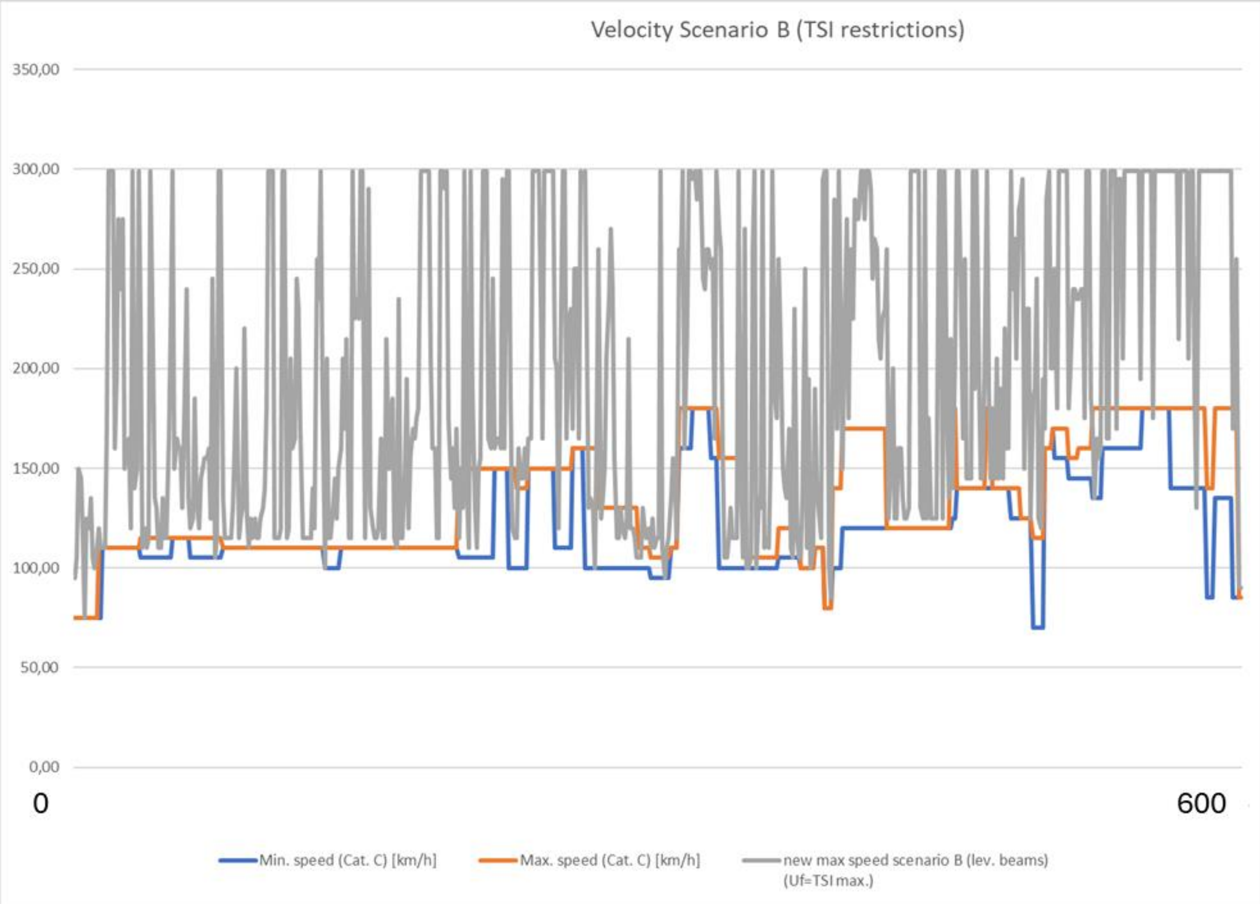


Figure *45*: Calculation of new speed in curves for scenario B

The first calculation shows that respecting todays regulations will bring only very small effects compared to the status quo: today's restrictions, focused on mixed traffic (passenger and heavy freight trains), will not fit for a new traffic system of lightweight levitation pods because they might be too restrictive. Therefore, a second calculation was done with values assumed for the new system. The assumptions were made for the following three values:

Maximum built-in cant

For the levitating pods, it can be much bigger if the used infrastructure elements of different traffic systems can be separated from each other. Today's restrictions mainly focus on the slow and heavy freight trains. The higher the built-in cant, the bigger the load on the inner (lower) rail would be when slow and heavy trains run through the curve. This will cause massive wear on the lower rail and wheels of the trains. With the MDS technology, low and high-speed trains are separated to standard rail or levitation beams. So, the built-in cant of the levitation beams can be much higher than today's regulations. For the calculations the value is set to an additional built-in cant of 171mm in maximum. Combined with possible traditional cant of max. 180 mm, this would lead to 351mm in maximum, which was also used for the Transrapid trains.

Cant deficiency

It is a value set mainly for the passenger comfort. The goal is to limit the lateral acceleration to the passengers in curves. But to limit this lateral acceleration also secures the maximum load and wear to the outer (higher) rail, if trains run on high speeds. For the new MDS technology there might be higher possible values, as the pods will not have a classic dinning wagon service and also seatbelts might be conceivable. As the guiding system will also be on a magnetic basis, there will be no problem with additional wear. In Transrapid, the max. value of lateral acceleration in curves was up to 3,6 m/s². Because of this, it can be assumed that the allowed lateral acceleration in curves can be increased from 1,0 m/s², which is the basis of the 153 mm of cant deficiency, to 1,2 m/s² which still ensures high passengers' comfort. Therefore, the new cant deficiency will be

$$u_{def} = a_q \cdot \frac{1500}{g} \cong 180mm$$

- u_{def}: cant deficiency,
- a_q: lateral acceleration in curves (here 1,2m/s²),
- g: gravitation acceleration (9,81 m/s²).

Cant increase

It is not easy to find comparisons of the allowed grade of the cant increase. One possibility could be the allowed roll rate of passenger planes. The A320, for example, has a maximum rollrate of 20° per second. A tilting angle of 20° is equal to a cant of 546 mm in railways. Referring to a MDS maximum travel speed of 300 km/h, the change from zero to 546mm within one second would result in a grade of 1:150. The Transrapid system used up to 1:345. Oriented on the Transrapid trains, a value of 1:350 is assumed for this study.

Using these new restrictions for the MDS system brings much better effects on the possible speed increases as shown in the following Figures for the two scenarios.

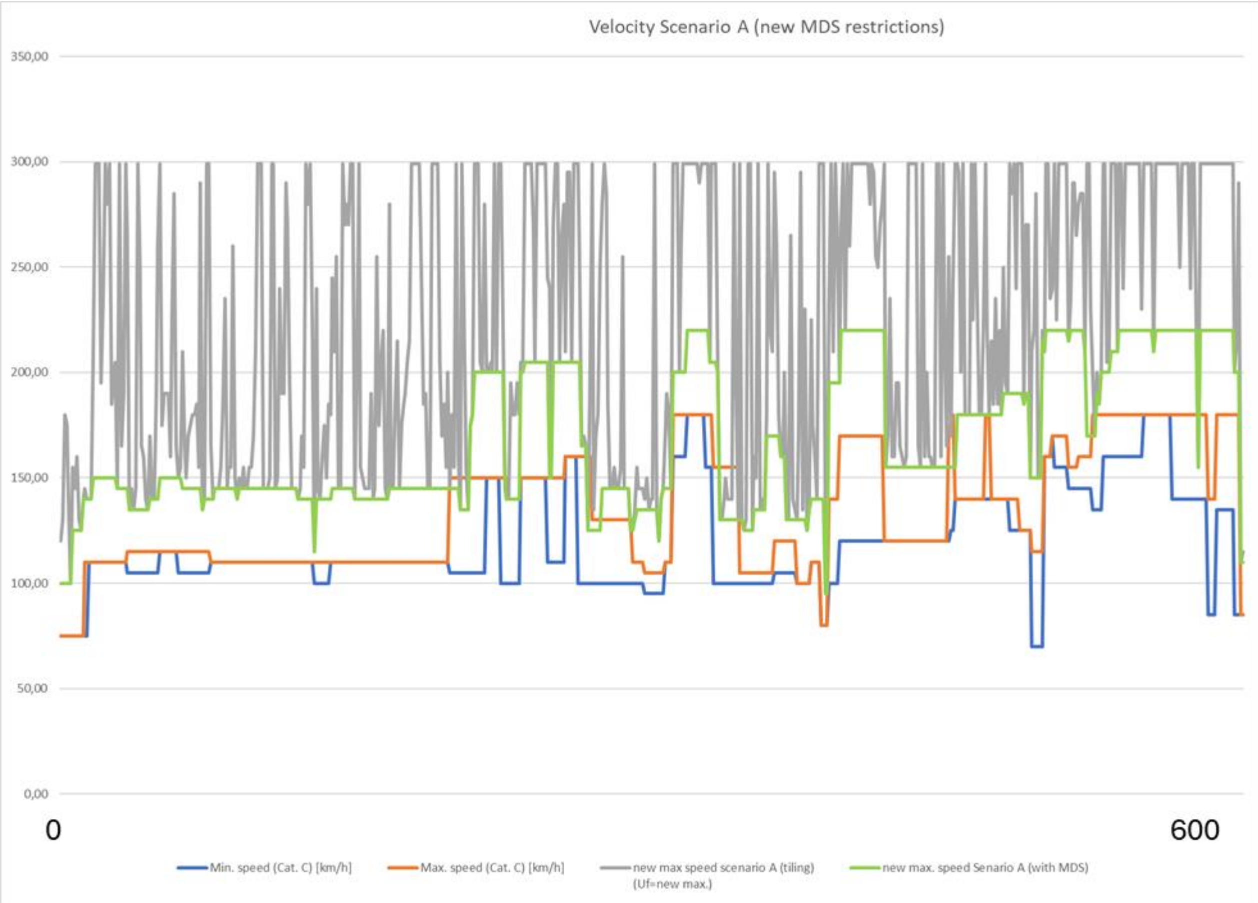


Figure *46*: Speed profile with new MDS restrictions for scenario A

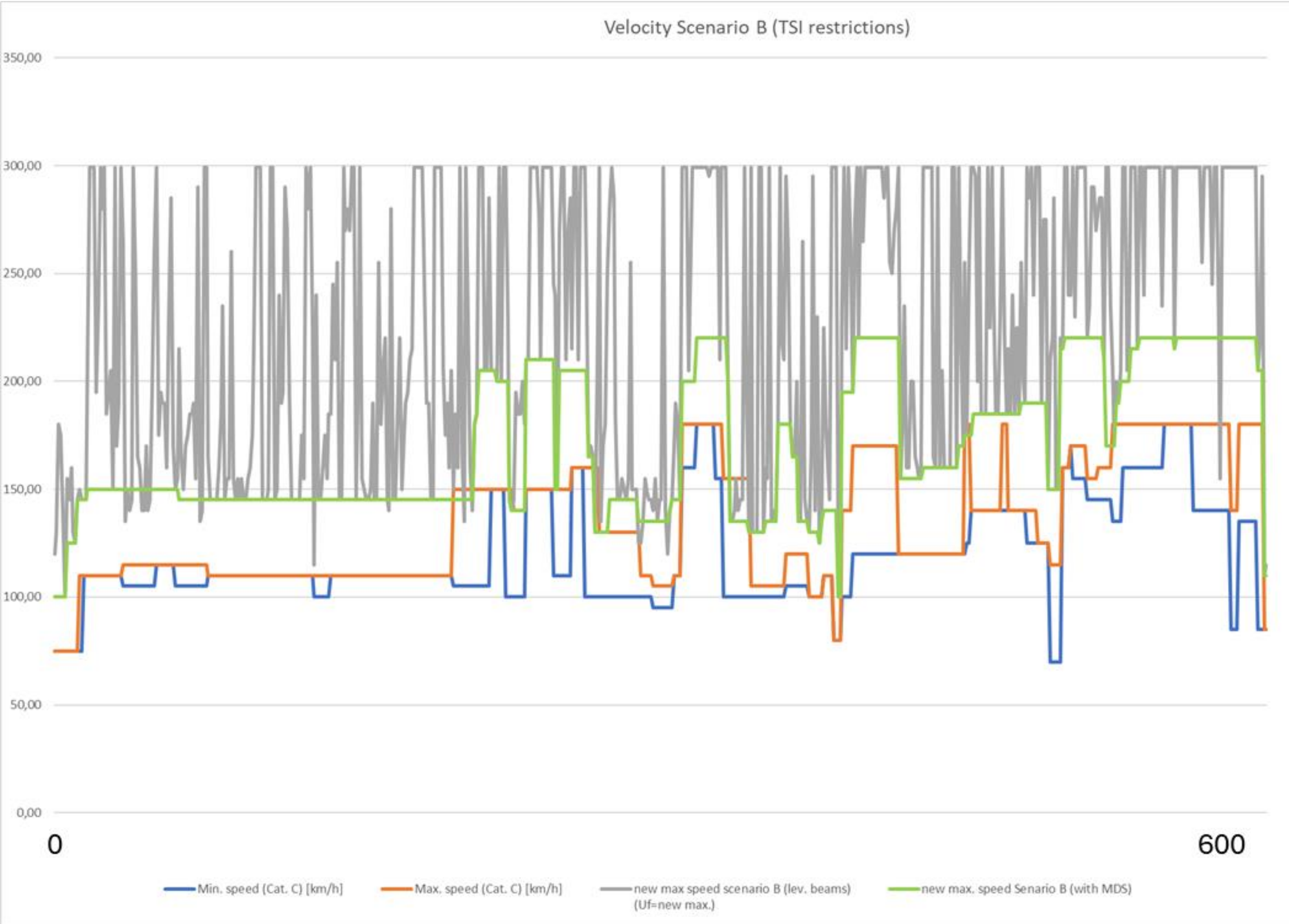


Figure 47: Speed profile with new MDS restrictions for scenario B

The results show a very positive effect on the maximum allowed speeds. In most sections of the line, the speed can be increased by 30-50 km/h. In combination with a better ability to accelerate and holding speeds on incline sections, travel times might be much better.

From the comparison of these two scenarios, it is visible that both of them bring very comparable results, and the new possible speed profile of the line looks almost identical. Only in the last section between the two cities the Scenario B gives slightly better results of 5-10 km/h higher speeds.

9.2.1.2 Acceleration and deceleration

The project also checked acceleration and deacceleration parameters for different traffic systems as it is shown in the next table. For the MDS technology, both values have been assumed to be 1.5 m/s^2. It is important to remember that the technology will allow for much higher values, but it could negatively influence passengers' comfort. However, passengers accept accelerations almost up to 2.0 m/s^2 while they choose to take an aircraft, what leaves some margin for further reconsiderations, but as for now conservative approach has been adopted.

System	Type	Max. Acceleration [m/s2]	Max deceleration [m/s2]
MagRail	MDS	1,5	1,5 (up to 5,0 with safety belts)
Linimo	Maglev	1,1	1,25
Germany	Railway	1.5 according to standard but HS have about 0.6 m/s2 due to the comfort	1.5 - standard no limit for emergency
France - conventional line	Railway	1.5 according to standard	1.5 - standard no limit for emergency
France - high-speed line (TGV)	Railway	0,472	1.5 - standard no limit for emergency
Japan (Shinkansen)	Railway	0,72	ND
Transrapid	Maglev	1	1,5
Yokohama Subway	Subway	0,97	1,3
Osaka Subway	Subway	0,69	1,25
Hyperloop	Hyperloop	1,5	
Passenger aircraft	Aircraft	1,82	1,82

Table *19*: Max. accelerations & decelerations for different systems

Gradient based on the data provided by RFI, the terrain gradients along the route between two major cities were analysed, categorized by two directions: from the first city to the second and vice versa. The maximum gradient along the route from the first city to the second was recorded at 14.58 per mil, whereas along the route in the opposite direction, it reached a maximum of 13 per mil.

The range of terrain inclinations has been divided into 5 categories, taking into account various factors such as performance, safety, and economic efficiency of railway operations.

- "Downhill": Terrain inclinations smaller than 0 are interpreted as downhill. A value less than zero indicates that the train is moving downhill, which may require a different approach to speed control and braking compared to flat or ascending terrains,
- "Flat surface": Terrain with inclinations from 0 to 2 per mils is considered flat, implying minimal terrain inclination that has little impact on energy consumption and train safety,
- "Light incline": Terrain inclinations from 2 to 5 per mils are classified as lightly inclined, potentially causing slight increases in energy consumption and requiring slightly greater attention during braking,
- "Medium incline": Terrain with inclinations from 5 to 10 per mils is deemed moderately inclined. In this range, terrain inclination leads to increased energy consumption,
- "High incline": Terrain inclinations above 10 per mils are considered the threshold beyond which terrain inclination may be significant.

Type Of Slope	Values [‰]
Downhill	x<0
Flat Surface	0=<x<=2
Light Incline	2<x<=5
Medium Incline	5<x<=10
High Incline	10<x<=15

Table *20*: Incline categories

These categorizations allow for a better understanding and adjustment of train engine parameters to terrain conditions, crucial for maintaining safety and operational efficiency of the railway.

Two critical points along the track were identified, which warranted further detailed analysis. Analysing these critical points is crucial for ensuring the safety and potential adjustments to infrastructure to enhance performance and passenger comfort.

The first critical point, located just over a hundred kilometres from the beginning of the line, is a steep incline measuring about of 12 ‰, this value is the same for both the sense. The point is located a few

The second critical point represented the segment just after the middle of the route between the two cities. The highest value was recorded on the sections between stations amounting to 14.58 ‰.

All stages conducted on the segment between two major cities in one direction were also carried out in the opposite direction. On this segment, three critical points were identified, which then needed to be considered when determining the parameters of the linear motor and the inverter.

The first critical point represented a segment located just over a hundred kilometres in the even direction. The highest value was recorded on the sections near a station, amounting to 13 ‰.

The second critical point is located more or less in the middle of the line. The highest value was recorded on the sections between stations, amounting to 11,33 ‰.

The third critical point represented the segment almost at the end of the route in the even direction. The highest value was recorded on the sections between two stations, amounting to 12 ‰.

Compared to the route between two major cities, most kilometres of the route in this direction were flat not negative terrain inclination.

9.2.1.3 Virtual coupling

The possibility to use a linear motor to control fully automated pods can increase flexibility and enhance efficiency of the rail system. On-demand operation and personalized services can be realized. Such pods can operate individually or in groups, providing tailored services for different routes or passenger volumes. This optimizes the capacity use on the tracks. To reach the maximum of operational flexibility, groups of pods should be able to connect and disconnect everywhere without using physical couplers but always have the control of a defined distance between each other depending on the fact if they run alone or in a group.

In recent years, the railway sector has focused its efforts on increasing the capacity and flexibility of lines by improving the current railway operation. Research has focused on increasing capacity by reducing the headway or the distance between trains. Moreover, railway traffic control and signalling systems based on moving-block systems (MBSs) have been developed, such as the Communication-Based Train Control (CBTC) system (IEEE, 2004), which is mainly used in urban and Automated People Mover (APM) railway lines, and the European Rail Traffic Management System (ERTMS L3, recently denominated ERMTS Level 2 with moving block) (Furness et all, 2017) for main and commuter lines.

Additionally, the coupling of train units to form consists has been proposed, for enhancing the average passenger train speed, energy efficiency, and capacity utilization of railway infrastructure, among other aspects. One approach is based on the use of virtual coupling (VC) to virtually change the compositions of the consists at the cruising speed via communication (Felez et al, 2019). Thus, VC is a train-centric next generation signalling system that enables multiple trains to operate in a formation just like one train or decouple separately, either on-the-run or at station, flexibly or as planned. VC is an evolution of the current MBSs, similar to the way in which road vehicles operate, where vehicles run at a safe distance from the vehicle in front and the driver reacts to the brake lights of the vehicle in front, and this safe distance is far shorter than the braking distance required for a complete stop, as considered in current MBSs.

Clearly, more trains can run on the line if the spacing between trains is reduced. Thus, the line capacity is increased. In (Quaglietta et all, 2020), a multi-state train-following model was developed for describing VC procedures conduct a comparative capacity analysis with other signalling systems. The results indicated that VC has a superior capacity to MBSs, and it was estimated that VC could reduce the distance between trains by 64% for European Train Control System (ETCS) Level 2 and by 43% for ETCS Level 2 with moving block.

Consequently, in addition to increasing the capacity of the line, VC can provide a more flexible mode of operation, with trains or new designed pods behaving as if they are physically coupled. This makes it possible to run rail vehicles in smaller sets but adapt to the circumstances (Felez & Vaquero-Serrano, 2023).

9.2.1.4 Moving block systems: Absolute against Relative braking

There are two modes of train operation control in the MBS (Ning, 1998): the Absolute Distance Braking Mode (ADBM) and the Relative Distance Braking Mode (RDBM). These two control modes have different efficiencies and risks.

The ADBM (Figure 48) is based on the concept that two consecutive consists running on the same track must always be separated by a sufficient margin to ensure that each train can reduce its speed and will be able to stop before reaching the last known position on the track of the consist immediately preceding it, regardless of the current speed and the braking curve of the preceding consist.

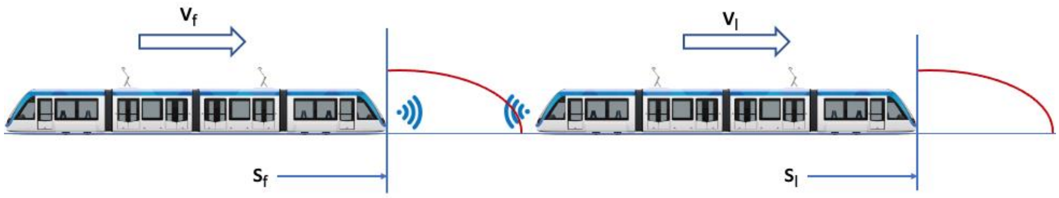


Figure *48*: Absolute braking (Felez & Vaquero-Serrano, 2023)

In the ADBM, the position of the follower train s_f is calculated as:

$$s_f = s_l - d_{min} - \frac{{v_f}^2}{2a_f}$$

where d_{min} represents the minimum safe distance between two consecutive consists, s_l represents the position of the leader, and v_f and a_f represent the velocity and braking deceleration of the follower, respectively.

The ADBM is applied in CBTC and in ERTMS Level 2 with moving block. However, its conservative character results in trains tending to run far apart.

Depending on the braking decelerations of the two consecutive consists, the safety margin between two trains can be reduced by applying RDBM (Relative Distance Braking Mode) principles. RDBM concepts have been widely applied in control systems for road traffic, autonomous vehicles, and platoon cars. The RDBM system is similar to the on-road mode of operation, where vehicles drive at a safe distance from the vehicle in front and the driver reacts to the brake lights of the vehicle in front, which is far shorter than the required braking distance for a full stop. This idea is fundamental to vehicle platooning and autonomous vehicles.

In the RDBM, it is assumed that two consecutive consists are in motion, and depending on their braking speeds, the safety margin between them can be reduced. Thus, if the first train (leader) is running at speed v_l and braking with deceleration a_l and the second consist is running at speed v_f and braking with deceleration a_f, the position of the follower s_f can be calculated as:

$$s_f = s_l - d_{min} + \frac{{v_l}^2}{2a_l} - \frac{{v_f}^2}{2a_f}$$

Figure 49 shows a schematic of the relative-braking concept.

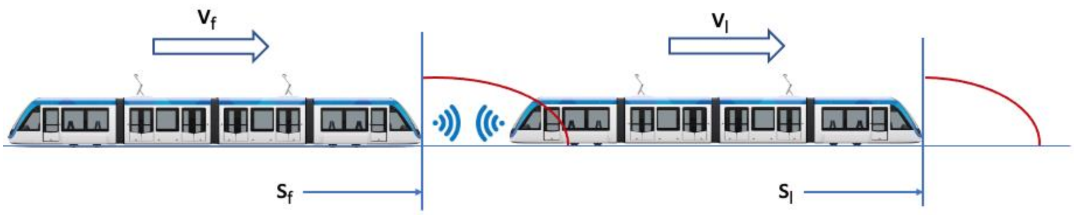


Figure *49*: Relative braking (Felez & Vaquero-Serrano, 2023)

In order to realize dynamic train coupling, position and speed information must be reliably exchanged between trains (Winter et all, 2016). New communication technologies offer this ability of direct communications between vehicles with high rate and low latency. The VCTS requires sensors to know at all times the relative distance to and velocity of the preceding train. It also requires a communication link between consists for them to exchange information such as their positions, velocities, and accelerations.

9.2.1.5 Aerodynamic drag in virtual coupling configurations

As shown in the next figures, due to the proximity of trains in the virtual coupling, the airflow between trains can significantly affect factors such as air resistance during train operations, thus altering the train dynamic model. Therefore, building an accurate model for train drag in the virtual coupling plays a crucial role in achieving smooth tracking control of the trains in the virtual coupling and facilitating the real-world application of the virtual coupling. These effects are very relevant as there is a reduction of drag which results in lower energy consumption.

In this way, different CFD (Computer Fluid Dynamics) calculations have been carried out with the ultimate aim of obtaining the aerodynamic drag coefficient (Cx) for the train convoy. The Cx coefficient is dependent on the distance between trains and the driving speed, so, as a final result, a 3D mesh has been obtained for each train to obtain its value.

Figures 50, 51 and 52 show the results of the CFD calculations for a single pod configuration, where a coefficient of 0.31 has been obtained. This is the coefficient of an individual train and is the one to which the trains of a convoy tend asymptotically when the separation between units is sufficiently high.

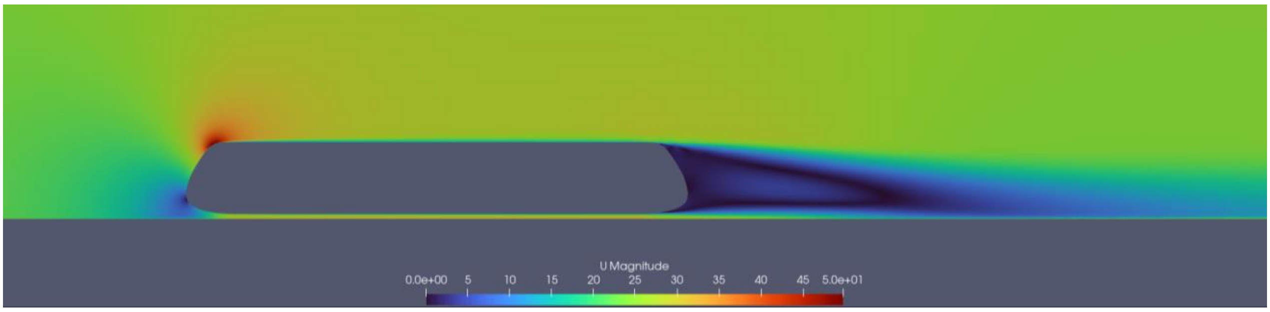


Figure *50*: Flow velocity (m/s) for a single pod composition

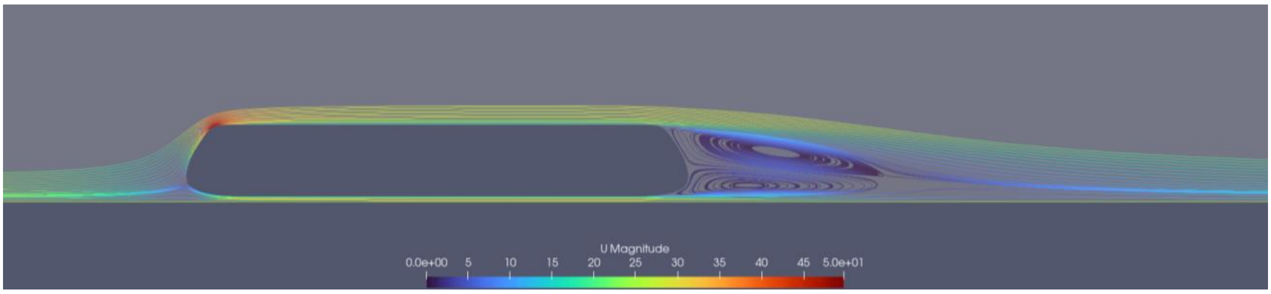


Figure *51*: Streamlines (m/s) for a single pod composition

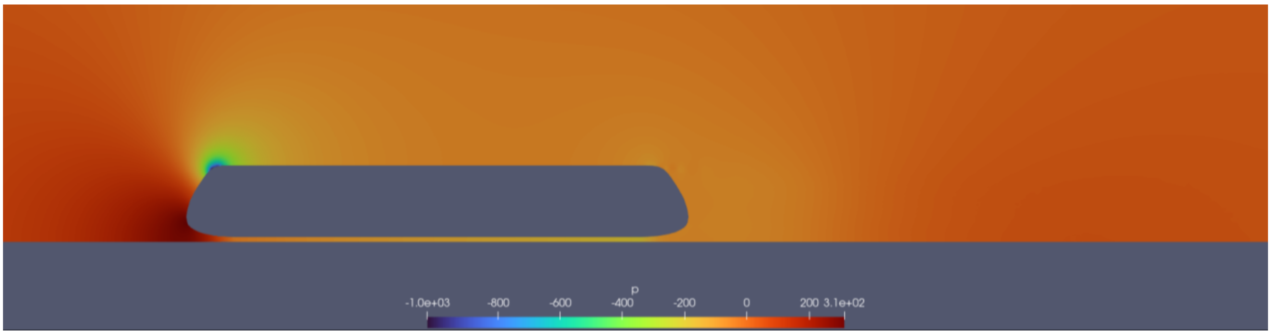
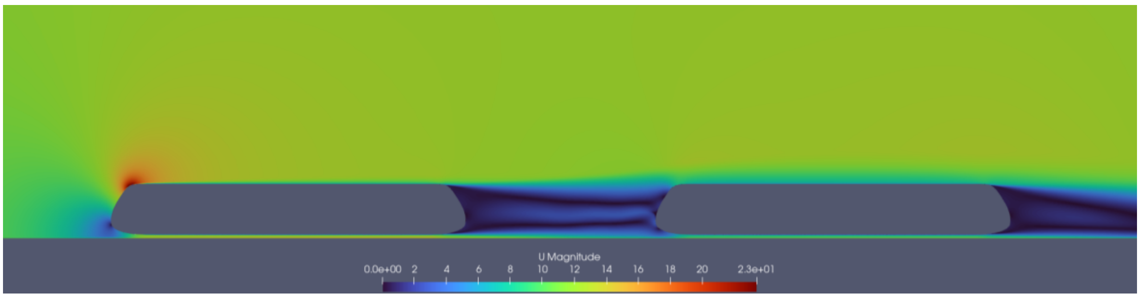


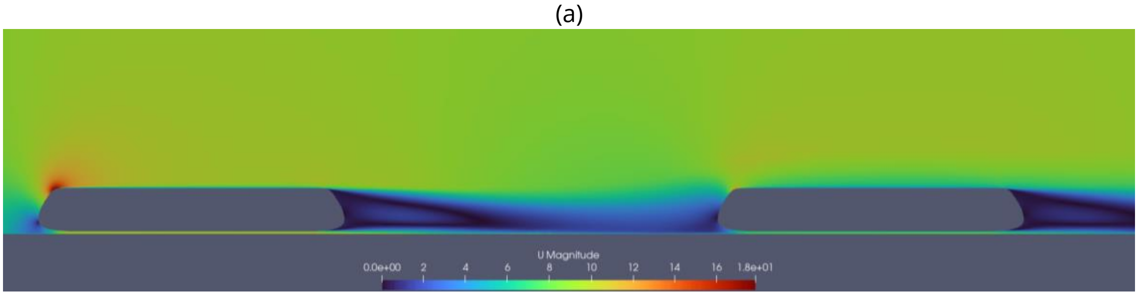
Figure *52*: Pressure distribution (m^2/s^2) for a single pod composition

Figures 81, 51 and 52 show results for a 2-pod configuration. They clearly show the slipstream effect and how, when the trains are close together, a vacuum effect is produced between them which results in a reduction of drag.

Calculations for both relative braking (virtual coupling) and absolute braking (ERTMS L2 with moving block) have been included. The figures show that in absolute braking, given that the separation between trains is greater, the slipstream effect is lower, which translates into greater drag, and therefore greater energy consumption.

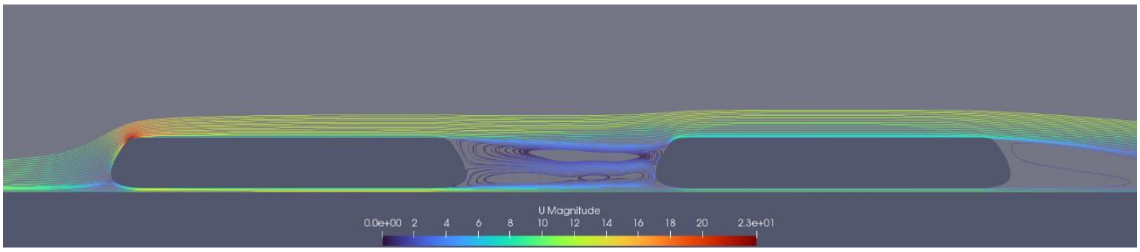


(a)

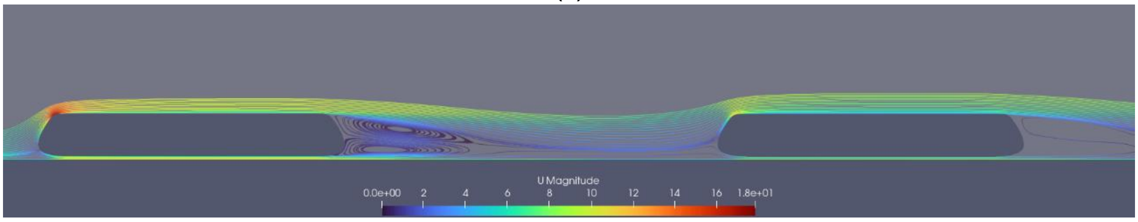


(b)

Figure 53: Flow velocity at 9 m/s for a composition of two pods, (a) with relative braking spaced 15 m from each other and (b) with absolute braking spaced 40 m from each other

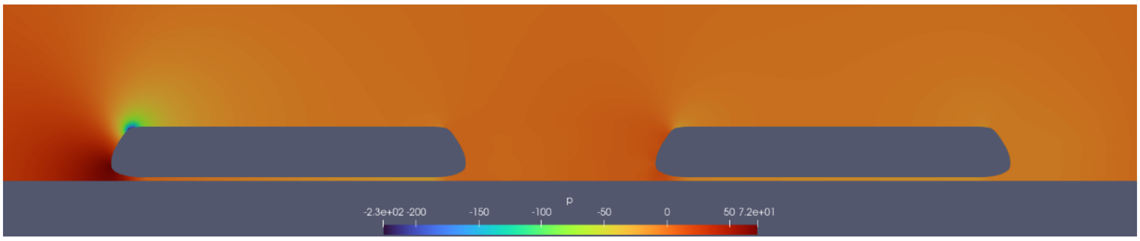


(a)

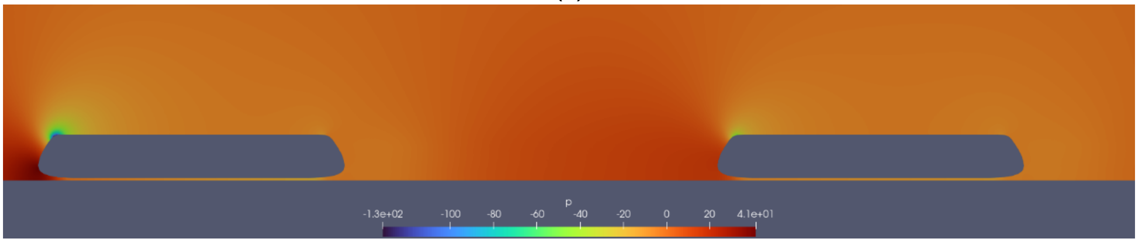


(b)

Figure 54: Streamlines at 9 m/s for a composition of two pods, (a) with relative braking spaced 15 m from each other and (b) with absolute braking spaced 40 m from each other



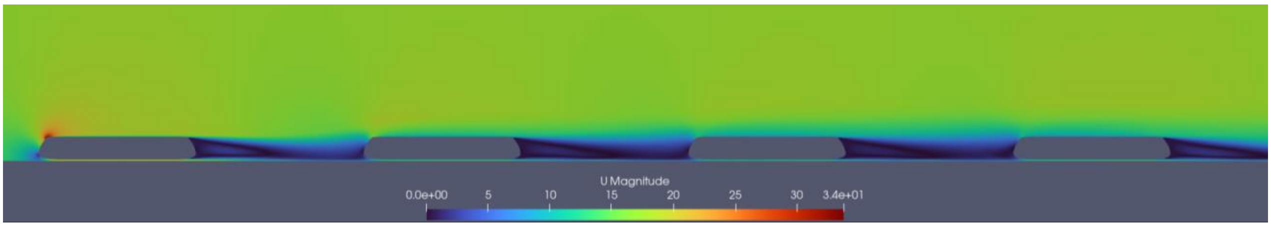
(a)



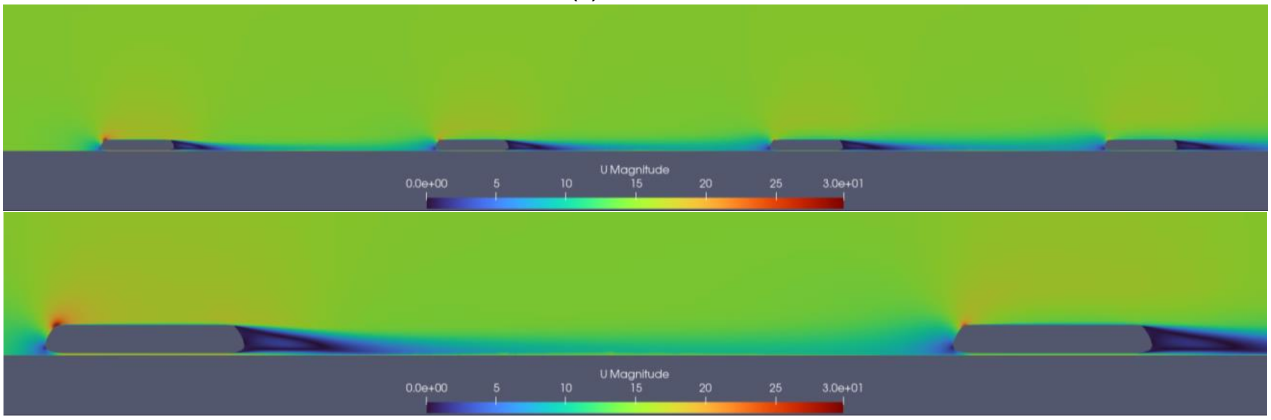
(b)

Figure 55: Pressure distribution (m^2/s^2) at 9 m/s for a composition of two pods, (a) with relative braking spaced 15 m from each other and (b) with absolute braking spaced 40 m from each other

Finally, figures 56 and 57 show results for a 4-pod configuration, which is the one used in this use case to compare it with a conventional train (ETR 421). The same effects as explained above can be seen.

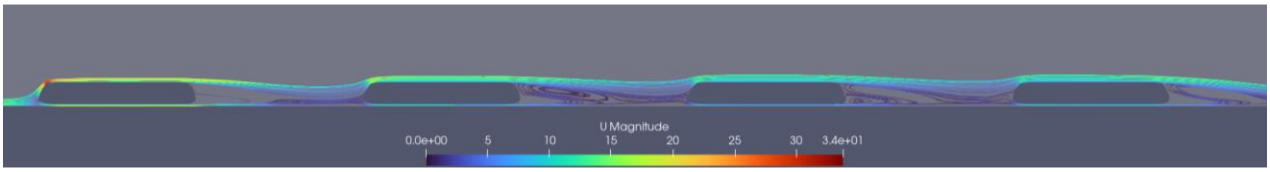


(a) Pods 1-4

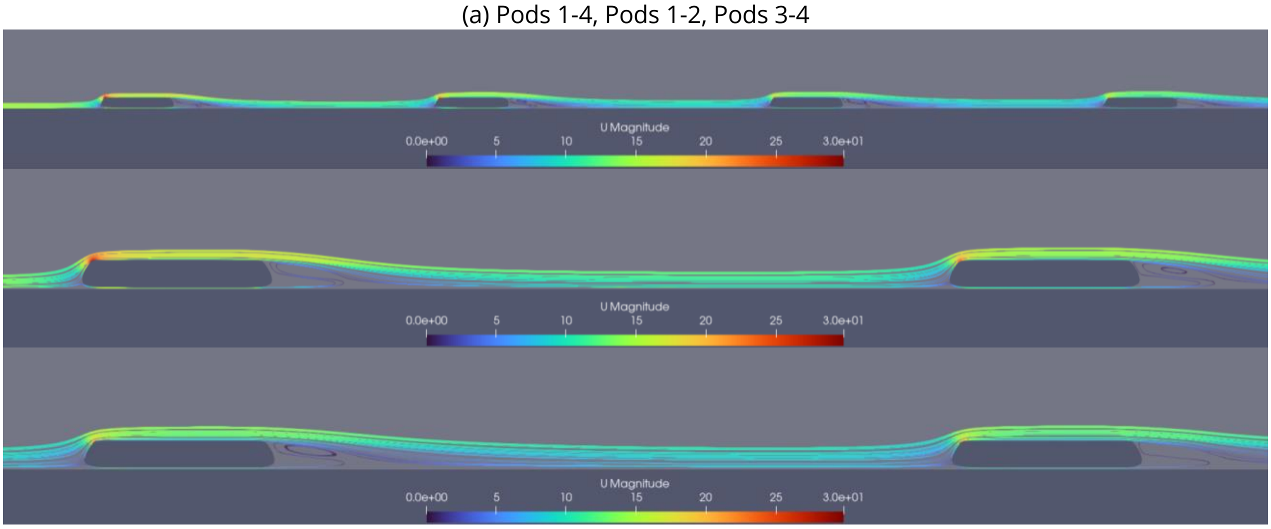


(b) Pods 1-4, Pods 1-2

Figure 56: Flow velocity at 15 m/s for a composition of four pods, (a) with relative braking and (b) with absolute braking



(a) Pods 1-4, Pods 1-2, Pods 3-4



(b) Pods 1-4, Pods 1-2, Pods 3-4

Figure 57: Streamlines at 15 m/s for a composition of two pods, (a) with relative braking and (b) with absolute braking

To conclude, Figure 58 shows the Cx functions obtained for each of the 4 pods, representing the variation of Cx as a function of the distance between pods and of the driving speed. These results are the ones to be used in the simulations carried out in the following subchapter.

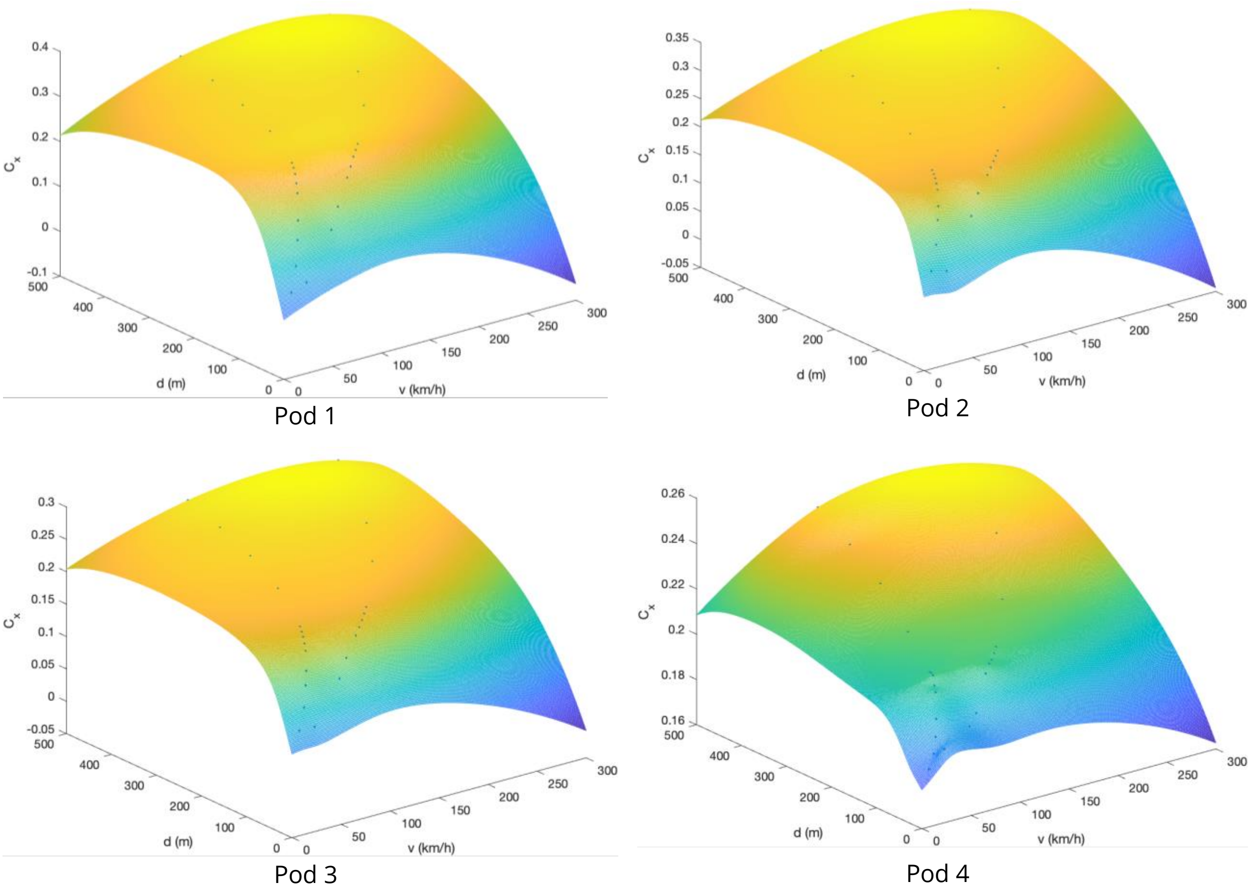


Figure 58: Cx variation for the different pods

9.2.1.6 *Analysed configurations*

To assess these scenarios, two possible MDS vehicle configurations have been evaluated with respect to the basic configurations of a conventional rail vehicle which is currently running on the line under study. The characteristics of this conventional rail vehicles are as follows:

Table 21 shows the main characteristics and main parameters for the actual train (ETR 421):

Parameter	Value
Mass:	267,914 ton
Length:	109,6 (4 coaches)
Normal acceleration	1,1 m/s^2
Power:	3.400 kW

Traction/brake maximum force:	+/- 300 kN

Table 21: Passengers train (ETR 421) to be compared with the new vehicles

And for an individual pod (Table 22:), the following characteristics have been considered (as defined in WP8):

Parameter	Value
Mass:	43,6 ton
Length:	28 m
Maximum speed	220 km/h

Table 22: Pods main characteristics

For the pod, two different alternatives have been considered in terms of traction capacities:

1. Maximum acceleration of 0.75 m/s^2. This acceleration leads to a maximum tractive effort of 35 kN. This option has been limited to 1500 kW of power. In order to be able to implement acceptable virtual coupling conditions, a maximum braking deceleration of 1.2 m/s^2 was set, leading to a maximum braking effort of 52.32 kN. This maximum deceleration is also justified as a way of establishing a braking capacity similar to that originally proposed (of 1.5 m/s^2) but within the usual maximum deceleration margins for conventional trains,
2. Maximum acceleration of 1.5 m/s^2. This acceleration leads to a maximum tractive effort of 71 kN. This option has been limited to 2263 kW power. The maximum braking deceleration is 1.5 m/s^2, which leads to a maximum braking effort of 71 kN.

These values are summarized in Table 23.

Normal acceleration (m/s^2)	Maximum traction force (kN)	Power (kW)	Maximum deceleration (m/s^2)	Maximum braking force (kN)
0,75	35	1500	1,2	52,32
1,5	71	2263	1,5	71

Table 23: Pods configurations for traction capacities

9.2.1.7 Simulation model

As in the previous use cases, the model defining the train motion of this work is based on the principles of longitudinal train dynamics (LTD). The parameters considered for the rolling resistances are summarized in the following table (Table 24). The values for the pod have been obtained from the magnetic drag calculations carried out in the following sections:

Coefficient	ETR 421	Pod
A - N	1789,79	20,3
B - N/(m/s)	100,18	14,1
C - N/(m/s)^2	8,32	2,07

Table *24*: Pods configurations

9.2.1.8 Simulation results

Figure 59 presents the line characteristics with two simulation scenarios. Scenario A is for 220 km/h and scenario B is 220 km/h with optimized infrastructure

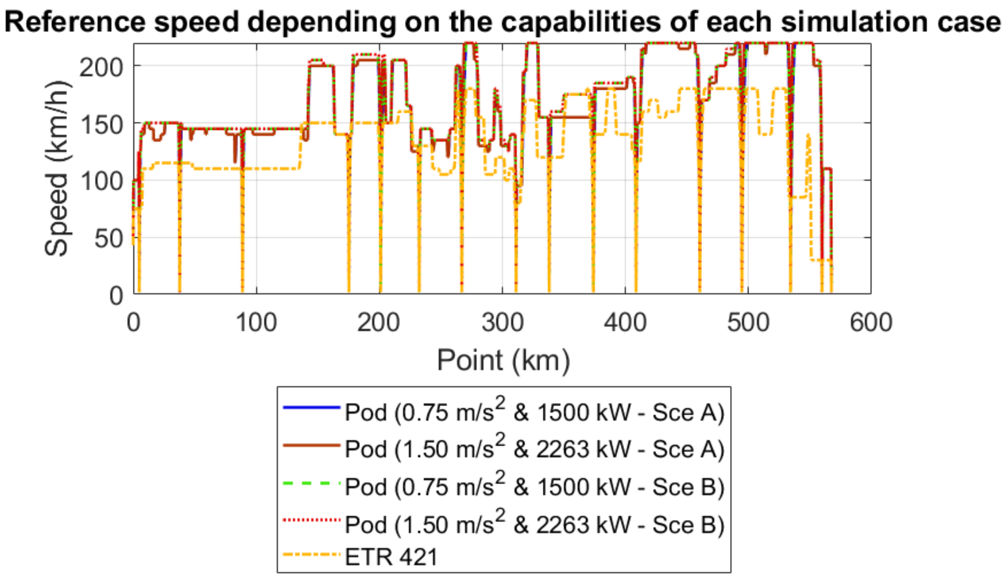


Figure 59 Line characteristics with two simulation scenarios

This figure 59 presents the reference limit speeds for the 2 scenarios (A and B) and the ETR 421 as a reference. As can be seen, the maximum speed profile of Scenario B is slightly more stable than Scenario A in some sections, maintaining the maximum speed for a longer time. Slightly higher maximum speeds are also reached at some points along the line. The ETR profile is the one with the lowest speeds.

Both simulation scenarios are described in more detail in section 9.3.1.1. In summary, the difference between the two scenarios is that in Scenario B the infrastructure is optimised to achieve sections of the line with higher speeds than in Scenario A. However, the maximum speed of the line is also 220 km/h.

The simulations were carried out by dividing the total route into three sections. The first comprises stops 1 to 3, the second from stops 3 to 9 and the third from stop 9 to the end of the line.

The behaviour of the different vehicles on the line has been simulated using the model presented in the previous section. The following Figures show the obtained results. Only the 1st pod of each convoy is plotted for simulation and no follower pods are included for clarity.

Figure 60 shows the plot of travel time versus train position on the railway line (only for the second sector, stops 3 to 9). It shows how, for the same route and with the same stops, the current passenger train is much slower and takes more time to complete the journey. In contrast, the different pod configurations achieve similar performance, reducing total travel time from 5.39 hours with the ETR to times ranging from 3.96 to 4.13 hours depending on the pod configuration considered, achieving an average reduction in travel time of 25%.

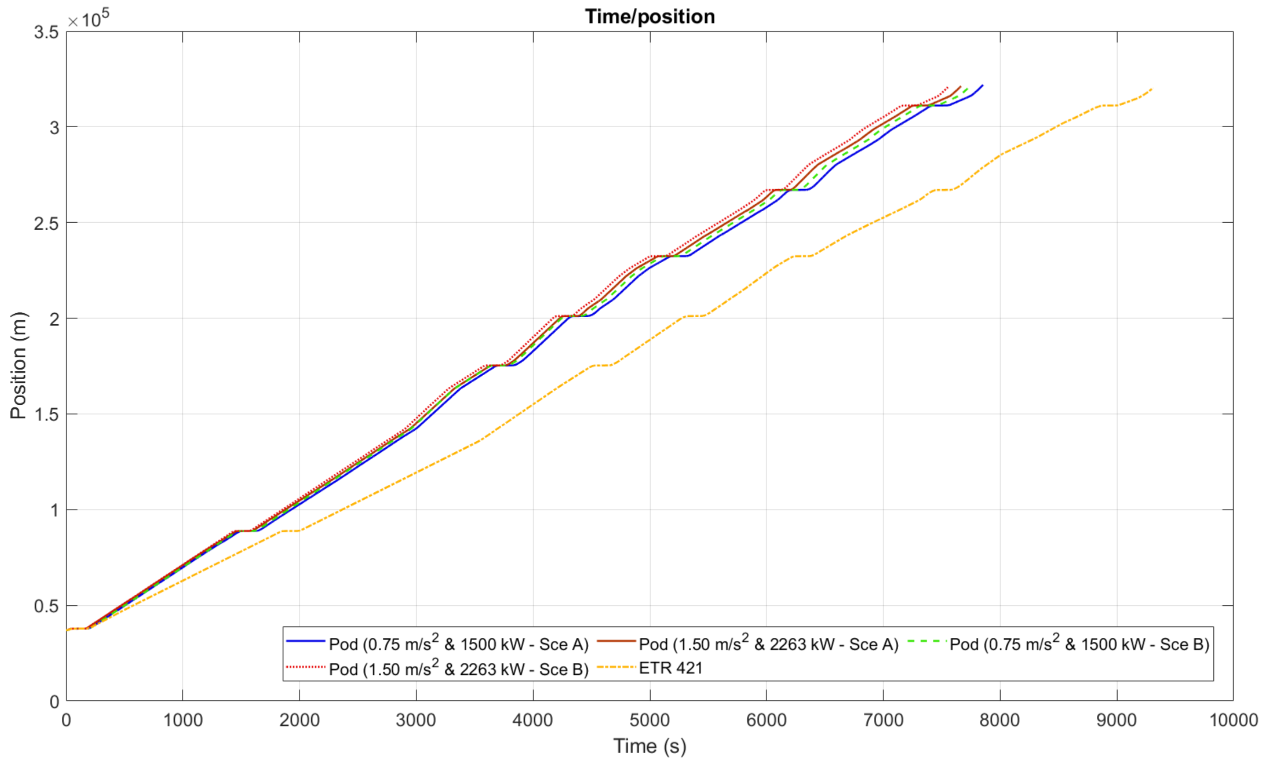


Figure *60*: Time/position diagram for the different trains (stops 3-9)

Figure 61 shows the speed and longitudinal acceleration of individual railway vehicles at each point of the journey. On the left-hand side, it is shown as a function of journey time, and on the right-hand side, as a function of kilometre point.

It should be noted that, as the line has been simulated in sections, the initial simulation time is 0, but the final results take into account that there will be a time lag due to the necessary travel times of previous sections. This time lag is different depending on each simulation case, as the time advances of each of the different options simulated (one train goes faster than another) are accumulated. The simulated section is the one between stations 3 and 9, which involves 6 stops (not counting the departure station).

The Figure shows the first pod of each simulation case (follower pods are not shown for clarity). The maximum speeds and accelerations are those expected for each case. It also shows an improvement of all pod simulation cases with respect to the ETR and again visualises how pod configurations need considerably less time to complete the route.

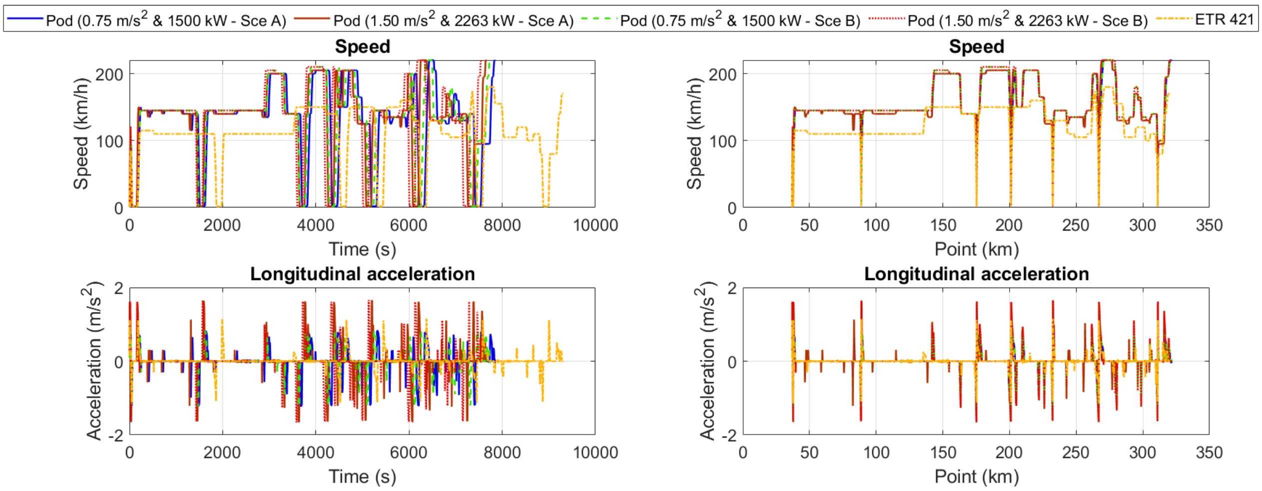


Figure *61*: Speed and longitudinal acceleration for the different trains (stops 3-9)

Figure 62 shows the traction/braking requirements in terms of force and power for the different considered configurations. Here, the same trend can be seen again. As the current freight vehicle has less traction/braking capacity, it will need a longer travel time and will consume less energy than the two configurations considered for the booster.

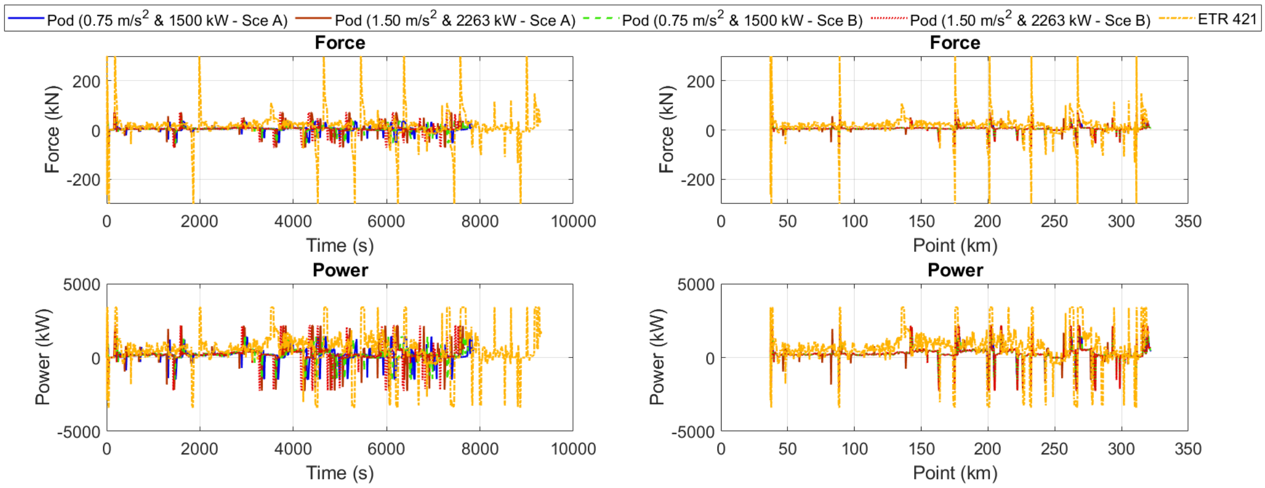


Figure *62*: Traction/braking force and power for the different trains (stops 3-9)

For greater clarity, Figure 63 shows force and power plots with zoom in the section between two stations.

It can be seen that the ETR reaches its 300 kN and 3400 kW and that the pods use forces and powers according to the constraints set for each simulation case. As expected, the highest traction and braking capacities are used during changes of speed and remain relatively low during cruise speed sections.

It can also be seen that for most of the journey the vehicle is travelling at cruising speeds, and that maximum traction and power capacities are only required during acceleration or braking manoeuvres. This higher traction and power capacity of the train means that the more powerful pod configurations allow for shorter journey times, but, as they are only used in very specific areas of the route, the final travel times are very similar for all pod configurations.

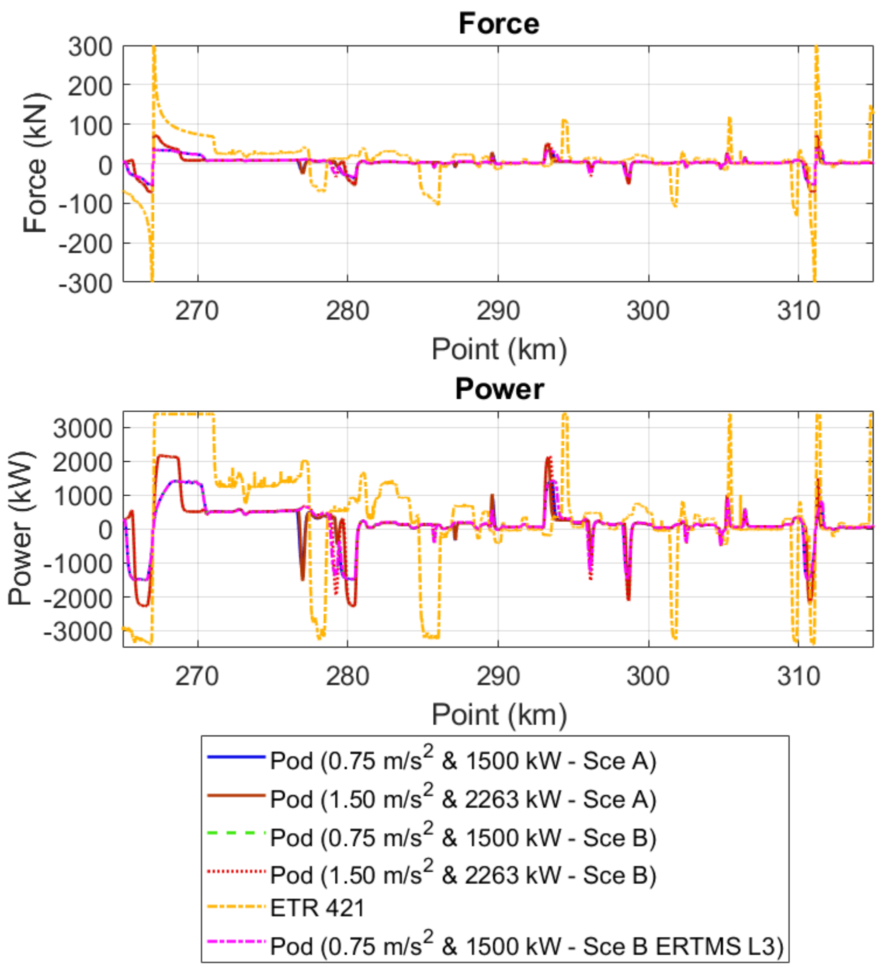


Figure *63*: Traction/braking force and power for the different trains (stops 3-9)

Finally, and in order to have elements to evaluate the use of this technology, Figure 64 is included, where the energy consumption during the whole journey is evaluated. Two values have been calculated, one for a system without regenerative braking, and the other with regenerative braking, considering an efficiency of 85%.

Figure 64 shows the energy consumed in each simulation case. By "total" is meant the total of all the vehicles involved. Therefore, in the ETR the consumption of ETR 421 alone is represented, while in the rest the sum of the 4 pods is represented.

"Net energy" refers to the net energy consumed if a recovery efficiency of 85% is considered. In other words, during braking, energy is subtracted from the sum accumulated in the graph.

In the lower plots there is no recovery.

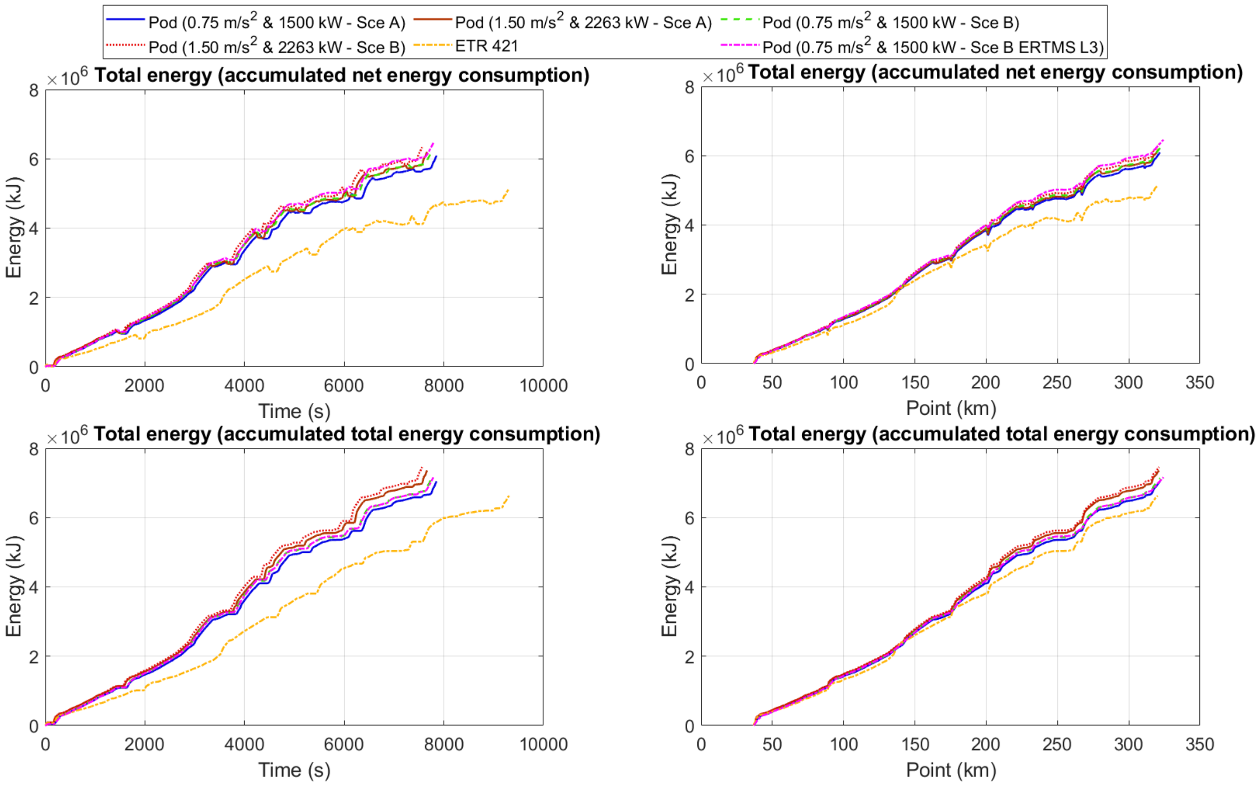


Figure *64*: Energy consumption analysis (only stops 3-9)

9.2.1.9 Conclusions

With regard to travel time, the results show how, for the same route and with the same stops, the current passenger train is much slower and takes longer to complete the journey. In contrast, the different capsule configurations achieve similar performance, reducing the total journey time, achieving an average reduction of 25%, as seen in Table 25.

This is due to the increased running speed achieved by the extra cant implemented using magnetic levitation technologies and is one of the main contributions demonstrated by this use case.

Simulation	Scenario	Travel time (h)		
		Absolute value (h)	Reduction (h)	Reduction (%)
ETR 421	Current line	5,39	0,0	0,0
Pod 0,75 m/s^2	A - V Coupling	4,13	1,3	23,4
	B - V Coupling	4,07	1,3	24,5
	B - ERTMS L3	4,07	1,3	24,4
Pod 1,50 m/s^2	A - V Coupling	4,02	1,4	25,3
	B - V Coupling	3,96	1,4	26,5

Table *25*: Travel time analysis

However, when comparing the energy consumption of the different configurations, the current conventional train consumes less energy than the pod convoy. This result is logical since they run at lower speeds and, even if the journey takes longer, the main component conditioning energy consumption is aerodynamic drag, which depends on the square of the speed.

The results of these analyses are shown in Table 26.

Simulation	Scenario	Energy consumption				Energy consumption (85% recovery)			
		GJ	kWh	Increase (kWh)	Increase (%)	GJ	kWh	Increase (kWh)	Increase (%)
ETR 421	Current line	13,9	3862,3	0,0	0,0	10,4	2879,2	0,0	0,0
Pod 0,75 m/s^2	A - V Coupling	15,4	4268,4	406,0	10,5	13,2	3673,0	793,8	27,6
	B - V Coupling	15,7	4361,5	499,2	12,9	13,6	3769,6	890,4	30,9
	B - ERTMS L3	17,1	4739,2	876,9	22,7	13,8	3825,6	946,4	32,9
Pod 1,50 m/s^2	A - V Coupling	16,0	4432,7	570,4	14,8	13,4	3730,9	851,7	29,6
	B - V Coupling	16,3	4526,6	664,2	17,2	13,8	3829,1	949,9	33,0

Table *26*: Energy consumption analysis

The results show an increase in power consumption of the pod convoy by 10-17% compared to the ETR 421. Of these cases, the lowest consumption is Scenario A with virtual coupling and 0.75 m/s^2, while the highest consumption occurs in the case of higher performance (Scenario B and 1.5 m/s^2).

However, it is worth noting the great advantage of virtual coupling from the operational point of view. While in a conventional vehicle, its length remains constant at all times of the operation, in a pod convoy the number of pods can be decided according to the demand needs in a given time slot, so that in low-demand considerations the convoy could be formed by one or two pods, reducing then the consumption to a quarter or a half. In this case, the new proposal is clearly more advantageous than the traditional fixed trainset solution.

On the other hand, to see the beneficial effect of virtual coupling on consumption reduction, a simulation has also been made for Scenario B configuration with 0.75 m/s^2 for absolute braking (ERTMS L3), where the pods run at a greater distance from each other.

If the results are compared with brake energy recovery, although this use case is not very relevant because not many braking situations occur, the results are more favourable for the conventional rail vehicle, probably due to its higher mass.

In any case, it is shown that the increase in energy consumption is smaller in percentage terms than the increase in the type of travel.

On the other hand, since the main factor influencing consumption is aerodynamic drag, better aerodynamic design will undoubtedly result in lower energy consumption.

In this use case, and in order to compare conventional vehicle and pod configurations as similar as possible, we have chosen to use pods with the same aerodynamic characteristics with the same front end, so there is no doubt that improving the aerodynamics of the pods will significantly reduce energy consumption. As an estimation, Table 27 shows how by optimizing the aerodynamics of the pod, it is possible to obtain Cx reductions that imply a reduction in the consumption of the pod convoy that would allow to achieve a consumption practically equal to that of the conventional vehicle currently in service, but with an increase in average speed and the consequent decrease in travel time very significant (25%).

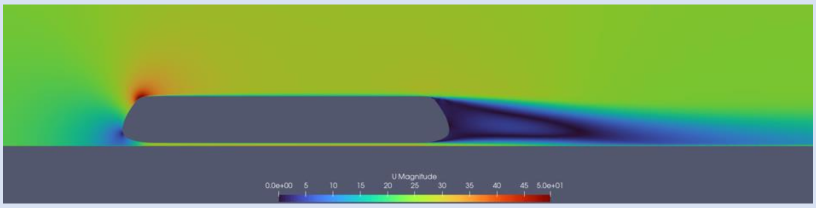
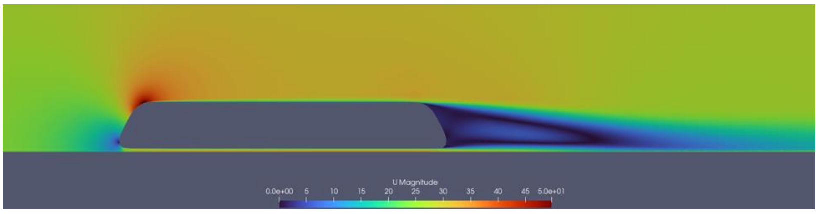
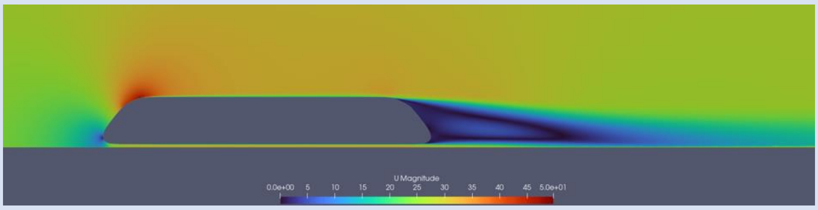
Estimated reduction in energy consumption due to aerodynamics	Cx	%
	0,31	-
	0,28	9,6 %
	0,25	19 %

Table *27*: Energy consumption analysis

Finally, when comparing ERTMS L3 with virtual coupling, from the table data, it is also possible to estimate the improvement in energy consumption due to the use of virtual coupling (VC) instead of ERTMS L3, which is 9%, due to the aerodynamic optimization caused by the slipstream effect when the vehicles drive closer together.

Consequently, the results show that the considered proposals are of great interest and show potential for application.

9.2.1.10 Risk analysis

In the following paragraphs, a high-level analysis on the hazards derived from the implementation of the MDS based on magnetic levitation on the line connecting two cities is presented, including an identification of the accidents that may occur, the possible events of malfunction, the external factors that may influence the safety of the system, and finally, the human errors that may lead to accidents. More in-depth, the analysis is based on the hazards identified in WP3 (MaDe4Rail D3.1, 2024) and is enriched by considering the singularities of the technology and the characteristics of the line.

From a geometrical point of view, the line is quite heterogeneous: tome sections are curvy, while others are characterized by fewer and smoother curves.. The maximum incline along the line is 14.58 ‰ and the current maximum speed allowed along the line is 180 km/h, although the proposed system could go up to 220 km/h. The entire line is electrified with an electrical tension of 3 kV.

The hazards identified can be categorized into four groups, as detailed below:

Derailment

Derailment is a type of accident that may occur in the field of guided transport. It consists of a loss of contact between the rail and the wheel or, more generally, the removal of rolling stock from the tracks. While most derailments are minor, they always cause temporary disruptions to the railway system. They pose a significant risk and can lead to substantial losses, such as collisions with adjacent trains, obstruction of tunnels, and infrastructure damage. In severe cases, derailed wagons may collide with nearby passenger trains or fall from bridges, potentially resulting in significant casualties. Specific examples for the use case include:

- Collision with the infrastructure or other vehicle; vehicle damage; personnel and passengers may be harmed,
- Derailment due to collision with the infrastructure,
- Derailment associated with fire incidents.

Collision

A train collision is a type of accident that involves rolling stock moving along the railway or elements of the railway infrastructure. In this sense, the train collides with neighbouring trains or infrastructure. This kind of accident can be caused by miscommunication, serious derailment, or malfunctions. The collisions considered concern, for example, the presence of obstacles on the line, problems due to the new technology used (strong deceleration of the vehicle), severe derailment, etc. For instance, when the derailment is serious, because of tight gauging in the tunnels, the derailed vehicle can hit the wall, which can cause serious injury. The derailed vehicle can also damage infrastructure, e.g., signalling systems, catenary masts, and the stator of the linear motor. Since the route passes through populated areas, there are many railways over bridges. The worst case is that the derailed vehicle crashes into one of the railway bridge pillar. Once the bridge structure collapses, the personnel on-board and the bypassing persons/vehicles on the bridge could be greatly affected, leading to significant casualties. Specific examples for the line include:

- Collision with infrastructure; derailment,
- Collision of a technically secured maglev vehicle with non-technically secured vehicles,
- Collision with system equipment in the clearance gauge.

Fire

Fire is one of the most dangerous type of accidents in the railway sector and can be caused by several factors. In the specific case of the hypothesized use case, considering the proposed technology, the fire can be derived from the overheating of magnets which are responsible for the traction of the rolling stocks.

Electrocution

Since the high-voltage windings are located on the track, their insulation is more likely to be damaged by flying stones, falling objects, improper track maintenance, animals, and even vandalism compared to the railway catenary. The exposed high-voltage conductor is also more accessible to intruders, trackside workers, and evacuated passengers during emergencies than the railway catenary. Given that the route passes through a populated area, the likelihood of intruders entering the track area is higher. If the damage goes undetected and the protection circuit fails to shut off the power in time, individuals in the track area risk electrocution, potentially leading to casualties. Additionally, during track maintenance, repair, or inspection, if the winding power supply is not turned off due to human error, personnel may suffer electrocution. The electrocution, in the specific case of hybrid MDS based on magnetic levitation, can involve passengers as well. In fact, an accidental breaking of a segment of the winding composing the linear motor can result in an electrocution of the passengers within the train. Specific examples for the use case include:

- Electrocution of personnel and passengers,
- Contact of people with powered equipment on the track.

9.2.2 Selected use case "Hybrid MDS based on magnetic levitation configuration" – Scenario A

9.2.2.1 Civil works

Railway track retrofitting

The goal is to obtain a railway track with a speed of at least 160 km/h (for conventional trains), even where those speeds are not possible today. Therefore, some general measurements are needed to be done before the MDS components can be installed. Infrastructure must fit to the requirements of the used system. Preliminary works will be:

- Rail quality standard for speeds over 160 km/h and up to 220 km/h (rail quality, sleepers, track geometry and stability),
- Sufficient axle loads to the new vehicles and dynamic loads.

To secure the needed quality, it will be necessary to maintain the tracks to a high quality level before starting the implementation of the new MDS technologies. These efforts are not only specific for the new traffic system and cannot be estimated for this study, as the conditions of the route are unknown.

Track alignment

The analysis of curve radii along the line has shown that 24 curve segments have radii below 400 m, which was, according to the system requirements coming from definitions in Deliverable 4.2, not permissible.

Most of the segments are parts of a multi radius curve, which might not be so critical. But especially for a few curves in , it must be checked if the smaller radii down to 330 m are feasible in the specific case or the alignment of the track must be adapted.

Distance between tracks

The distance between tracks is regulated in the EN 15273-3 and depends on the allowed speed. If speed increases over 160 km/h or over 200 km/h, the distance between tracks must be wider than below those limits. It must be checked whether the distances are permissible everywhere.

MDS infrastructure integration

The sample implementation method of the MDS components on conventional infrastructure is shown in the following overview for the Scenario A configuration. It will use the existing rails for the levitation function, therefore no additional levitation beams are not needed.

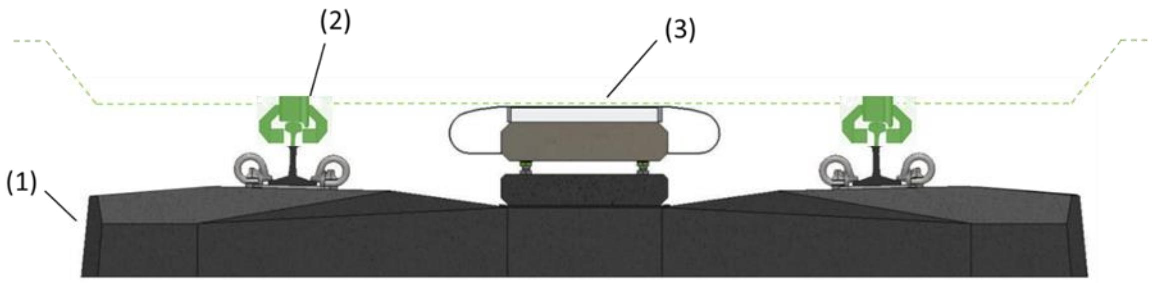


Figure 65: Example symbolic picture of the MDS components

In the cross-section, to the conventional elements like sleeper (1) and rails (2) and linear motor (other configurations are being analysed in WP8) (3) between the rails are installed. The configuration must be designed in such a manner that the UIC structure gauge is respected (green dashed line is the structure gauge).

MDS technology will use two types of switches – low-speed and high-speed. The low-speed switch is used when the MDS vehicle crosses the switch on wheels i.e. below 50-80 km/h (depending on the vehicle configuration). Such a switch is very similar to conventional ones. The high-speed switch is used for high-speed operation when the vehicle is coasting frictionless over the track on levitation suspension.

The new system needs additional components to provide the needed energy for the linear motor. Deployment of the power electronics subsystems contains especially grid and motor power converters, section switches, cables for power and communications and the centre for motor control. The levitation system will use passive levitation and needs no additional energy provided by the infrastructure.

For the line under analysis, the needed implementations length can be estimated as the following:

- Main line: ca. 600 km per track=ca. 1.120km,
- Equipment of station tracks: 8,7 km,
- This will lead to 1.128,7 km all together.

Existing superstructures

Adaptation of the existing railway superstructures to MDS needs will not be significant. For the bridges, there will be no construction changes planned as the weight and axle load of the new pod will be lower than for today's rail cars. It has to be checked if dynamic loads would reach limits because of higher velocities. In those cases, speed will be limited to the maximum allowed limit given by maximum allowed dynamic load of the bridge. This is very specific and needs a detailed study on each bridge. For this study, it is assumed that the stability of the existing bridges is strong enough. For the tunnels, there are no restrictions or major changes anticipated. For single-level crossings – in cases the vehicle will operate at increased velocities over 160 km/h, the single-level crossings should be rebuilt into multi-level ones due to safety issues. For low-speed sections (under 160 km/h) and service operation, it can be allowed to leave them unchanged.

On the line there are five level crossings in sections, where today's allowed speed is limited to 140 or 150 km/h.

One of the crossings is at the station area nearby a strategic Italian station, where speed will not be higher than today, as this will be a stopping station for MDS pods.

The other four level crossings are located between two other stations, where the line speed will be increased over 160 km/h up to 220 km/h. Therefore, those four crossings must be reconstructed to multi-level crossings.

If driverless operation is considered, all the existing level crossing may require modification also at the low speed, as a requirement from the grade of automation.

Stations

One of the biggest challenges is leading the infrastructure into the historical urban tissues of the city centres. The main goal of the MDS is to use the existing stations, when applicable. In other cases, new modular stations should be proposed.

On the line connecting the two cities, there will be several stations for the MDS service. For most of the stations, two equipped platforms will be feasible. Additionally, for certain major stations, two additional platforms will be equipped, because additional pods or interconnections with non-stop-services could be realized. In these same stations, two additional parking tracks for MDS pods will be equipped.

When using existing stations, both by MDS and conventional trains, platform configurations are the first challenge to concentrate on. A first step could be to use different time slots –

separate for MDS and conventional trains. It must be considered where the existing platforms can be used either by MDS pods and conventional trains, as well as separate platforms for MDS vehicles. The latter allows for higher capacity and frequent departures (see also deliverable 6.2 chapter 7.4). Each of the solutions has its advantages and disadvantages, so the choice should be made considering available conditions on an individual basis for the line between two cities.

9.2.2.2 Vehicle control and command systems

Compared to a traditional train, the TCMS must manage a different traction and a different brake control unit. In any case, it must be checked the compliance with EN 50155.

9.2.2.3 Signalling systems

The solution provided meets the ERTMS/ETCS principles, although it does not fully comply with the ETCS Level 2 requirements due to the introduction of a virtual balise.
The following ETCS Level 2 signalling system is used based on the following principles:

1. New Train Detection System along the line: in case it is not possible to create a TDS based on magnetic systems, a TDS with different technologies (for example laser, radar, etc.), in order to maintain compatibility with the ETCS L2 principles, can be created,
2. No Eurobalises for MDS along the tracks, only Virtual Balises: for MDS vehicles, there will be no EUROBALISEs along the tracks; only Virtual Balises will be used in their place. Adopting the principle of Virtual Balises leads to the elimination of the BTM on board,
3. Compliant to ERTMS/ETCS specification: the introduction of MDS vehicles, in this context, does not change the implementation of the RBC, which will manage conventional trains and MDS vehicles in the same way knowing the characteristics of the braking curves applicable to all rolling stock in circulation. The only RBC modification respect the current one is the management of the Virtual Balise together with the EUROBALISE,
4. Communications based on FRMCS: when the MDS will be introduced into the line, the radio communication between the train and Radio Block Centre will be compliant with the applicable TSI. The analysis made during MaDe4Rail project have highlight the compatibility with the future FRMCS,
5. Application of ATO principles: ATO principles can be applied similarly for conventional trains and for MDS vehicles from GoA2 up to GoA4, depending on the degree of automation required. The result is certainly a uniformity of operation and an optimization of energy consumption. For MDS vehicles, ATO will use the virtual balise information instead of the EUROBALISE,
6. TMS with some changes: in general, the TMS in cooperation with ATO will manage the timetables. The TMS will have to know the type of rolling stock, whether conventional or MDS, to try to avoid/reduce being simultaneously present side by side along the line,
7. Specific new sensors have to be included in the on-board systems: virtual coupling also requires sensors to know at all times the relative distance to and velocity of the preceding consist, and a communication link between consists for them to exchange information such as their positions, velocities, and accelerations

9.2.2.4 Telecommunications

Considering the communication wayside on-board, these are the potential open point:

a) Verify that the new vehicle configuration complies with ERTMS standards included FRMCS,

b) No other potential open points are identified.

9.2.2.5 Energy and power systems

The MDS technology uses a linear synchronous motor and consists of two subsystems:

- Stationary system — the track infrastructure,
- Mobile system — the vehicle and its appliance.

The stationary part of the motor is a stator with a three-phase winding. The distributed type of winding is placed between rails in the track. The moving part of the motor called the mover — which is the equivalent of the rotor in rotary motors — is placed in the vehicle and consists of surface-mounted permanent magnets in an N-S-N-S pattern placed on the flat steel yoke. The power electronic system is a part of the stationary infrastructure. From the drive system viewpoint, the vehicle is a passive component.

Linear motors with a long stator are by nature of their construction characterized by a high impedance. To improve the efficiency of the drive system the stator is divided into shorter pieces called sections. This division allows the use of smaller converters and supplying only specific sections, i.e., those sections on which the vehicle is located. A separate substation with a power electronic converter will provide power to each section.

Additionally, further subdivision of the stator into smaller parts called segments is done within one section. The segment division differs from the section division, however not increasing the number of inverters. Thus, stator segmentation requires switching elements enabling a connection of a given segment to the inverter. The segmentation has two main advantages:

- Increased coverage factor understood as the ratio of mover length to the length of the supplied stator,
- Cost reduction by decreasing the required converter power.

MDS propulsion system is constructed based on a two-inverter configuration. Inverters operate interleaved, supplying alternately the segments over which the vehicle is currently located. Each inverter can be connected to the stator by every two-segment using a segment switch. This configuration allows supplying all segments under the mover, also when the vehicle is moving from one segment to the next one.

To estimate the needed electrical power supply coming from the grid network, the system can be configured by the parameters of the infrastructure, the used vehicles and the operational concept. The most important parameters to calculate the needed traction force are:

MDS pods:

- Weight of the pods: 46 to (incl. 70 passengers),

- Max. speed of the pods: 220 km/h,
- Max. acceleration and deceleration: 1,5 m/s²,
- air resistance coefficient: 0,31.

Infrastructure:

- Steepest incline gradient: 15 ‰,
- Average incline gradient: 4 ‰,

Smallest curve radius: 350 m.

The maximum needed traction force of a vehicle is calculated using the tractive force equation:

$$F_T = m_{pod} \cdot g \cdot (r_{roll} + r_{air} + r_{grad} + r_{rad} + r_{acc})$$

Where:

- F_T: needed traction force [N],
- m_{pod}: total mass of MDS pod [kg],
- g: gravitation [m/s²],
- r_{roll}: rolling resistance [-],
- r_{air}: air drag resistance [-],
- r_{grad}: gradient resistance [-],
- r_{rad}: resistance in curves [-],

r_{acc}: acceleration resistance [-].

Using the input parameters, a maximum traction force of 89 kN is required to accelerate the pod up to 220 km/h in a steep and curvy section. Calculating the necessary force for this worst-case scenario ensures that the provided force will always be sufficient. However, this approach can result in a more powerful and expensive system than necessary.

It's important to note that the majority of the force (70 kN) is needed for acceleration. The force required to maintain a steady speed of 220 km/h is highly dependent on gradient resistance. Since the maximum gradient does not occur where the maximum speed of 220 km/h is reached, it is possible to reduce the system's traction power. The average incline gradient in the high-speed section of the line is 5-6 ‰. Using this as a guideline, a traction force of 71 kN should be sufficient, avoiding an overpowered system. In this configuration the mechanical power of the system will be 2.263 kW as maximum.

In the next step the configuration of the propulsion system can be estimated. This will be different for the different types of linear motor.

The NEVOMO system MagRail Booster uses a linear synchronous motor whilst the system of the project partner TACV-Lab produces the force by a U-shaped linear inductive motor. Both systems have advantages. As already mentioned before, for this case study the configuration of the NEVOMO system is considered.

To calculate and design the system, additional parameters are needed.

MDS pods:

2. Length of the pods: 25 m,
3. Length of the installed magnets: 15 m.

Infrastructure:

- Length of the sections: 5 km,

Segmentation of the sections: 20 m.

By employing a nine-turn winding configuration, the magnetic field generated by the stator is optimized for the desired traction performance. The inverters play a crucial role in regulating the current and voltage supplied to the windings, ensuring consistent and efficient operations. The specified current of 1,2 kA and voltage of 2,2 kV are chosen to achieve the necessary electromagnetic force for the MagRail Booster system.

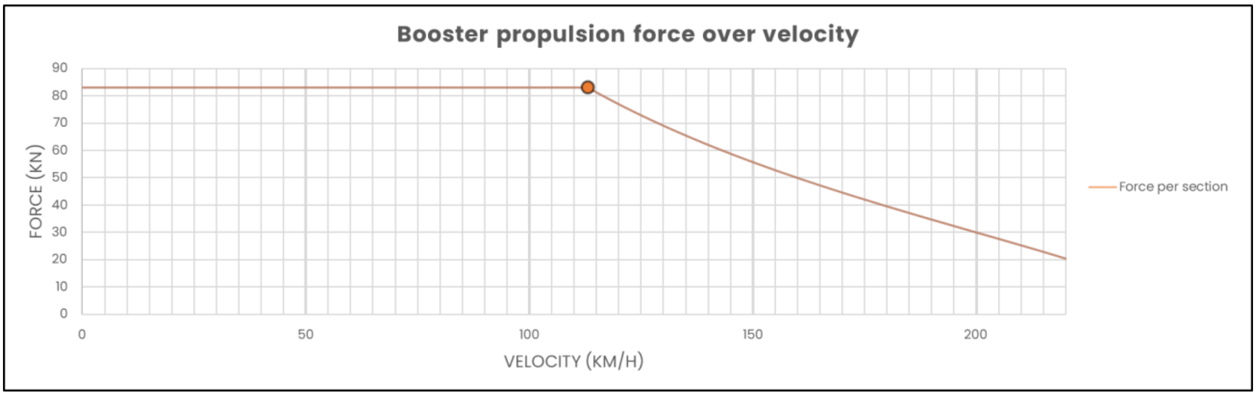


Figure *66*: force over velocity diagram

The resulting traction curve, illustrated in the diagram, reflects the relationship between the applied traction force and the velocity of the MDS pod. This curve is crucial for understanding the performance characteristics of the system. It demonstrates that the maximum traction force is provided up to 90 km/h to ensure rapid acceleration during the initial phase, allowing the passive levitation system to generate sufficient power to lift the pod.

After reaching this point, the provided traction force gradually decreases. At a speed of 200 km/h, the system can still deliver 30 kN of force. To overcome the driving resistances at this speed, 22 kN of force are required. The remaining 8 kN can be used for additional acceleration, enabling the pod to accelerate at approximately 0.2 m/s².

Splitting the line between two major cites into sections of 5 km length will produce 112 sections for each direction. Each section needs two inverters to guarantee a smooth movement of the pod, especially at the acceleration phase. To have more flexibility at the stations, it will make sense to consider an additional section which will be powered by its own inverter.

- Main line: 2 x 112 sections x 2 inverters = 448 inverters,
- Equipment of station tracks: (12 x 2 platforms + 4 x 4 platforms) x 1 section x 2 inverters =80 inverters.

This will lead to 528 inverters all together.

To enhance the overall efficiency of the system, each section of the track will be divided into segments of 20 m length. This segmentation requires the installation of 250 segment switches per section along the line. These segment switches play a crucial role in managing and optimizing the flow of the MagRail Booster system, allowing for precise control and increased performance.

At the stations, the sections will be also designed with short segments to accommodate the specific operational needs. These sections will have the same length of 20 m.

By segmenting the sections in this manner, the system can better manage power distribution, improve responsiveness, and enhance overall operational efficiency. The short segmentation of the main line and the stations ensures that each part of the system is optimized for its specific function, whether it is high-speed travel with high need of traction force or precise, controlled movements within station boundaries.

- Main line: 2 directions x 112 sections x 250 segment switches = 56.000 segment switches,
- Equipment of station tracks: 8,7 km track length in stations / 20 m segment length = 435 segments = 435 segment switches.

This will lead to 56.435 segment switches all together.

9.2.2.6 Interferences and interoperability

In the context of introducing the Maglev Derived System (MDS) in Scenario A, several critical points have emerged that require thorough evaluation to ensure operational effectiveness and interoperability with the existing railway infrastructure.

Scenario A includes:

- The use of Linear Synchronous Motor (LSM) for propulsion,
- U-shaped sliders on existing rails for the levitation system,
- New M4R pods,

  Existing line alignment (the newly designed pods will operate within the existing line alignment).

One of the critical aspects to consider is electromagnetic and geometric compatibility with the existing infrastructure.

The interface document ERA/ERTMS/033281 ver. 5 “Interfaces Between Control-Command and Signalling Trackside and Other Subsystems” referenced by the 2023 TSI CCS outlines several requirements regarding subsystem compatibility with ground elements.

Nevomo’s Linear Synchronous Motor generates a magnetic field with a strength over 400 times higher than specified in Eurobalise regulations during transit. This could interfere with

Eurobalises, and also with other existing systems like axle counters and other railway equipment, necessitating thorough research into the interaction between the linear motor, Eurobalises, and other trackside devices.

In the future, a continuous analysis in this field is essential, for example including designing effective magnetic shielding systems to reduce EMI and evaluating the optimal positioning of trackside devices relative to the linear motor.

The above is important because it is crucial to ensure electromagnetic compatibility with the Eurobalise ERTMS Level 2 system for interoperability with the existing railway system.

Electromagnetic simulation studies indicate that the electromagnetic field flux reaches allowable values at approximately 0.27 meters from the stator longitudinally. Therefore, for safe operations, a clearance of at least 0.5 meters is necessary. This aspect requires further research and validation, particularly for axle counters.

Possible solutions include reshaping the stator geometry (interrupting it at the balises group or placing two stators alongside the balises, within the track), conducting tests to confirm the required safety distance, and developing operational guidelines for the installation and maintenance of Eurobalises in the presence of the linear motor.

As highlighted at the beginning of the paragraph, document ERA/ERTMS/033281 ver. 5 includes many requirements concerning the geometric and electromagnetic compatibility of subsystems with CCS ground elements. For example, paragraph 3.1.3.2 specifies the minimum wheel diameter requirement based on speed (for example, in the Nevomo system the wheels have diameter of approximately 370 mm), while paragraph 3.1.3.5 outlines requirements for free space between wheels.

Therefore, the document should be thoroughly examined to determine if technological solutions can be developed to meet existing requirements or if the standards can be modified to accommodate the adoption of new technological solutions (maintaining equivalent safety levels).

Continuing, the impact on maintenance is another crucial point. Installing the linear motor between the rails will require adapting track maintenance procedures. Activities such as tamping, rail grinding, and the replacement of sleepers and rails will need to be rethought to consider the new line layout. This will lead to defining specific maintenance procedures for the MDS infrastructure, including the timing and tools necessary to ensure system durability and reliability.

Speed on curves is another critical aspect. Current regulations on cants and cant deficiencies significantly limit MDS performance.

Finally, the adequacy of the MDS system concerning Technical Specifications for Interoperability (TSI) is of fundamental importance. The selected MDS subsystems and components must comply with TSI requirements to ensure interoperability with the conventional railway system. This includes aspects such as interaction with track infrastructure, the suspension system, the electrical system, and the vehicle control system, ensuring that the MDS vehicle can operate safely and in compliance with current safety regulations.

It is essential to verify MDS component compliance with TSI specifications through compatibility tests and simulations, also evaluating the potential impact of MDS systems on TSI. In some cases, technology will evolve to meet TSI requirements, while in others TSI may evolve to consider the use of new technologies and solutions not currently contemplated.

Since Scenario A is in Italian territory, compliance with national standards, if more restrictive, must also be verified. For example, the presence of electrodynamic emergency brakes might not be accepted, because magnetic track brakes are not allowed on the RFI rail network.

In conclusion, as of today, the "Hybrid MDS based on magnetic levitation configuration" system is not interoperable with the conventional railway signalling system because it requires compatibility with traditional infrastructure elements, which is currently not guaranteed.

These compatibility “open points” would decrease with the upgrade of the CCS system to ERTMS L3 and with the support of radio communication technologies such as 5G or FRMCS (currently under experimentation and/or development).

On a line equipped with ERTMS L3, physical elements (switches, balises, etc.) are still present (though in a reduced number compared to a traditional line), which require precise verification of physical/electromagnetic interference with the "Hybrid MDS based on magnetic levitation configuration" system.

The adoption of ERTMS L2 requires further studies and technological developments due to the physical and electromagnetic interference of the balises with the linear motor, which is also positioned in the middle of the track.

Finally, it should be noted that the information about the instantaneous position of the vehicle is necessary to energize the linear motor sections at the right moment, as they are not always powered but only go under voltage when the vehicle is passing.

9.2.2.7 Magnetic analysis

In this chapter, the magnetic analyses are performed on a system comprising U-shaped levitation sliders interacting with standard rail tracks. The system described does not require additional infrastructure intervention and is characterized by very promising levitation and power consumption performances. In addition, the self-shielded configuration avoids magnetic field dissipation outside the shape of the slider, making it possible the coexistence of other electronics and signalling devices along the line.

The magnetic analyses aim to evaluate the main parameters of the levitation system, based on the hypothesis of exploiting the traditional railway tracks without the need of additional infrastructure intervention. Based on the characteristics of the track in terms of section geometry and magnetic permeability, the analysis started with an evaluation of the magnetostatic performances of the rail, in terms of maximum exploitable load per meter of vertical load capability. The analysis then was conducted by optimizing the section of the slider both in terms of shape (section geometry) and slider load per meter. The U-shaped geometry was then optimized with rounding shapes with the aim of optimizing the weight and the magnetic field passing through the slider. The results are shown in the picture presented below.

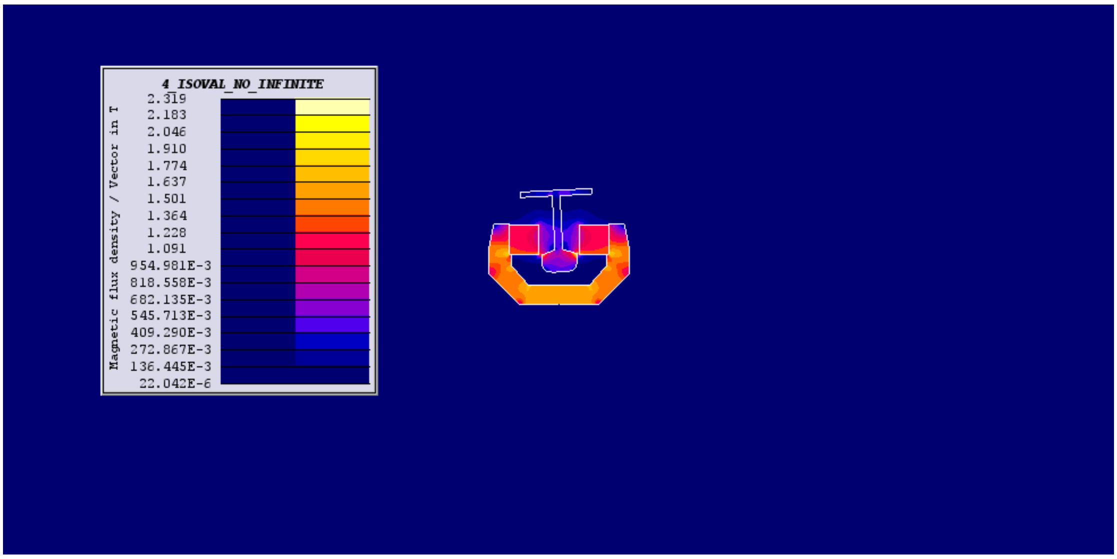


Figure 67: Magnetic analysis “section geometry”

After the magneto-static solution type, the slider was analysed with a magneto-dynamic solution type to evaluate the main parameters affecting the performances of the levitation system with the magnetic power dissipation. The power dissipation is due to the interaction between the sliders and the rail. In order to evaluate it and to evaluate the dissipation as function of the relative speed, a simplified model was built consisting in two Ironlev sliders with head and tail elements. The simplified model was studied to evaluate the power dissipation of the basic slider element, with a length of approx. 1 m and then extrapolate the values for a pod weighting around 43 tons at full load (70 passengers). The final results are shown in the diagrams below. They refer to a total of n° 18 sliders per side rail, for a full load capacity of 54 tons.

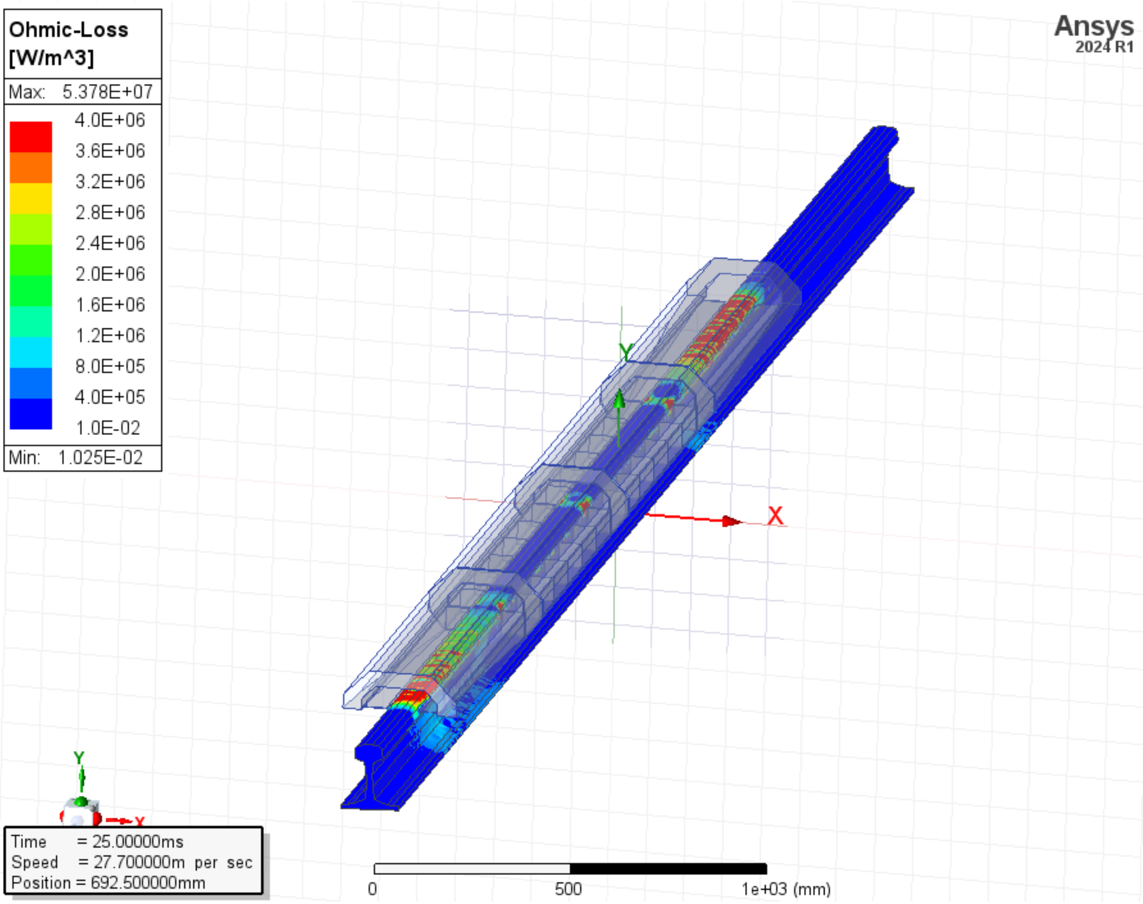


Figure 68: Magnetic analysis “slider load per meter”

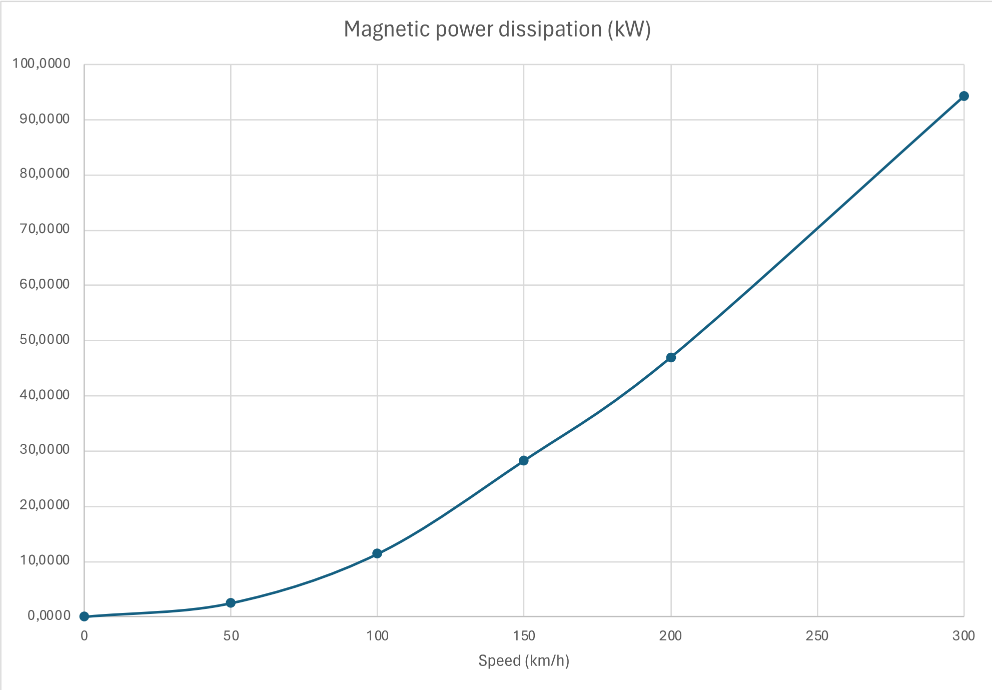


Figure 69: Magnetic analysis final results: “Magnetic power dissipation”

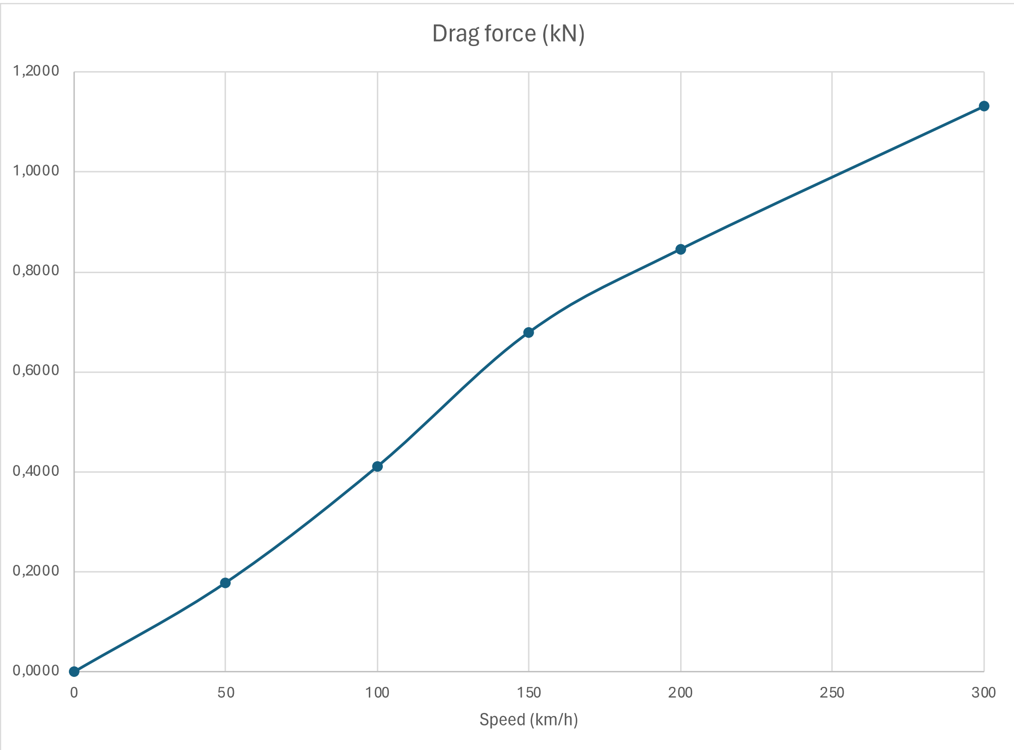


Figure 70: Magnetic analysis final results: “Drag force”

Lastly, the magnetic field around the slider was calculated to analyse the possible interaction of electronics, signalling or auxiliary elements with the residual magnetic field, due to the levitation sliders. The results are represented in the Figure below, that shows how the magnetic field is confined within the section of the slider that, thanks to its shape and material, self-shields the magnetic field.

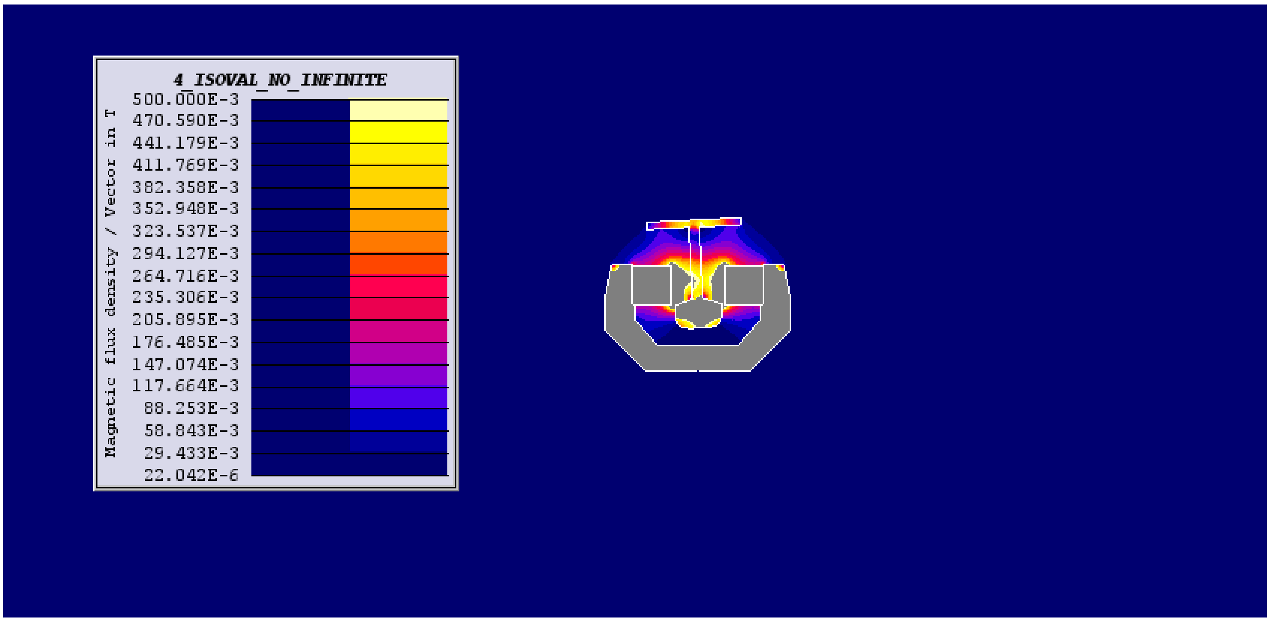


Figure 71: Magnetic analysis results (how the magnetic field is confined within the section of the slider)

9.2.3 Selected use case “Hybrid MDS based on magnetic levitation configuration” – Scenario B

9.2.3.1 Civil works

Railway track retrofitting

As for Scenario A, it might be necessary to maintain the tracks to a high quality level before starting the implementation of the new MDS technologies. These efforts are not only specific for the new traffic system and cannot be estimated for this study, as the conditions of the route are unknown.

Track alignment

For the Scenario B it was checked if smaller changes in the track alignment could lead to a better speed profile. The main goal is to avoid critical speed drops and their consequential needed braking and reaccelerating. Therefore, the planned stops were combined with the calculated speed profile and the allowed speeds were optimized.

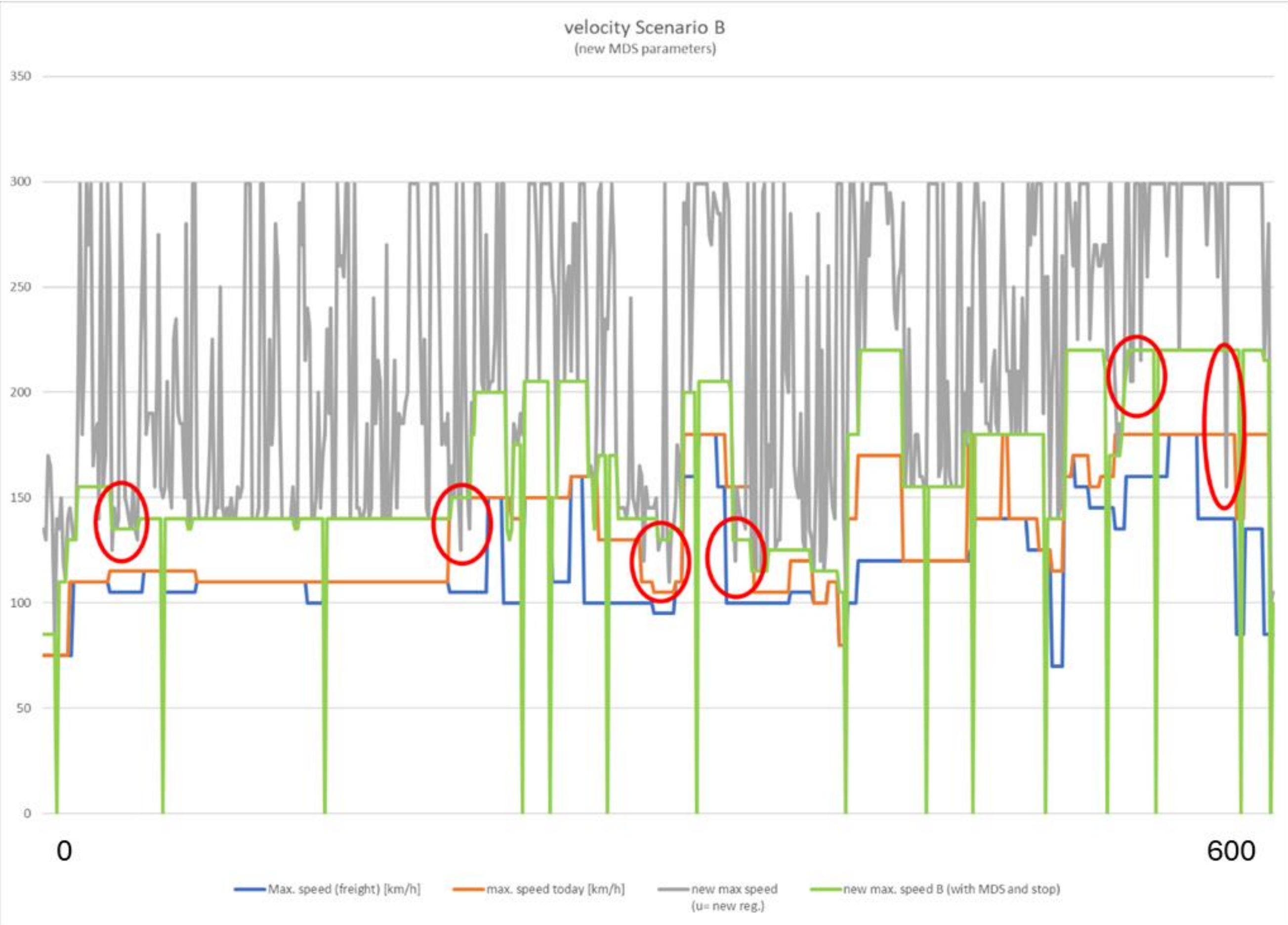


Figure 72: Optimized speed profile including stops and marked areas with needed changes in track alignment

Six areas with 13 relevant curves have been identified, where changing the track alignment could bring benefits for a better speed profile. Changing the curve radius on an existing line is usually very critical and requires checking the different possibilities in detail. In this study it is not possible to do a complete infrastructure planning. So, it is only to be checked if the infrastructure might be anyhow feasible. As a first step, the location of the curve is checked.

The necessary adaptations to the alignment are calculated using the maximum permissible cant deficiency of 200 mm and the maximum allowed MDS specific cant for this scenario, as described in chapter 9.2.1.1, of 351 mm. Because changing the curve radius can cause a lot of problems, in a first step it is checked if the cant can be increased by prolonging the transition curve, which might be the better solution instead of changing the curve radius. If the cant reaches the maximum allowed limit of 351 mm, the radii are increased stepwise until the speed requirement is met.

The results show differences in the possibilities of adapting the curves. On five of the curves, it might be feasible to change the length of transition curves and reach higher cants within the curves. For eight other curves, it might also be interesting to check the specific surroundings, as the changes might not be too big, so it could be feasible to change the alignment.

More critical are the other five curves and especially last one in the , near a major city . Theses curve needs to be changed from ca. 600 m radius to ca. 1.100 m radius, which might hardly be possible. Nevertheless, it can be checked what could be changed by reasonable costs, so that at least parts of the required speed increase of 65 km/h can be realized in this curve.

For this feasibility study, these detailed checks cannot be done, and it is assumed that the changes at the alignment are technically feasible for the following calculations and simulations.

MDS infrastructure integration

The sample implementation method of the MDS components on conventional infrastructure is shown in the following overview for the Scenario B configuration, which will use additional beams for the levitation function.

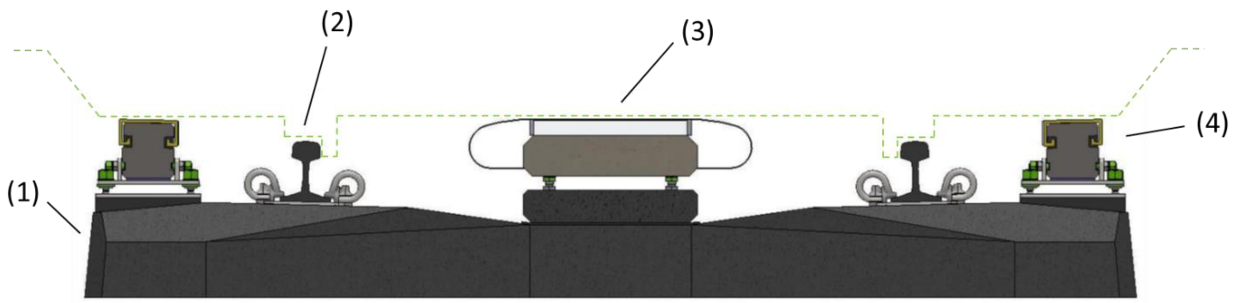


Figure 73: Symbolic picture of the MDS components

In the cross-section next to the conventional elements, like sleeper (1) and rails (2), the linear motor (3) between the rails and additional levitation beams (4) outside the rails are installed. The configuration must be designed in such a manner that the UIC structure gauge is respected (green dashed line is the structure gauge).

MDS technology will use two types of switches – low-speed and high-speed. The low-speed switch is used when the MDS vehicle crosses the switch on wheels i.e. below 50-80 km/h (depending on the vehicle configuration). Such switch is very similar to conventional ones. The high-speed switch is used for high-speed operation when the vehicle is coasting frictionless over the track on levitation suspension.

The new system needs additional components to provide the needed energy for the linear motor. Deployment of the power electronics subsystems contains especially grid and motor power converters, section switches, cables for power and communications and the centre for motor control. The levitation system will use passive levitation and needs no additional energy provided by the infrastructure.

For the route between the two cities the needed implementation length can be estimated as the following:

- Main line: ca. 600 km per track = ca.1.120 km,
- Equipment of station tracks: 8,7 km (without levitation beams).

This will lead to ca. 1.128,7 km to be upgraded with propulsion system, and ca. 1.120 km where the levitation beams need to be installed additionally.

Existing superstructures

For adaptation of the existing railway superstructures to MDS needs, the same requirements as in Scenario A have to be taken into account. For the bridges, there will be no construction changes planned, as the weight and axle load of the new pod will be lower than today's rail cars' one. However, it has to be checked if dynamic loads would reach limits due to higher velocities. In those cases, speed will be limited to the maximum allowed limit given by maximum allowed dynamic load of the bridge. This is a very specific aspect and needs a detailed study on each bridge. For this study, it is assumed that the stability of the existing bridges is strong enough. For the tunnels, there are no restrictions or major changes anticipated. For single-level crossings – in cases the vehicle will operate at increased velocities over 160 km/h, the single-level crossings should be rebuilt into multi-level ones due to safety issues. For low-speed sections (under 160 km/h) and service operation it can be allowed to leave them unchanged.

On the line between the two major cities there are five level crossings in sections, where today's allowed speed is limited to 140 km/h or 150 km/h. One of the crossings is located at a station area, where speed will not be higher than today, as this will be a stopping station for MDS pods. The other four level crossings are located between two stations, where the line speed will be increased over 160 km/h up to 220 km/h. Therefore, those four crossings must be reconstructed to multi-level crossings.

If driverless operation is considered, all the existing level crossing may require modification, also for low speed, as a requirement from the grade of automation.

Additionally to Scenario A, it has to be checked if the different distribution of the loads on the sleepers is significant. New propulsion and levitation equipment with the needed fixtures to the sleepers can exert various forces on sleepers in both straight and curved track sections. It is essential to evaluate if current sleepers and rail fastenings can be. Possibly, a new type of sleepers may be required to handle the forces from the MDS systems. This could cause additional costs if sleepers must be exchanged.

Stations

For Scenario B, the same stations have been considered. On the route, there will be several stations for the MDS service. Most of these stations will have two equipped platforms. At the major stations, such as the central hubs, two additional platforms will be equipped to accommodate extra pods or interconnections with non-stop services.. These stations will also have two equipped parking tracks for MDS pods.

The additional tracks in these station areas will not be equipped with levitation beams since the pods will operate at slow speeds, rolling on their wheels. However, two "main tracks" will be equipped with levitation beams to provide flexibility in scheduling, allowing for "sprinter trains" that do not stop at every station but pass through at speeds high enough to use the levitation mode.

When using existing stations, both by MDS and conventional trains, platform configurations are the first challenge to concentrate on. A first step could be to use different time slots – separate for MDS and conventional trains. It must be considered where the existing platforms can be used either by MDS and conventional trains, as well as separate platforms for MDS vehicles. The latter allows for higher capacity and frequent departures (see also deliverable 6.2 chapter 7.4). Each of the solutions has its advantages and disadvantages, so the choice should be made considering available conditions on an individual basis.

9.2.3.2 Vehicle control and command systems

Compared to a traditional train, the TCMS must manage a different traction and a different brake control unit. In any case, it must be checked the compliance with EN 50155.

9.2.3.3 Signalling systems

Considering what is indicated in the use case, the use of ETCS L2 is envisaged for signalling. The open points are:

a) To manage to install the Balises in the central position of the track,
b) Magnetic flux must not be intrusive in Balise On-Board Antenna communication,
c) Since there is no contact between the wheel and the track, the odometric sensors that count the rotations of the wheels cannot be used. ETCS OB Odometry must be adapted to new vehicles,
d) Since there is no contact between the wheel and the track, the TDS may not work, thus further research is required.
e) It is also necessary to evaluate the influence of the magnetic flux produced by the system towards the TDS.

As pointed out in the previous sections, a potential in this Scenario is not detecting the presence of a vehicle along the line. This could be due to the interference of the MDS vehicle with the adjacent lines. Especially for ETCS Level 2, it a new field device must be introduced, connected to the interlocking, that can detect the MDS vehicles in safe way with a new sensor.

Other potential signalling identified risks, that will require further research, include:

- not reading the encountered balise,
- occupying a section unduly,
- losing the radio connection,
- interfering with the train traveling on the adjacent track.

9.2.3.4 Telecommunications

Considering the communication wayside on-board, these are the potential open point:

- Verify that the new vehicle configuration complies with ERTMS standards included FRMCS,

- No other potential open points are identified.

9.2.3.5 Energy and power systems

Same considerations as for Scenario A, reported in chapter 9.2.2.5.

9.2.3.6 Interferences and interoperability

In the context of introducing the Maglev Derived System (MDS) in Scenario B, several critical points have emerged that require thorough evaluation to ensure operational effectiveness and interoperability with the existing railway infrastructure.

Scenario B includes:

- the use of Linear Synchronous Motor (LSM) for propulsion,
- sliders on additional levitation beams for the levitation system,
- new M4R pods,

adapted line alignment, which requires significant modifications to the track geometry to prevent speed drops and improve overall system performance. One of the critical aspects to be considered is the electromagnetic and geometric compatibility with the existing infrastructure.

The interface document ERA/ERTMS/033281 ver. 5 “Interfaces Between Control-Command And Signalling Trackside And Other Subsystems” referenced by the 2023 TSI CCS outlines several requirements regarding subsystem compatibility with ground elements.

Nevomo’s Linear Synchronous Motor generates a magnetic field with a strength over 400 times higher than specified in Eurobalise regulations during transit. This could interfere with Eurobalises, and also with other existing systems like axle counters, and other railway equipment, necessitating thorough research into the interaction between the linear motor, Eurobalises, and other trackside devices.

In the future, continuous analysis in this field is essential, for example, including designing effective magnetic shielding systems to reduce EMI and evaluating the optimal positioning of trackside devices relative to the linear motor.

The above is important because it is crucial to ensure electromagnetic compatibility with the Eurobalise ERTMS Level 2 system for interoperability with the existing railway system.

Electromagnetic simulation studies indicate that the electromagnetic field flux reaches allowable values at approximately 0.27 meters from the stator longitudinally. Therefore, for safe operations, a clearance of at least 0.5 meters is necessary. This aspect requires further research and validation, particularly for axle counters.

Possible solutions include reshaping the stator geometry (interrupting it at the balises group or placing two stators alongside the balises, within the track), conducting tests to confirm the required safety distance, and developing operational guidelines for the installation and maintenance of Eurobalises in the presence of the linear motor.

Another challenge related to adapting existing infrastructure to MDS technology involves the new sliders and the new additional levitation beams, which must meet the geometric clearance requirements specific to the loading gauge of each line and country. In this case also, it is essential to avoid interference with ground devices such as Eurobalises, axle counters, switches, and level crossings.

Future solutions may include designing and manufacturing of new sleepers to handle the different forces generated by various propulsion systems or developing a conversion kit for existing sleepers, to ensure compatibility with existing systems and optimize performance.

As highlighted at the beginning of the paragraph, document ERA/ERTMS/033281 ver. 5 includes many requirements concerning the geometric and electromagnetic compatibility of subsystems with CCS ground elements. For example, paragraph 3.1.3.2 specifies the minimum wheel diameter requirement based on speed (for example, in the Nevomo system the wheels have diameter of approximately 370 mm), while paragraph 3.1.3.5 outlines requirements for free space between wheels.

Therefore, the document should be thoroughly examined to determine if technological solutions can be developed to meet existing requirements, or if the standards can be modified to accommodate the adoption of new technological solutions (maintaining equivalent safety levels).

Continuing, the impact on maintenance is another crucial point. Installing the linear motor between the rails and installing the levitation system will require adapting track maintenance procedures. Activities such as tamping, rail grinding, and the replacement of sleepers and rails will need to be rethought to consider the new line layout. This will lead to defining specific maintenance procedures for the MDS infrastructure, including the timing and tools necessary to ensure system durability and reliability.

Speed on curves is another critical aspect. Current regulations on cants and cant deficiencies significantly limit MDS performance. However, in Scenario B, it is possible to increase the cant for levitating MDS vehicles without changing it for conventional wheel-based vehicles, but static and dynamic tests of the infrastructure are necessary to evaluate ballast wear, sleeper twist, and other critical parameters.

Future steps in this regard may include implementing advanced monitoring systems to evaluate ballast wear and sleeper stability in curves, enabling preventive interventions.

Additionally, regarding cant and its variations for MDS systems compared to traditional systems, the effects on passengers and travel comfort must be considered.

Finally, the adequacy of the MDS system concerning Technical Specifications for Interoperability (TSI) is of fundamental importance. The selected MDS subsystems and components must comply with TSI requirements to ensure interoperability with the conventional railway system. This includes aspects such as interaction with track infrastructure, the suspension system, the electrical system, and the vehicle control system, ensuring that the MDS vehicle can operate safely and in compliance with current safety regulations.

It is essential to verify MDS component compliance with TSI specifications through compatibility tests and simulations, also evaluating the potential impact of MDS systems on TSI. In some cases, technology will evolve to meet TSI requirements, while in others the TSI may evolve to consider the use of new technologies and solutions not currently contemplated.

Since Scenario B is in Italian territory, compliance with national standards, if more restrictive, must also be verified. For example, the presence of electrodynamic emergency brakes might not be accepted, because magnetic track brakes are not allowed on the RFI rail network.

In conclusion, as of today, the "Hybrid MDS based on magnetic levitation configuration" system is not interoperable with the conventional railway signalling system because it requires compatibility with traditional infrastructure elements, which is currently not guaranteed.

These compatibility “open points” would decrease with the upgrade of the CCS system to ERTMS L3 and with the support of radio communication technologies such as 5G or FRMCS (currently under experimentation and/or development).

On a line equipped with ERTMS L3, physical elements (switches, balises, etc.) are still present (though in a reduced number compared to a traditional line), which require precise verification of physical/electromagnetic interference with the "Hybrid MDS based on magnetic levitation configuration" system.

The adoption of ERTMS L3 requires further studies and technological developments due to the physical and electromagnetic interference of the balises with the linear motor, which is also positioned in the middle of the track.

Finally, it should be noted that the information about the instantaneous position of the vehicle is necessary to energize the linear motor sections at the right moment, as they are not always powered but only go under voltage when the vehicle is passing.

9.2.3.7 Magnetic analysis

In this chapter, the case scenario “Hybrid MDS based on magnetic levitation configuration”, with the additional rails option, is assessed and evaluated. Maximum potentiality of 7 tons per meter and very low power dissipation stand out, at a cost of infrastructural intervention for the construction of additional parallel rails.

The case scenario of MDS vehicle with upgraded infrastructure is based on the use of additional ferromagnetic guideways for the application of the magnetic levitation sliders. In this case, a geometrical optimization can be performed without constraints given by the use of the existing guideways. This will result in outpaced performances in terms of magnetic power dissipation, but with huge investment costs for the deployment of the additional rails. The rails’ base structure is based on the same standards of rail fittings to connect the base of the rail with the sleepers. On top of the rail, the levitation head is instead based on laminated steel to cut down magnetic drag due to eddy currents, but with a very competitive raw materials cost. The geometry of the rail is represented in the picture below.

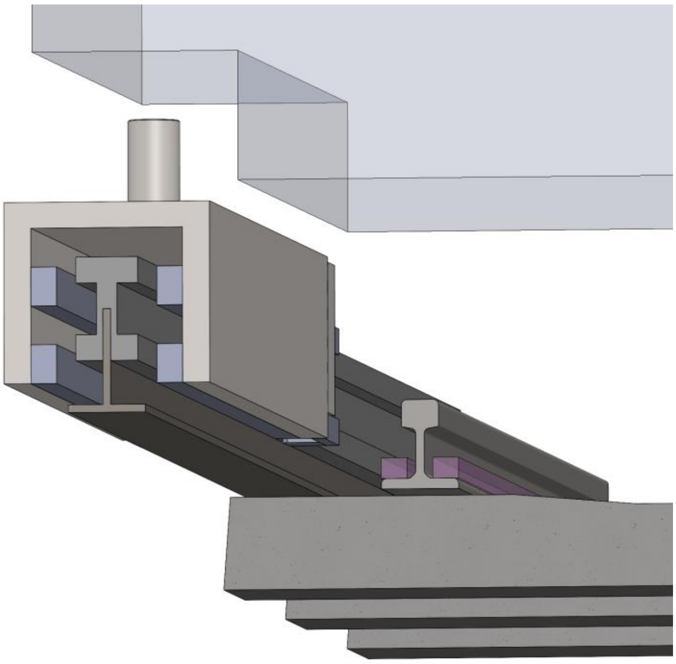


Figure 74: Rail geometry

The sliders are based on a U-shaped geometry, which magnetically couples them with the rail head. The performances of the sliders depend on the section of the rail and the slider itself.

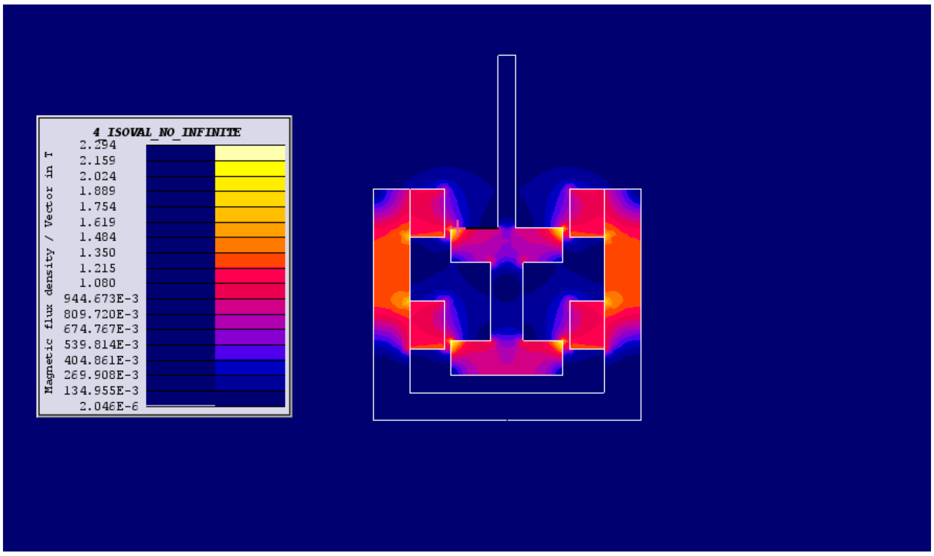


Figure 75: Slider section magnetic analysis

With this solution, static magnetic performances of up to 7 tons/m can be achieved, at the cost of adding additional rails in parallel to traditional rails.

After the magneto-static solution, the analyses were conducted to evaluate the magneto-dynamic performances for power dissipations and the corresponding drag force. The results are presented in the diagram below with a comparison chart.

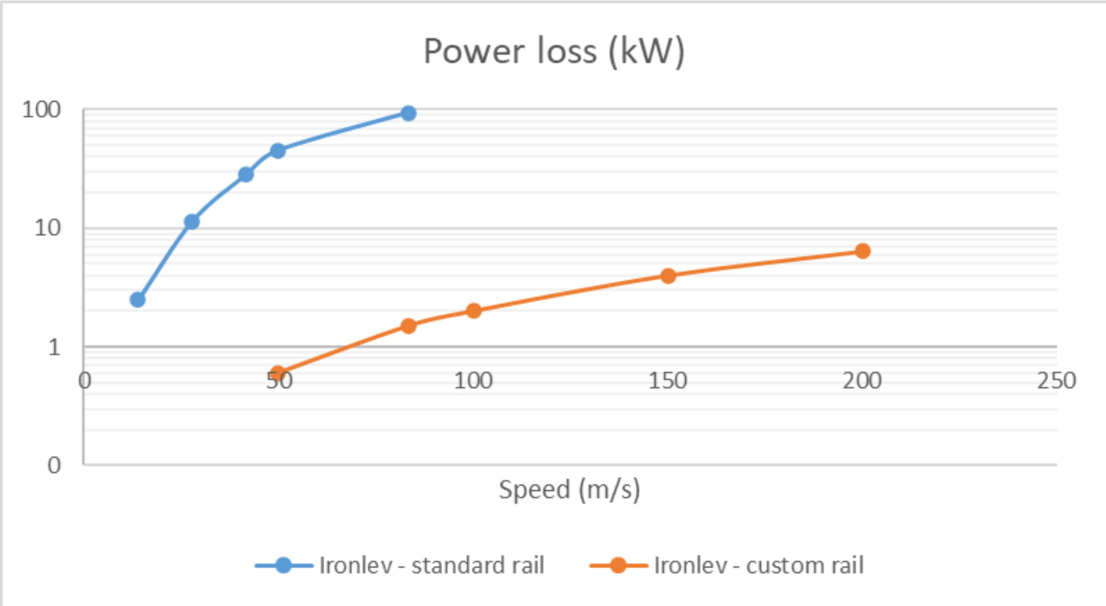


Figure 76: Magneto-dynamic performances results

In a manner similar to the main configuration, the lateral centering system in the case of a custom rail is achieved through an advanced active electromagnetic system. This system is specifically designed to dynamically adjust and balance lateral forces acting on the rail, ensuring optimal stability and precision during operation. The active nature of this system allows it to respond in real-time to varying conditions, providing consistent performance and enhancing the overall reliability of the system. For a better understanding of the technical specifications and operational principles underlying the auxiliary systems, please refer to the detailed documentation provided in WP8.

10. Conclusion

This chapter presents the main findings of the deliverable D7.2. When all the elements from the technical and socio-economic feasibility have been examined, general conclusions about the different use cases and corresponding configurations for MDS applications will be presented in Deliverable D7.3. In this document, the technical feasibility analysis for the three use cases identified in task 7.1 has been carried out.

The deliverable successfully in defines the key technical components for each use case and scenario, identifying and describing the main subsystem of the MDS system and their potential challenges and possible solutions.

During the following tasks of WP7, the information and the insights from this deliverable will be used to develop the LCC (Lice-Cycle Cost) and CBA (Cost-Benefit Analysis) of the 3 use cases, identifying the main benefits associated with the implementation of the MDS system. Moreover, the key challenge and solution will be the base to identify a European Roadmap for the MDS implementation.

This document also defines the expected performance of MDS for each use case, comparing it with the reference scenario.

The first use case analysed is related to the use of an upgraded railway vehicle MDS configuration serving as an incline pusher. This configuration is designed to provide the adequate traction needed to overcome the steep incline on the railway line in Sweden, ensuring adequate capacity and speed in a cost-efficient manner. Alternatively, it can enable an increase in the maximum gradient of the line, thereby reducing the earthworks and the cost of a new infrastructure.

In the Swedish use case, Scenario A, substantial time savings have been identified to be achievable with the installation of the linear motor along the line. This improvement is primarily due to the reduction of different speed in mixed traffic operation and the challenge of freight vehicles in maintaining full speed across different sections. Although energy consumption is expected to increase considerably, the introduction of regenerative braking could mitigate this effect.

According to conducted simulations. But there are flat parts where it would be unnecessary to install the MDS technology, which could reduce the total cost of installation: the trackside linear motor stators could be installed only in the track sections with high track gradients, to provide extra tractive force for freight trains, which also allows avoiding additional locomotives.

Several risks have been identified, including derailment, collision, fire and electrocution. Since the route features numerous tight curves, if the train driver applies severe emergency braking, , the wagons, particularly the upgraded ones with magnets, maybe pushed aside and climb up rails, especially when unloaded. Moreover, if the protection circuit immediately cuts off the power supply to the linear motor or if the permanent magnet has been overheated, the braking system will fail. Running at speeds exceeding the recommended limits in tight curves could result in derailment. Such a scenario could lead to a serious collision, making preventive measures essential. All narrow curves with radii below 400 m along the existing line has been analysed. Altogether, a total of 41 curves with radii below 400 m should be assessed to determine if the track stability is sufficient for faster freight trains.

Of these, 15 of these curves have radii below 300 m and may require specific analyses or inspections.

The insulation of the windings can be damaged by flying stones, falling objects, improper track maintenance, animals and even vandalism. If the protection circuit is not properly triggered, the grounded or short-circuited conductor can generate heat or spark, which can ignite the wooden sleepers on the track. Additionally, an exposed high-voltage conductor is more accessible to intruders, trackside workers, and evacuated passengers in an emergency than the railway catenary.

When it comes the Scenario B, for the Swedish use case a completely new line between two major cities has been considered. Simulations with steeper gradients on this line indicate minimal time savings.

However, an advantage of incorporating a linear motor is the possibility of using less powerful locomotives, reducing energy consumption to some extent.

Alternatively, the MDS could be used to haul longer trains once it is assured that the new track is adapted for this. However, the energy consumption for this option is not calculated in the report.

The new line is not yet constructed, and it has been considered as an option to use the capability of the extra adhesion the MDS provides in order to investigate the construction cost in steeper inclines. By enabling trains to tackle steep gradients more effectively, incline pushers might reduce the need for extensive earthwork, such as soil and rock excavation and filling, which are typically required to create gentler slopes for conventional rail systems. This also could help to conserve natural landscapes minimizing environmental disruption. Additionally, the reduced need for large-scale earthmoving could decrease the project's carbon footprint, making it a more sustainable option. However, the results of the calculations so far neither exclude nor show that such improvements could be achieved. But there will be more on this in a continued work with a proper cost-benefit analysis. The risks that are identified in Scenario B are very much the same as in Scenario A.

The final use case focuses on an inter-urban application between two major cities in Italy, introducing a hybrid MDS based on maglev configuration on the conventional regional railway line. The hybrid MDS would provide additional capacity to the network, higher speeds to the existing conventional lines, higher flexibility to the system and lower operational costs through automation.

For the use case involving the railway line between three cities, detailed simulations were conducted to evaluate two MDS vehicle configurations compared to the current conventional rail vehicle (ETR 421). This analysis focused on travel time, acceleration, and braking performance under two different infrastructure scenarios: one with existing infrastructure (Scenario A) and another with optimized infrastructure (Scenario B).

The main findings reveal significant advantages of MDS pod configurations compared to the ETR 421, particularly in terms of travel time and operational efficiency. Both configurations achieved an average reduction of 25% in journey duration, with the optimized infrastructure of Scenario B enabling more stable maximum speeds and further time savings. Evaluations were conducted across two levels of traction capacity, demonstrating that the higher acceleration configuration (1.5 m/s²) outperformed the lower one, offering improved travel times and efficiency. These results were supported by a detailed analysis of the trade-offs between power consumption and journey duration. Simulations highlighted the pods' superior acceleration and braking capabilities, which significantly reduced transit times between stations when compared to conventional trains.

Key parameters influencing these outcomes include traction and braking forces, with the ETR 421's maximum tractive effort of ±300 kN contrasted against the optimized range of 35 kN to 71 kN for the pods. This optimization, combined with the pods' lighter mass and shorter lengths, allowed for superior acceleration profiles. Additionally, the pods exhibited substantially lower rolling resistance coefficients due to their reliance on magnetic drag, contributing to improved energy efficiency. Infrastructure compatibility also played a crucial role, with Scenario B's optimized infrastructure enabling higher and more consistent speeds along specific sections, underscoring the benefits of targeted upgrades.

These findings carry profound implications. The adoption of MDS technology, even on current infrastructure, offers significant improvements in travel efficiency, while further enhancements could unlock additional performance gains on high-demand routes. Integrating pods into existing rail systems will require updates to signalling and control systems to accommodate their distinct operational characteristics, such as shorter braking distances and higher acceleration rates. Moreover, a comprehensive evaluation of energy consumption and lifecycle costs for the pods will be necessary in future deliverables to fully assess their benefits relative to conventional rail systems.

The simulation results demonstrate significant potential for the adoption of MDS pods, particularly in reducing travel times by an average of 25% compared to the conventional ETR 421 train. These gains are attributed to the higher speeds enabled by advanced magnetic levitation technologies and optimized infrastructure in certain scenarios. The operational flexibility offered by virtual coupling further enhances the system's feasibility, allowing the dynamic adaptation of pod convoy sizes to meet variable demand conditions.

While the advantages of MDS technology are significant, they must be carefully weighed against the challenges and risks identified in this analysis, particularly for its deployment along the \corridor. Derailment remains a primary safety concern, with potential causes including collisions, fire incidents, or infrastructure failures. While minor derailments might result in temporary service disruptions, severe incidents could lead to substantial casualties and extensive infrastructure damage. Collisions also pose a critical hazard, especially in high-speed operations, where system malfunctions, miscommunication, or obstructions on the line could have catastrophic outcomes. Fire hazards are another key risk, exacerbated by the use of magnets for traction, which are susceptible to overheating under certain conditions, potentially endangering passengers and causing significant damage to rolling stock and infrastructure. Additionally, the proximity of high-voltage components to populated areas and the increased accessibility of these components heightens the risk of electrocution.

To address these risks, several mitigation measures are recommended. Enhanced safety protocols should include advanced monitoring systems capable of detecting derailment or collision risks in real-time, as well as automated emergency braking systems. Infrastructure hardening, such as reinforcing bridges and tunnels along the line, is crucial to minimize the impact of severe derailments or collisions. Effective thermal management systems must be integrated to prevent overheating of magnets, thereby reducing the likelihood of fire incidents. Finally, protective barriers and advanced insulation materials should be employed for high-voltage components, alongside rigorous training programs for trackside personnel, to mitigate the risks of electrocution and ensure overall system safety.

While the technical feasibility and performance advantages of the MDS system are evident, its implementation must consider the identified risks and their mitigation. The improvements in travel time, operational flexibility, and system efficiency make the MDS pods a transformative solution for rail transport.

Future work in WP7 will refine these findings through life-cycle cost (LCC) and cost-benefit analysis (CBA), providing a comprehensive framework for decision-making. The results of this analysis will also inform the development of a European roadmap for MDS implementation, addressing technical, operational, and safety challenges holistically.

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