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Vehicle Prototype – Design Report

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1 Executive Summary

This deliverable describes the results of the WP8 of the project MaDe4Rail which aimed to define the concept design of a vehicle prototype based on MDS technology that can be used for one of the three use cases analysed in the WP7.

The concept design of the vehicle prototype has been based on the following steps:

1) The first step aimed to select the use case among the three identified in the D7.1 (Ref. [21]) to use as reference for the concept design of the vehicle.
2) The second step aimed to define the inputs for the design of the vehicle prototype. The inputs have been derived from:
   a. Data defined in the other deliverables,
   b. Technical and functional requirements defined in D4.2 (Ref. [18]);
   c. Data defined in the WP7 during the definition of the use cases for the technical feasibility study and CBA;
   d. Analysis performed in the WP8.
3) The third step aimed to develop the concept design of the different subsystems of the vehicle for the use case identified at point 1) according to the vehicle breakdown defined in the D4.1 (Ref. [17]).

The document includes also the design of the bogie based on air levitation and electro-dynamic wheels (Ref. 15), developed as additional activity to those included in the work package. It was foreseen in the initial proposal independently by the use cases identified and the results obtained during the project.

During the development of the concept design, the impact on the existing infrastructure due to the integration of the MDS technology has been analysed. This analysis has allowed to:

1) Identify the compatibility issues between the MDS vehicle/wayside subsystems and the existing infrastructure.
2) Define the points of investigation and design options for the MDS vehicle subsystem.

The studies of the issues raised by the integration of the MDS technology in the existing infrastructure is a crucial point for further step to evaluate the cost and feasibility for the introduction and transition to the new technology from the current network.

The results of this study will represent a key element to evaluate the feasibility of the MDS and will allow to define more precise solutions on the architecture of the MDS vehicle prototype.

2 Abbreviations and Acronyms

BTM	Balise Transmission Module
CBA	Cost Benefit Analysis
CSM RA	Common Safety Method of Risk evaluation and Assessment
CCS	Control, command and signalling
CCTV	Closed-Circuit Television
EDW	Electro-Dynamic Wheels
EN	European Normative
ERTMS / ETCS	European Rail Traffic Management System/European Train Control System
EU-RAIL MAWP	Europe's Rail Joint Undertaking Multi-Annual Work Programme
ETR	Rapid Electric Train (for example: High Speed Train Freccia Rossa 1000)
EVC	European Vital Computer
FEM	Finite Element Method
FRMCS	Future Railway Mobile Communication System
GNSS	Global Navigation Satellite System
HSL	High Speed Line
HSR	High Speed Railway
ISM	Industrial, Scientific, and Medical (ISM) frequency bands
LIM	Linear Induction Motor
LM	Linear Motor
LSM	Linear Synchronous Motor
LOC&PAS	Locomotives and Passengers
MCA	Multi Criteria Analysis
MDS	MagLev Derived System
MV	Medium Voltage
OCC	Operation and Control Centre
PRM	Person Reduced Mobility
PWM	Pulse-width modulation
RBC	Radio Block Centre
TOR	Top of Rail
TSI	Technical Specification for Interoperability
U-LIM	U shape Linear Induction Motor
VBM	Virtual Balise Reader
VIRM	Verlengd InterRegio Materieel (Electric multiple unit (EMU) double-deck trains operated by Nederlandse Spoorwegen)
WP	Work Package

3 Background

The present document constitutes the Deliverable D8.1 “Vehicle Prototype – Design Report” 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 MDS vehicle prototype. The concept design aims to define an architecture and solutions of a MDS vehicle prototype that can be used in one of the use cases identified in the D7.1 (Ref. [21]).

After the selection of the use case for which the MDS vehicle prototype must be developed, the input data needed for the design of the MDS vehicle, such as operating condition, dimension, weight have been defined.

The design of the MDS vehicle prototype has covered all subsystems included in the vehicle system breakdown defined in the deliverable D4.1 (Ref. [17]) with main focus on the subsystems strictly linked to the introduction of the MDS technology such as propulsion, guidance and suspension and that require major modifications compared to the conventional vehicle.

Two different solutions have been studied for the levitation and guidance system:

- Levitation and guidance system based on magnetic levitation, based on the use case selected from WP7;
- Levitation and guidance system based on air levitation, developed as additional activity to the project.

Two different solutions have been evaluated for the propulsion system:

- A linear motor with active part on the track (Linear Synchronous Motor)
- A linear motor with active part onboard (U-shape Linear Induction Motor)

The design of other subsystems requires different level of adaptation compared to the conventional vehicle depending also on the requirements defined for the use cases, in particular:

- Ensure mixed traffic operation with conventional and MDS vehicles
- Ensure the compatibility with the existing signalling system (ERTMS)

The design of the vehicle subsystems has allowed to identify the impact of the MDS technology on the existing infrastructure and evaluate different solutions. In some cases, more detailed studies must be performed to evaluate the impact of the MDS technology on the existing infrastructure and compare the different solutions proposed.

5 Selection of use case

5.1 Background

The first task of the WP8 is the selection of the use case to adopt as base for the design of the MDS vehicle prototype.

The results of the D6.1 (Ref. [15]) shows that the MDS configurations with the greatest potential for use in today's rail infrastructure are the hybrid magnetic levitation and the air levitation MDS, closely followed by the rail upgraded vehicles. In contrast, systems that are the most challenging to use on the current infrastructure are the existing pure maglev systems.

In the same document, 19 generic use cases for the implementation of the hybrid MDS technologies listed above were identified combining different criteria, such as technology, interoperability, type of service (passenger, freight, local, high speed) and type of composition (Fixed trainset, pod). Estimated time horizon for their implementation and possible applications have been specified for each use case.

In the D7.1 (Ref. [21]), a set of workshops involving over 40 participants from 8 countries and several fields such as Infrastructure Managers (IM), Railway Undertakings (RU), Terminal operators, End customers (freight), and other railway stakeholders were organized to identify the lines for the implementation of the 19 generic use cases.

Finally, a MCA has been performed on the 19 generic use cases to identify the three that must be further studied for technical feasibility and cost benefit ratio. The MCA has taken into consideration the criteria related to the operations and traffic control aspects, technology, interoperability, environmental sustainability, and implementation and economics.

From the steps above, 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 three use cases identified are the following:

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

A short summary of the three use cases identified in the D7.1 (Ref. [21]) is reported in the following paragraphs.

The design of the vehicle prototype will be based on one of three use cases. The selection of the use case to adopt for the design of the vehicle is described in the chapter 5.

5.1.1 Selected use case 1 – Rail vehicle upgraded MDS

An upgraded conventional vehicle with MDS technologies on wheels will be used to carry out transportation tasks in specific facilities and areas with existing rail infrastructure. In particular, the largest group of target applications are facilities that rely on transportation within that facility, for which high throughput and flexibility of operations are desired. In principle, the basis of operations is moving loads between reloading points in a shuttle traffic arrangement.

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, an MDS based on upgraded traditional railway vehicles solves the problem with much lower costs using the existing infrastructure.

The considered existing line, connecting two main cities, is a single-track, curvy and has limitations in capacity, speed and travel time. The route is part of a large commuting area and the existing railway is not a competitive alternative to road traffic. Commuting on that connection is currently mainly made by car or bus. The same applies to trips to and from the local Airport, which currently has no railway connection today.

A new railway line between the two abovementioned cities would provide faster train journeys, smoother work commuting and increased accessibility to and from 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,
- Boost conditions for strong labor market regions and regional development through increased accessibility and new travel origins and destinations and
- Promote sustainable travel and transport.

The new planned line comprises approximately 60 kilometers 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, using a MDS with upgraded rail vehicles and linear motors trackside could provide a solution with low costs to the steep incline of the line providing the required operational parameters specifically where they are needed.

5.1.2 Selected use case 2 – Hybrid MDS based on air levitation

The use case of air levitation on existing infrastructure is proposed on an historical regional line, based on the implementation of a hybrid MDS with air levitation and electro-dynamic wheel propulsion. The definition of the use case reflects the need to evaluate the performance of a hybrid MDS with air levitation on main line, as an alternative to constructing new HSR lines.

MDS with air levitation will operate at least with speeds at 180 km/h that could be expected higher when upgraded into HSR lines.

The entire route, connecting two main cities which together account for about 36% of the region's total population and attract a significant number of tourists, consists of about 36.93 km of lines, divided into two sections. The entire route is in a flat area, with no steep slopes or tunnels. However, there are bridges and subways along the line to optimize the elevation profile. High-speed trains complete the journey between the two cities in just 26 minutes, while regional services currently take around 45 minutes.

Hybrid MDS based on air levitation is one of the potential solutions to increase the offer to the service between the two cities. The main advantages of using Airlev trains is a reduction in shuttle time, improvement of traction/braking performance in slippery conditions, and less maintenance work disrupting the service. In addition, more traction and braking capacity can be expected in slippery conditions comparing to wheel-rail based railway (when leaves are on rail head for example).

The expected benefits for the line with the implementation of the MDS system include the increased capacity and potentially higher speeds for operating trains. The infrastructure, especially the tracks, can be upgraded to accommodate speeds of 180 km/h. However, increased speeds typically lead to more frequent maintenance and, consequently, more disruption in line usage.

The Airlev train evenly distributes the load of the train across the entire track and substructure, thus exerting less stress than current trains. Compared to standard track upgrades, such as adding slabs upon the ballast, a hybrid MDS configuration offers the advantage of reducing track wear and lower maintenance requirements. Furthermore, using a specific configuration, both Airlev and conventional trains could be running on the same track.

The technical features of the Airlev train and its corresponding track are detailed in the following figure. The principle of air levitation is based on creating a pressure differential between the air inside and outside an air chamber, generating sufficient mechanical force to lift a vehicle off the ground. This proven technology was used already on several lines in the past (see the review of air levitation in Deliverable 2.1). A significant improvement of the concept proposed is the new propulsion method, namely, electro-dynamic wheels (EDW, rotating magnets), as depicted in the subsequent figure. The EDW can create thrust force and provide braking when rotated in the opposite direction.

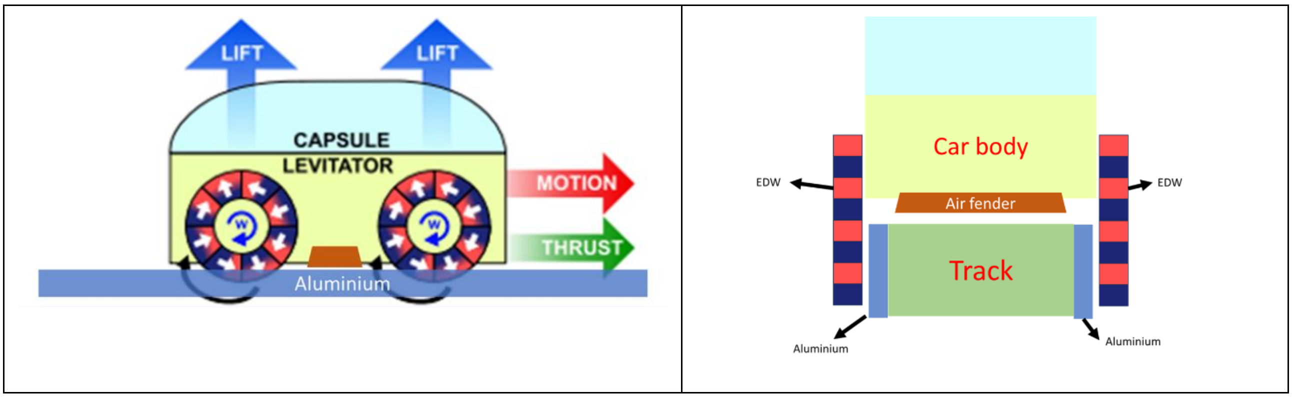

Figure 1 Schematic, levitation by air (fenders) and propulsion by rotating permanent magnetic wheels.

Next to load carrying, propulsion and braking is necessary without being dependent on friction to be able to increase the number of (faster) trains on a track. The magnetic propulsion and braking have been chosen, by using a wheel containing permanent magnets rotating contactless for instance along an aluminium conductor (stator) generating a Lorentz force for propulsion and braking.

5.1.3 Selected use case 3 – Hybrid MDS based on magnetic levitation

The use case of magnetic levitation on existing infrastructure is proposed on an historical regional line, parallel to the HSR line, based on the implementation of a hybrid MDS with magnetic levitation and propulsion. The definition of the use case reflects the need to evaluate the performance of a hybrid MDS on secondary regional lines, as an alternative to constructing new HSR lines.

MDS on secondary lines will not allow to reach top speeds (up to > 500 km/h) that could be expected on Hybrid MDS introduced on HSR lines. However, a hybrid MDS could bring as well potential benefits related to more flexible and automated operations with lower operational costs and safer services.

The entire route consists of six line-sections and four nodes with an entire length of 585 km. Travel time with the regional trains on this line can take up to 8 hours from one end to the other. The trains cuts from one coast to the other, with some sections on mountain terrain. Many trains stop halfway on the line, in one of the main stops of the route. On the 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.

5.2 Selection of the use case for the design of the MDS vehicle prototype

As described in the previous paragraphs, three use cases for implementation of hybrid MDS have been identified for the MDS configuration having the greatest potential for use in today's rail infrastructure such as rail vehicle upgrade, air levitation and magnetic levitation.

WP7 has performed the technical feasibility study and cost benefit analysis for each use case. However, the results of the analysis were not available at the start of the vehicle prototype design activity, therefore they have not been considered as criteria to select the use case for the design of the MDS vehicle prototype.

In consequence, the selection of the use case to adopt for the design of the MDS vehicle prototype has been based on the following considerations:

1) ProRail and TuDelft, as set out in the project proposal, proposed to study the air levitation bogie which is adopted as technology for the use case 2.
   To have at the end of the project different solutions available, the design of the MDS vehicle prototype based on air levitation has been left to ProRail and TUDelft, and another use case has been selected to develop the concept design of the MDS vehicle prototype.

   The concept design of the air levitation bogie developed by ProRail and TuDelft is described in the chapter 15.

2) The use case 1 and 3 are related to different service application, freight and passenger respectively. The use case 1 (Ref. §5.1.1) aims to introduce the linear motor on steep segments of the line to provide additional traction force. It foresees the re-use of the existing vehicles suitably equipped with linear motor (rotor or stator depending on the solution).

   The use case 3 (Ref. §5.1.3), on the other side, in addition to the introduction of the linear motor for the traction of passenger vehicles along the whole line, foresees the magnetic levitation as suspension and guidance system.

   The use case 3, even if related to different service applications and line than the use case 1, can be considered an extension of the use case 1. Indeed, in addition to the linear motor it also requires the magnetic levitation as suspension and guidance solution. It must be noted that the requirements and performance of the linear motor in the two use cases may be different, however, the same concept design may be used in both cases.

Based on the considerations above, the use case 3 has been selected for the concept design of the MDS vehicle prototype, since it encapsulates also most of the complexity of the use case 1. The design of the vehicle prototype has been based on the requirements defined for the use case 3 in the D.4.2 (Ref [15]) which describes the operating scenario of the line with the introduction of MDS. The results of the design are reported in the following chapters (from chapter 6 to 14).

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6 General description

The objective of this chapter is to describe the main characteristics of the MDS vehicle to adopt for the use case n.3. The vehicle can be also used for other line (with standard track) properly equipped with MDS technology and service (intercity or regional service).

The data defined in this chapter will be used as inputs for the concept design of the different subsystems of the vehicle, which are those reported in the vehicle breakdown shown in the D4.1 (Ref. [15]):

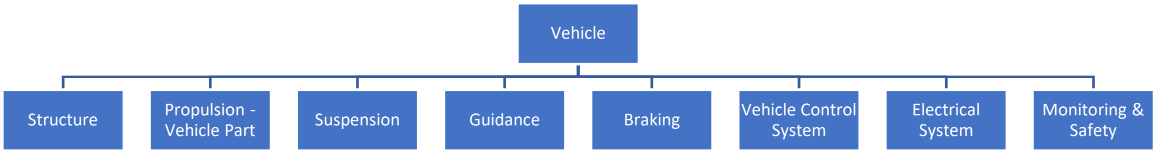


Figure 2 System Breakdown Structure for MDS vehicle

The concept design has been focused on the bogie of the vehicle which is the system mainly affected by the introduction of the MDS technology such as linear motor, levitation system and guidance. Interfaces with infrastructure have also been addressed.

For the other systems such as signalling, communication, auxiliary systems and electrical system, a general concept will be developed to give an overview of the architecture, functionality and performance that shall be considered in the overall design of the MDS vehicle.

6.1 Inputs from other WPs

The main inputs applicable to the design of the MDS vehicle for the use case 3 are reported in the D4.2 (Ref. [15]):

1) MDS vehicles/pods will use the existing infrastructure and will operate with conventional trains on the same lines.
2) The vehicle shall be a single pod (vehicle), similar to a single coach, and should carry up to 70 passengers. It will also be possible to combine single pods into a "platoon" which is made of two or more virtually coupled consists, which are not connected mechanically. Depending on the specific demand of capacity the pods can also be designed with physical couplings.

3) The propulsion, guidance and levitation shall be assured by magnetic systems. The vehicle begins to move when the electric power of precisely selected parameters is provided to the linear motor stator. Then the electromagnetic force starts to act and moves the pod. The linear motor must provide both the propulsion force and the force required to brake the vehicle.
4) The pods suspension and guidance are magnetic systems and require the use of permanent magnet or electromagnets arrangements onboard the vehicle. The interaction between maglev guideways and levitation skids is required to generate the appropriate levitation and stabilisation forces.
5) The vehicle shall be suitable for at least Grade of Automation 3 (GoA3) as defined by IEC 62290. This entails the vehicle's capability to operate autonomously without an onboard driver even on lines with mixed traffic of conventional and at least GoA3 vehicles. Therefore the compatibility with European Train Control System (ETCS) must be assured to potentially use ATO over ETCS functionalities. The cabin crew in those pods is meant for passenger care and emergency procedure.

6.2 Definition of the vehicle parameters

The first step of the design activity has been the definition of the vehicle parameters such as:

- Vehicle operating scenario and performance
- Vehicle dimensions
- Vehicle weight

fulfilling the requirements defined in the paragraph 6.1 and derived from the use case definition described in the D4.2 (Ref. [18]).

The definition of these parameters is an essential step to define the inputs for the design of guidance, suspension, propulsion and braking system.

6.2.1 Vehicle Operating Scenario and Performance

The MDS vehicle is mainly designed to operate on the existing line of the use case 3, properly adapted with MDS technology.

The vehicle will be used along the whole line both to replace existing regional services (whose origin-destination is included in the route under analysis) and to serve the new demand attracted by the increased performance. The operating parameters defined for the MDS vehicle are the following:

Operating parameter	Value	Remarks
Service hours per day	Max 15 h	
km per day	Up to 1500 km per day	It means at least a round trip per day (538 km x 2)
Stops per day	Up to 60 stops per days	The use case 3 foresees 17 stops (WP7.2 - Ref. [22]). More stop per day may be planned for a regional service
Average speed	120 km/h (without stops)	
Maximum speed	220 km/h	Based on WP7 analysis (WP7.2 - Ref. [22])
Duration of the trip	About 4 h (including stops)	Trip time for the specific use case with MDS vehicle (WP7.2 - Ref. [22])

Table 1 MDS Vehicle – Operating Scenarios Data

6.2.2 Dimensions

The dimensions of the vehicle prototype have been defined considering that it shall carry up to 70 passengers in a single coach as defined in the D4.2 (Ref. [18]).

In addition, the vehicle dimensions shall respect the structure gauge of the existing infrastructure, to avoid any conflict along the track.

The length of the MDS vehicle has been defined considering as reference the dimensions of a conventional coach able to carry up to 70 passengers.

An example of dimensions for conventional vehicle is reported in Figure 3 and Figure 4.

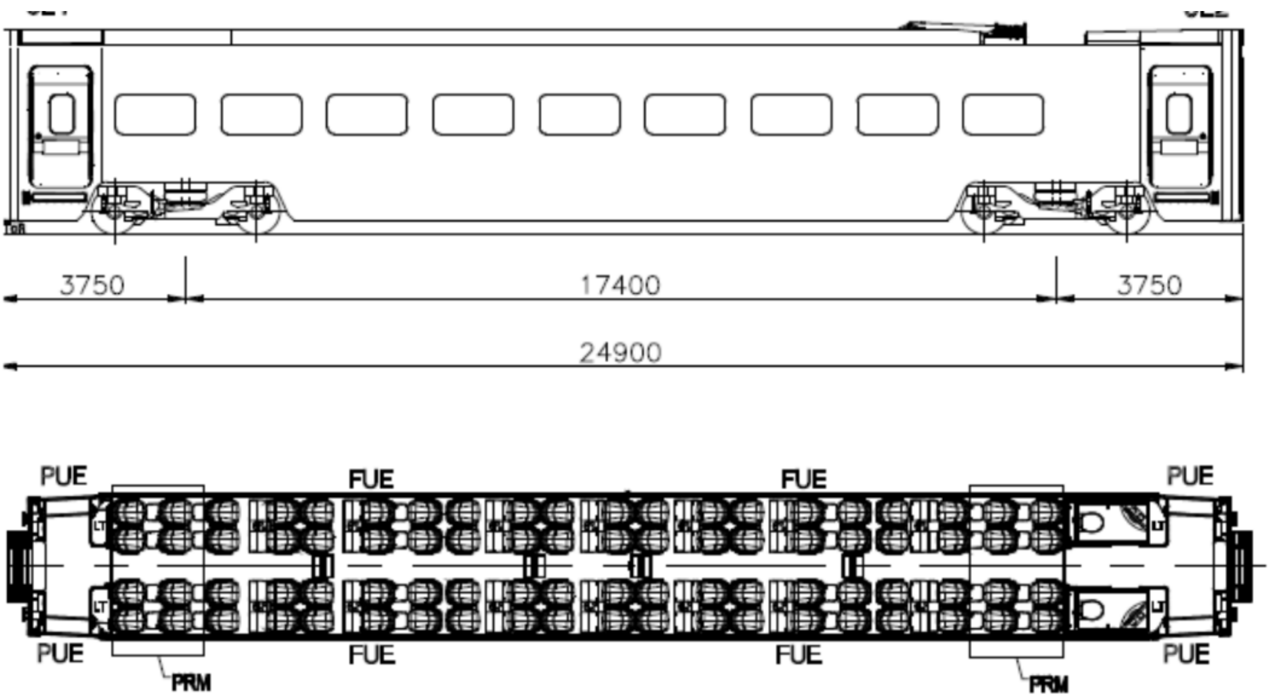


Figure 3 Example of coach of 25m with 80 seats and 2 toilets from ETR1000 layout (Ref. [49])

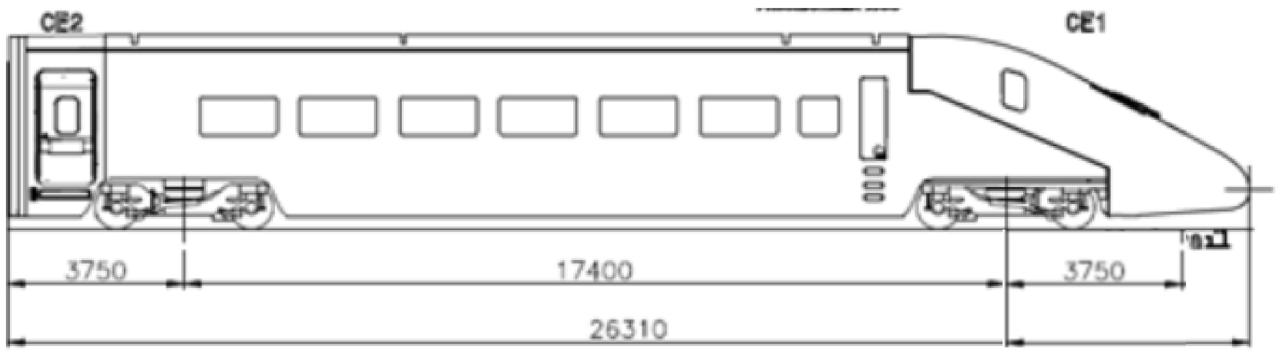


Figure 4 Example of coach with Nose / Tail from ETR1000 layout (Ref. [49])

A coach of 25m allows to host up to 80 seats (Ref. Figure 3), including two toilets and the on board systems. Additional space is required for the installation of the nose and tail. For this reason, 3 additional meters have been reserved for having a total length of the vehicle of 28m.

The shape of the vehicle, and in particular nose and tail are not defined at this stage because they will depend on style and aerodynamic criteria.

For the line of the use case 3, the structure gauge of the existing train is the GB according to the EN 15273-2 (Ref. [13]). The structure gauge applicable to the line of the use case 3 is the "G1, GI2":

- Static / Kinematic gauge G1 is generally used for the upper parts of interoperable international cars in Europe except for the United Kingdom.
- Static / Kinematic gauge GI2 is generally used for the lower parts of interoperable low-floor cars not capable of being hump shunted.

To ensure that the MDS vehicle fits the existing vehicle gauge, the height and width of the vehicle has been considered equivalent to a conventional railway vehicle with a single floor.

- The height of the vehicle from the Top of Rail (TOR) has been assumed 4m (Ref. [49]).
- The external width of the vehicle has been assumed 3m (Ref. [49]).

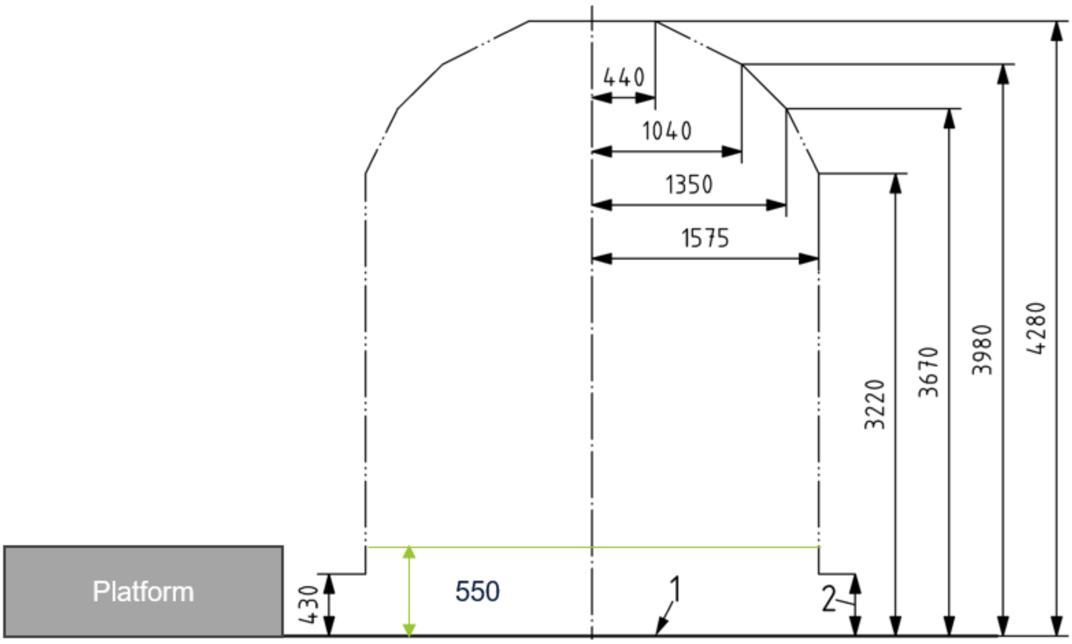


Figure 5 Train static structure gauge G1 according to EN 15273-1 (Ref. [13] Annex A.2.1)

The main constraints for the linear motor are defined in the lower part of the static and dynamic gauge.

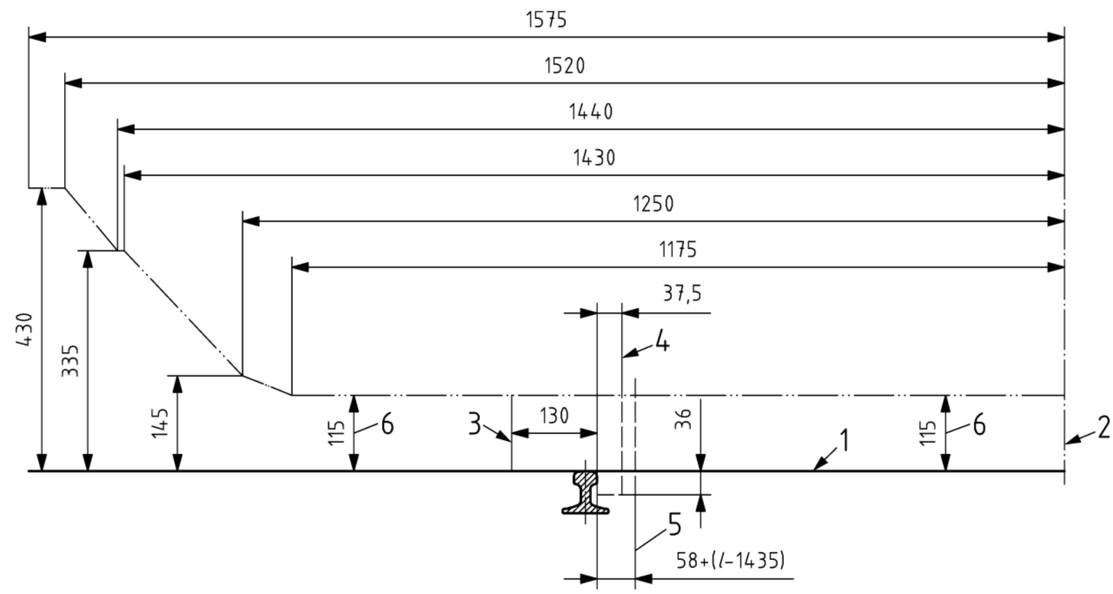


Figure 6 Train static structure gauge GI2 – lower part according to EN 15273-1 (Ref. [13] Annex A.2.2.2)

Starting from these values, detailed calculation shall be performed in the detailed design of the vehicle to ensure that static and dynamic envelope fulfil the requirements of the structure gauge “G2, GI2”.

The door has been considered at the same height than the platform to avoid any step during the embarkment of the passengers.

The distance from the TOR to floor/platform shall be 550mm as required by the TSI-INF (Ref. [5] Par. 4.2.9.2.):

Considering the data reported above, the geometrical shape of the MDS vehicle is shown in the Figure 7:

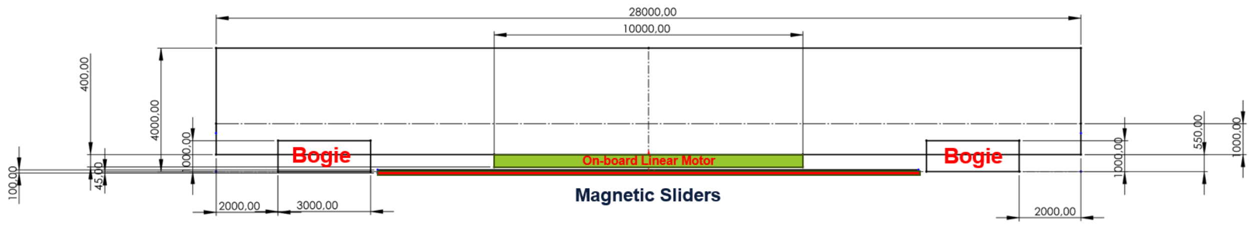


Figure 7 Raw longitudinal structure gauge of the MDS vehicle

6.2.3 Weight

The weight of vehicle is needed to size the suspension and guidance system as well as the propulsion system.

The definition of the vehicle weight depends on different parameters, such as the systems to be installed, type of materials for the construction, etc.

It must be noted that the systems in a conventional vehicle are usually distributed in the different coaches, while for the MDS vehicle all systems will be installed on one coach. The mass of the different subsystems has been derived from the following data:

System	Mass (kg)	Mass %	One Coach (kg)
Carbody	116856	26%	14607
Interior, windows and floor	87780	19%	10973
Bogie and running gear	143435	32%	17929
Propulsion and electrical system	88465	20%	11058
Comfort systems	14044	3%	1756
Total	450580	100%	56323

Table 2 ETR 1000 mass distribution (Ref. [50]) – Configuration 4M4T

More than the 50% of the mass is represented by the carbody and the bogies. Considering that it's composed by 8 coaches, the average mass of a coach is 56323 kg.

The masses assumed for the MDS vehicle are reported in the Table 3:

Vehicle Model	Mass (tons)	Remarks
Coach	20 tons	
Bogie	10 tons	
Magnetic levitation	7 tons	Calculated (Ref. chapter 7)
Traction	1 ton	Assumed for first iteration for LSM
Passengers	5.6 tons	70people x 80 kg (according to EN 15663)
Total	43 tons	

Table 3 MDS Vehicle – Mass distribution

These data are based on the following assumptions:

1) The bogie of the MDS vehicle won't be motorized, because the traction will be provided by the linear motor. A single non-motorized bogie used on the traditional vehicles have a mass of about 5 tons.
2) The mass of the coach of the MDS vehicle can be optimized compared to the existing vehicle, using materials that can allow to reduce the total weight (Ref. [23]) .

A more detailed analysis of the weight should be conducted considering the expected weight of the different subsystems.

6.2.4 Summary of MDS vehicle parameters

The input parameters for the design of the MDS vehicle are summarized in Table 4.

Parameter	Value	Remarks
Length total	28m	
• Length coach	25m	Car of 25m can hosts up to 80 seats
• Length nose / tail	1.5m	Ref. to Figure 3 and Figure 4
• Length bogie	3m	2.850m for ETR1000 (Ref. [49])
Height	4m	From the TOR - 4.080m for ETR1000 (Ref. [49])
• Height coach	3.450m	
• Height bogie	1m	
Width	3m	ETR1000 (Ref. [49])
Weight	43.6 tons	
• Weight coach	20 tons	
• Weight bogie	10 tons	
• Weight slider	7 tons	Calculated
• Weight Traction (LM)	1 tons	Assumed for first iteration

Parameter	Value	Remarks
• Weight Passengers	5.6 tons	70 people x 80 kg
Operation Speed	220 km/h	220km/h (max track speed according WP7)
Construction speed	249 km/h	Tests are performed at operation speed +10% (EN 14363)
Normal Acceleration	0.75 m/s2	0.7m/s2 for ETR1000 (Ref. [3])
Normal Deceleration	0.75 m/s2	Similar to existing train. It can be increased up to 1.5 m/s as analysed in the WP7 (Ref. [22]). This last solution increases the power consumption with a with a non-significant reduction in travel time but can be useful in urban services with frequent stops or other operational contexts.
Max Deceleration (emergency)	2.5 m/s2	TSI LOC&PAS 4.2.4.5.1 point (5)
Aerodynamic drag	0.31 m/s2	Calculated on 28m considering the shape of Bombardier Regina. It will depend by the shape of the vehicle.

Table 4 MDS Vehicle Parameters - Summary

Other parameters related to the design of the vehicle are not defined at this stage (fire resistance, crash resistance[1], etc), since they will not differ from a conventional vehicle nor impact the concept design of the MDS vehicle. In addition, for the systems not impacted by the introduction of the MDS technology the requirements defined in the TSI LOC & PAS (Ref. [7]) remain applicable.

[1] Crash resistance may be reduced for MDS vehicle applying other measures to control the vehicle and using the features of the linear motor to know the position of the vehicle along the line.

7 Levitation and guidance system

Among the various levitation technologies described in the D4.1 (Ref. [17] §6), the solution for levitation and guidance system identified for the MDS vehicle aims to minimize the impact on the existing railway infrastructure, which is the main goal of the hybrid MDS systems.

The solution identified ensures seamless integration with the current railway infrastructure, reducing the need for costly and disruptive modifications. By focusing on compatibility with existing tracks, the project aims to implement the new technology efficiently and economically, ensuring a smoother transition without compromising the operational integrity of the railway system. This approach supports the broader objective of modernizing transportation while maintaining practical and sustainable development.

7.1 Magnetic sliders description

The magnetic sliders are the core subsystem where the levitation force is transferred from the vehicle to the ground. The sliders can be based and equipped with different functions and characteristics, according to the configuration adopted.

The magnetic sliders equipped with ferromagnetic levitation have the function of vertically sustaining the load of the system, both in static and dynamic conditions. They engage on the standard rail tracks to generate the magnetic levitation force. The sliders integrate also lateral centering means that act as a guidance system.

The sliders are made of a ferromagnetic U-shaped profile with an installed array of permanent magnets and coupled with the standard tracks. The magnetic interaction generates the vertical force that sustains the vehicle upwards. The sliders are composed by a passive levitation system that passively sustain the vertical load coupled with a controlled guidance system that ensures that the lateral the gap is precisely controlled through an active centering system.

The centering system is composed by sensors and an electronic controller that controls an electromagnetic system that ensures the lateral force is minimized at each time step.

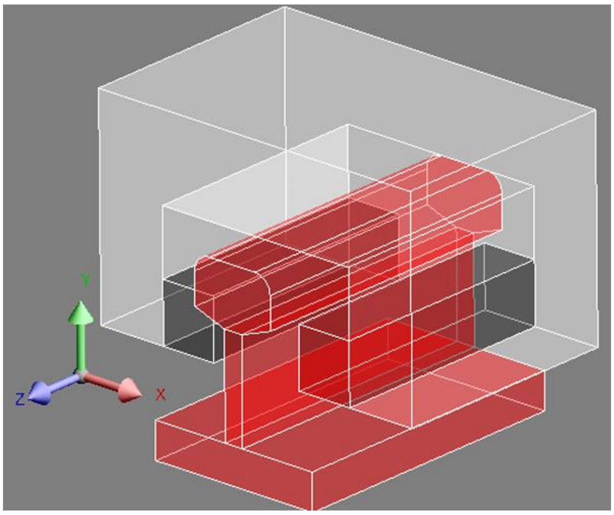


Figure 8 3D section of levitation sliders coupled with rail

Geometrically, the sliders surround the top part of the rail. For this reason, the dimensions in terms of lateral gap and maximum length must be evaluated accordingly. The total length of the sliders required to sustain the load is divided into sections of 1 m length to negotiate curves and face rail tolerances. In fact, lateral gap between slider and rail and the short length of the slider portions of 1 m allow to face railway curves without geometric interferences.

By maintaining the sliders centered on the rail, the lateral systems are unloaded. By controlling the lateral position, lateral magnetic force between slider and rail can be adjusted and lateral forces (ex. centrifugal) can be counteracted by magnetic force. This feature is called active lateral balancing.

The lateral control and centering system is based on EMS technology for force generation and control. The lateral system is essential during turning phases, where the lateral centrifugal force is balanced magnetically by misaligning each slider section. During turning phases, active lateral control misaligns the slider from central position, creating a magnetic lateral force that counteracts centrifugal action.

Lateral load is supported magnetically, without weighting on the lateral stability system.

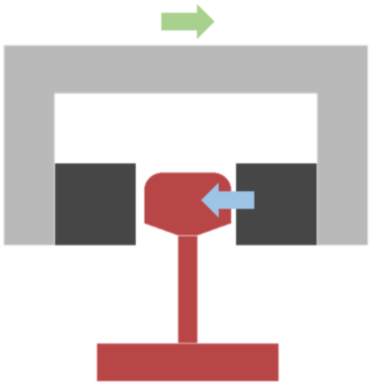


Figure 9 Slider lateral balancing system

From an installation perspective, the sliders can be connected to a frame or directly to the vehicle chassis to have a framed architecture or a frameless architecture:

- In the first case, the sliders are attached to a mechanical frame and the secondary suspension is placed between the frame and the car body;
- In the second case the sliders are directly attached to the car frame. In this case, an adequate auxiliary system between the sliders and the car body in order to ensure the correct system dynamics. It must be pointed out that the behaviour of the sliders gives vertically a low rigidity system compared to the high rigidity system of the wheel-rail contact.

7.2 Sliders dimensioning and magnetic analyses

In order to properly size the sliders, the analyses started with a FEM aided design with the aim of optimizing the section of the sliders for vertical static load transfer and dynamic performances. The analysis optimized the weight of the sliders and the load transferred to the vehicle.

To do so, the analysis starts with a simplified 2D model of the slider and the rail. The slider model comprises a U-shaped profile with permanent magnets that interact with the ferromagnetic rail. Multiple 2D simulations are performed with geometrical variations to optimize materials and save weight.

The simulations are performed with a stepped vertical motion to analyse the load at each vertical step. The procedure is then performed with a dynamic 3D model to evaluate the dissipation as a function of the speed.

At each phase of the procedure, the design is analysed and reviewed with the support of CAD software. The results are presented below.

For the design case under "pure" levitation mode, this implies having 43.6 tons over two arrays of 16 m sliders, giving a static distribution of load of 1,36 tons per meter.

The max weight supported by the sliders is 54tons which correspond to 1.68 tons per slider (1m). The difference between maximum and nominal load can be considered as safety factor of the levitation system.

Due to the elasticity of the levitation system, the vertical position is a function of the load applied on the slider. Here is a table of the vertical gap between the top of the rail position and the slider in static conditions.

Gap	Conditions
60mm	Max vertical gap from TOR (Top of Rail) considering only the load of the sliders
54mm	Max vertical gap from TOR considering also the load of the vehicle
40mm	Max vertical gap from TOR considering the max load on the sliders without safety factor
10mm	Max horizontal gap between rail and slider

Table 5 Gap between the rail and slider in static conditions

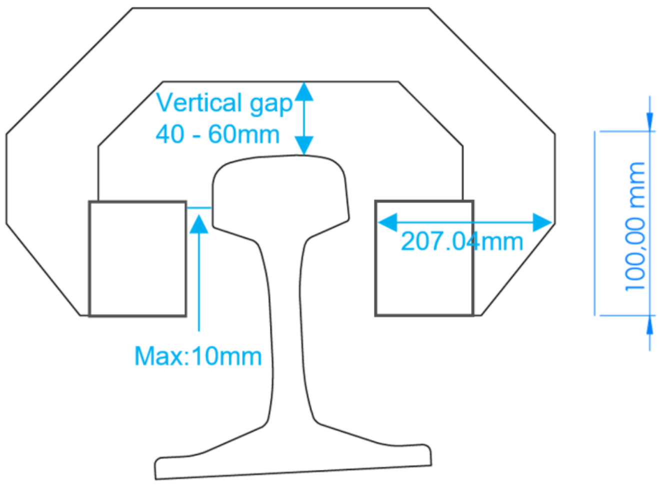
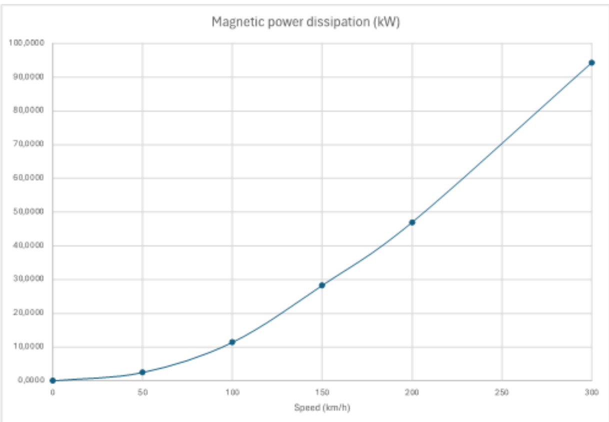
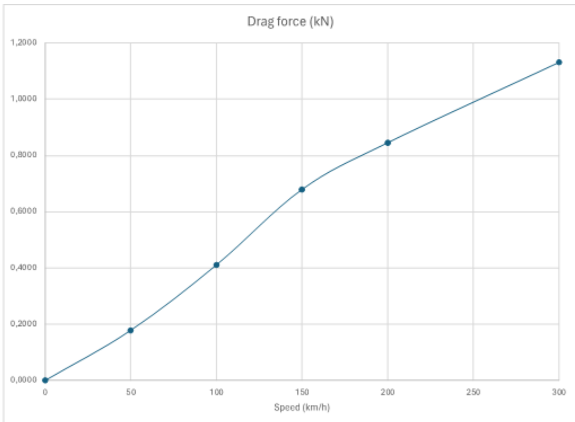


Figure 10 Slider section with reference dimensions

In the tables below are represented the magnetic power dissipation and the drag force of the full pod as a function of the pod's speed.

Speed (km/h)	Speed (m/s)	Magnetic power dissipation (kW)	Drag force (kN)	Coefficient of friction
0	0,00	0,0000	0,0000	0,00000
50	13,89	2,4760	0,1783	0,00042
100	27,78	11,4080	0,4107	0,00097
150	41,67	28,3200	0,6797	0,00161
200	55,56	47,0000	0,8460	0,00201
300	83,33	94,3000	1,1316	0,00268





Magnetic dynamic analyses with total weight = 43 tons and Rail: UNI60

Table 6 Magnetic power dissipation and the drag force of the full pod as a function of the pod's speed

7.2.1 Loads and load distribution

Passive ferromagnetic levitation sliders offer a significant improvement in load compatibility compared to traditional wheel-based systems. One of the primary advantages is that the levitation sliders distribute the load uniformly along the entire length of the rail. In contrast, conventional wheels apply localized, point-specific forces, which can cause concentrated stress points (Ref. Figure 62). This uniform load distribution leads to considerably reduced stress on the rail itself and on the infrastructure, as the forces are spread over a larger surface area. As a result, the overall strain on the infrastructure is diminished, contributing to the longevity and durability of the rail system.

This even distribution of load also means that the infrastructure is subjected to less intense and less frequent stress peaks, and therefore less damage over time. The reduction in localized stress points translates into a decrease in the potential for structural fatigue and failure. Furthermore, the elastic nature of the interaction between the levitation sliders and the rail significantly reduces vibrations. Unlike traditional systems, where the rigid contact between wheels and rail can generate considerable vibrations, the elastic interaction of levitation sliders smooths out the ride. This not only enhances passenger comfort but also minimizes the transmission of vibrations to the surrounding infrastructure.

In addition, magnetic levitation eliminates direct mechanical contact, meaning there is no mechanical friction to cause wear. This significant reduction in mechanical wear preserves the integrity of the rail, leading to lower maintenance costs and fewer operational disruptions.

If compared to traditional load distributions where there are peak loads of 17 tons per axle (8,5 tons per wheel) over an area of few mm^2, the levitation load distribution is an uniform distribution of 1,36 tons per meter without peak loads.

7.3 Guidance and bogie interaction

The levitation sliders are integrated onboard the vehicle and are equipped with a slider lifting/lowering system that provides guidance and vertical movement. The guidance is contactless in order to be combined with linear motor propulsion and exploit an integrated maglev solution. The vertical movement allows to couple the system with traditional bogies to overcome the conflicts with railway infrastructure. During maglev operations, the vehicle starts by levitating from a standstill.

As it approaches a conflict point like switches, check rail or level crossings, the system gradually retracts the sliders in advance, transitioning first to a hybrid mode and then fully to bogies.

Upon exiting the conflict point, the sliders are progressively lowered again, completing the transition back to full levitation.

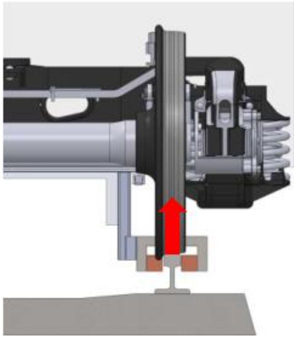
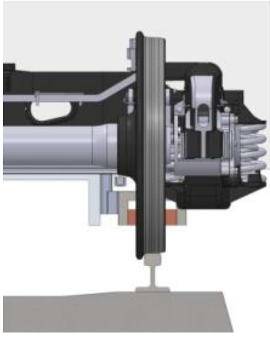
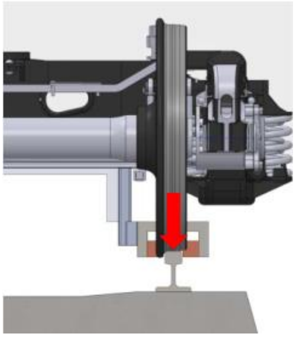
		
Before the switches	On the switches	After the switches

Figure 11 Operation of the Sliders/Bogies with rail interference

7.4 Integration of sliders in existing infrastructure

Evaluating the compatibility with the existing infrastructure is critical to ensure successful integration and optimal performances. This evaluation must encompass several dimensions: geometrical compatibility, mechanical compatibility, and electro-magnetic compatibility. Each of these aspects plays a vital role in ensuring that the system is compatible and maintaining the integrity and functionality of the infrastructure during future operations.

7.4.1 Geometrical compatibility

Geometrical compatibility is critical for ensuring that the magnetic sliders can integrate seamlessly the existing rail infrastructure. The primary focus is ensuring that the magnetic sliders can interact appropriately with rail portions and infrastructure sections, including fasteners and joints on the sleepers and all the additional elements of the infrastructure. The shape of the magnetic sliders surrounds the rail head, which extends beyond the standard gauge. This necessitates a thorough examination of the surrounding infrastructure to ensure there are no physical conflicts or constraints to the movement of the sliders or their function. This design necessitates an evaluation of the physical fit and alignment of the sliders with the rail elements.

- **Slider-Rail Interaction:** The shape of the sliders must accommodate the rail head without causing obstruction or interference with other components. This requires ensuring that the sliders conform to the rail's contours and do not impinge on adjacent elements such as fasteners or joints. The rail fastening systems can vary in designs and shapes.

Figure 12 Different fastening systems

In the long term, the rail can be substituted with a custom designed one that maximises levitation performances in terms of vertical linear load and magnetic power consumption, while maintaining the compatibility with wheeled operations.

- **Alignment:** Proper alignment of the sliders with the rail is crucial. Misalignment can lead to operational issues and potential failure. The standard tolerances prescribed by industry regulations can guarantee that the system works efficiently and reliably. However, it is essential to ensure that these tolerances are meticulously adhered to during both the production and operational phases. During manufacturing, control over the dimensions must be maintained through quality control processes, including detailed measurements and inspections to confirm that the components conform to the specified tolerances. Once installed, the alignment of the rail must be regularly monitored to ensure that it remains within the prescribed tolerances. Operational factors such as vibrations, thermal expansion, and wear can affect alignment over time. Regular maintenance and inspection routines are essential to detect any deviation from the standard tolerances and to implement corrective measures promptly. This ensures that the system continues to operate efficiently and prevents potential operational issues or failures. By adhering to the prescribed tolerances and maintaining rigorous quality control and monitoring practices, it is possible to ensure that the alignment of the sliders with the rail remains optimal throughout the system's lifecycle. Another critical aspect of geometrical compatibility is the verification of rail tolerances, which involves assessing the dimensional and geometrical properties of the rail sections. While the manufacturing tolerances are generally adequate, the most critical tolerances are those related to the mounting process. Geometric tolerances involve assessing the rail's shape and form to maintain the intended geometry without excessive warping, bending, or other deformations, verifying straightness, flatness, and angular deviations of the rail sections. The initial installation of the rail must be conducted with adequate longitudinal precision to ensure that the rail sections are mounted correctly and aligned perfectly with the sliders. Over time, operational factors such as thermal expansion, mechanical wear, and environmental conditions can affect the rail's dimensions and geometry, modifying the critical tolerances. Periodic inspections are necessary to monitor these changes and ensure that the rail continues to meet the required tolerances. To maintain geometrical compatibility over the lifespan of the infrastructure, regular inspections are crucial. These inspections can involve:

- **Routine Measurements:** Conducting routine measurements of the rail dimensions and geometry to detect any deviations from the specified tolerances.
- **Thermal and Environmental Impact:** Evaluating the impact of thermal expansion and environmental factors on the rail's geometry, ensuring that these factors do not compromise the overall compatibility.
- **Corrective Actions:** Implementing corrective actions based on inspection findings, such as realigning the rail, replacing worn components to ensure continued compatibility.

7.4.2 Interface between bogie and linear motor

Based on the type of bogie adopted, the geometrical and shape compatibility between bogie and linear motor must be analysed and verified. In particular, the compatibility between the stator (infrastructure part) and the bogie must be verified.

8 Propulsion and braking (Linear Synchronous Motor)

8.1 Functions and technical parameters

The function of propelling the vehicles, including both acceleration and deceleration (during regular operations and emergencies), is assigned to the linear propulsion system. Linear propulsion consists of:

a. power electronics that supply electrical energy with specific parameters to the stator. It composed by a set of transformers, rectifier and inverter
b. the linear motor, which includes both the stator and the mover:
    - Stator – part of the linear synchronous motor located on the infrastructure side between the rails. As an active part, it consists of a three-phased winding powered by an external power supply. With variable frequency and voltage.
    - Mover – part of the linear motor located on the side of the vehicle. It is an array of permanent NdFeB magnets

The type of linear motor proposed for the applications defined in the use cases is an ironless permanent magnet linear synchronous motor. This means that on the vehicle side, the mover consists of an array of NdFeB magnets that generates a constant electromagnetic flux.

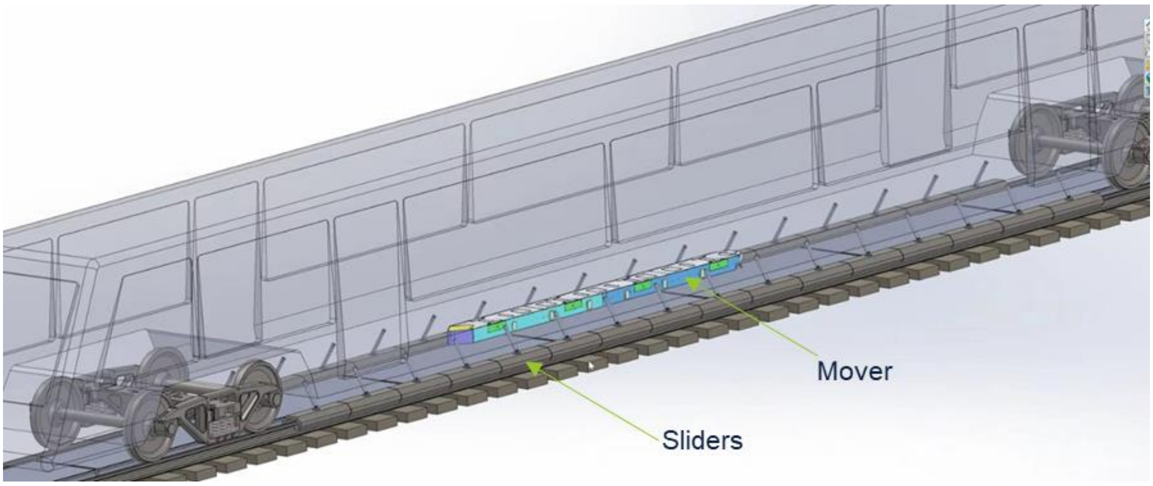


Figure 13 View of the mover installed under the coach of the MDS vehicle

On the infrastructure side, a three-phase winding without back iron will be installed. This configuration allows for motor control in a way that prevents the generation of vertical forces. This feature is crucial for maintaining the permissible axle load on the line without reducing the vehicle's cargo and passengers carrying capacity. Additionally, the horizontal synchronous motor, although being suboptimal from electromagnetic point of view, enables maintaining a 55 mm gap between the stator and the mover, ensuring compliance with G1/GI2 gauge requirements (Ref. Figure 5, Figure 6) which is a must-have feature to deploy such a propulsion on a railway track.

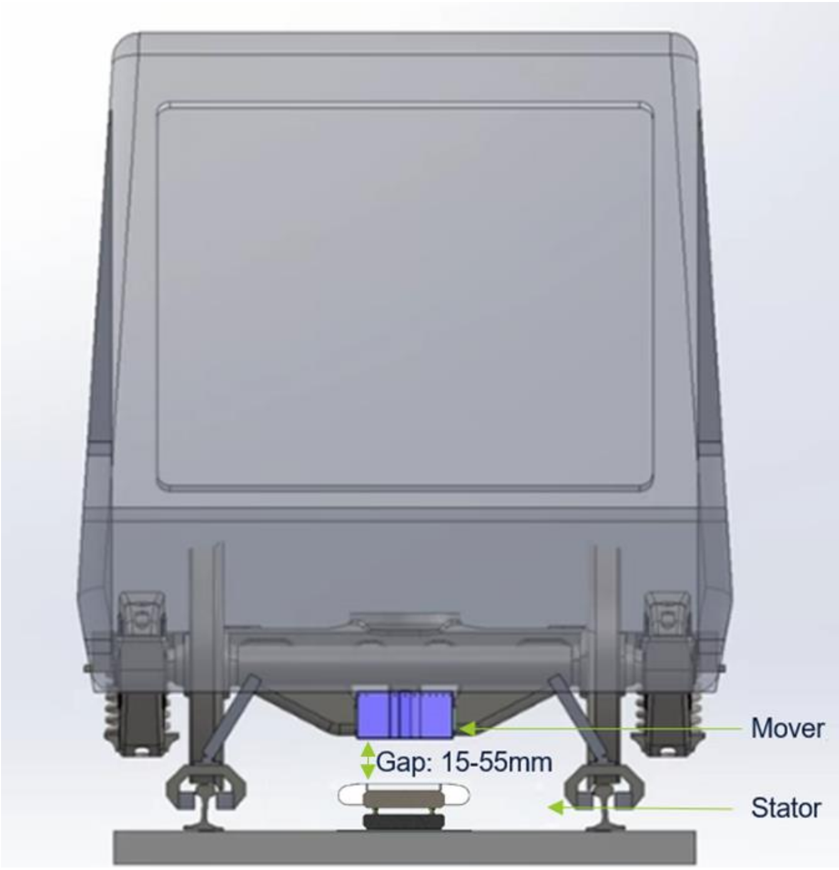


Figure 14 Section of the vehicle with mover and stator

A more detailed view of the stator is given in Figure 15:

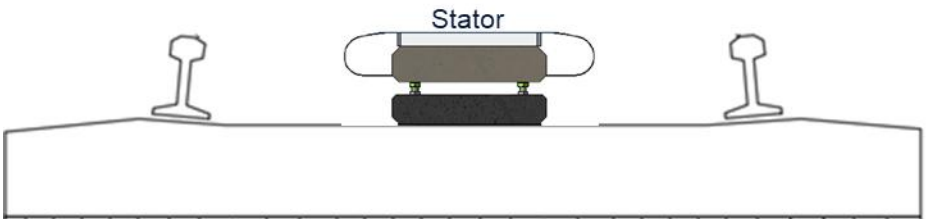


Figure 15 Installation of the stator on the track

8.2 Definition of the main components and architecture of the solution

The linear propulsion parameters defined to meet the operational requirements of the use-case 3 are listed in Table 7.

Parameter	Value	Unit
Mover (length x width x height)	15 x 0.35 x 0.15	m
Mover magnets type	NdFeB N48	-
Mover magnets array type	N-S	-
Stator width	0.75	m
Stator windings nominal voltage	2000	V
Peak acceleration force (design point)	83.5	kN
Peak mechanical power (design point)	2360	kW

Table 7 Basic linear propulsion parameters

These parameters are preliminary and may vary at further stages as next design iterations will be performed. Also, to assess the power electronics configuration in the next steps (substations location, segment lengths, etc.) the information about the grid power supply parameters and locations along the whole considered route should be known. The numbers have been assessed based on the use case analysis described in D7.2 (Ref. [22]).

A schematic drawing in Figure 16 depicts the architecture of the power supply chain from MV grid to the stator.

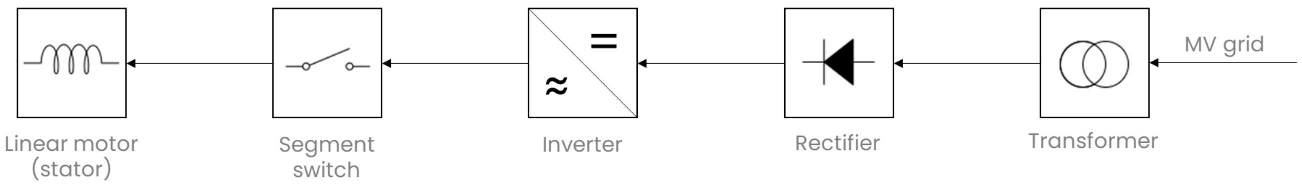


Figure 16 Power line from MV grid to the linear motor stator

8.3 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.

Linear motors with a long stator (with the active part on the infrastructure side) 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., the sections on which the vehicle is located. A separate substation with a power electronic converter supplies each section. This division is shown in Figure 17.

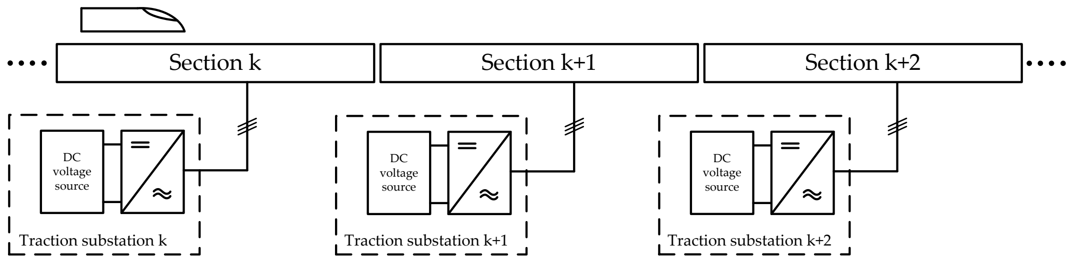


Figure 17 Linear motor stator division into the sections

In each section one vehicle can be moved individually. Sections length defines the minimum distance between vehicles, e.g in stations or areas with lower speed and higher density, the sections are shorter, than on high-speed lines with bigger distances between vehicles. Each section needs its own inverter station, so the length of the section decision is based on operational-economic analysis made case by case. For the use case 3, each section has been assumed 5km (in average).

Additionally, further subdivision of the stator into smaller parts called segments is done within one section. The segment division differs from the section division in that it does not increase the number of inverters.

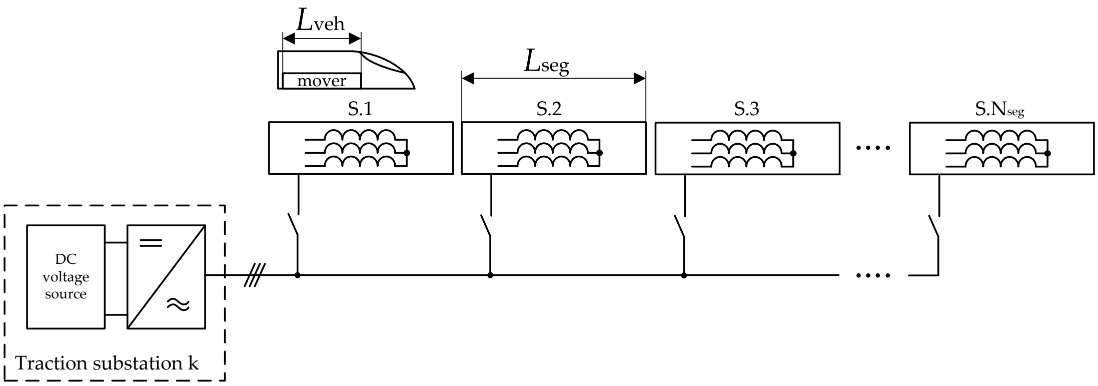


Figure 18 Linear motor section division into the segment

The shorter the segments, the better the efficiency, but also the more equipment (segment switches) is needed, what will bring more costs. For the use case 3, each segment has been assumed 60m.

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-segments 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.

The operation of the linear motor requires to know the position of the vehicle along the line to feed the right segments under the mover. Combining the segment number with additional voltage measurement, the position of the vehicle can be defined with a precision of ±5cm.

This information can be used by the signalling system, for example to define which section of the line is occupied or not. The linear motor can be used to integrate the existing signalling system installed on the track as track circuit and balise, which may not be compatible with the linear motor as explained in the paragraphs 10.3 and 16.5.

The linear motor implements the normal braking system of the MDS vehicle. Normal braking is done in the same manner as normal acceleration, so as the braking request from operator/signalling system has been sent, the braking curve implemented in the TMS is translated to change of frequency which in synchronous motor reflects the speed. The vehicle stops as the synchronous frequency reaches 0 Hz.

Since the linear motor is not meant to be safety critical component, the emergency braking of the MDS vehicle will be performed by an independent braking system installed on the vehicle, like to electromagnetic braking system or eddy braking system:

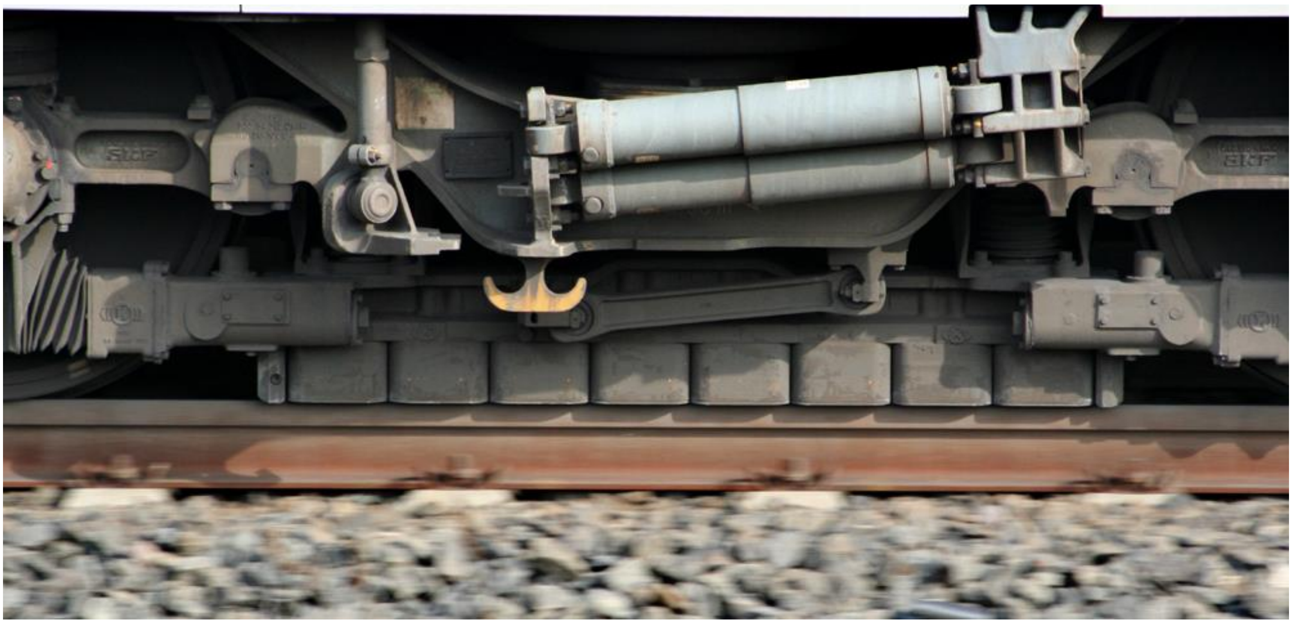


Figure 19 Example of linear eddy current brake

In case of total loss of power from linear motor, the vehicle will be equipped with a standard coupler to be towed by another vehicle. The coupler will be also used to move the vehicle in the depot and maintenance area.

9 Propulsion and braking (U-LIM Asynchronous Motor)

9.1 Functions and technical parameters

The vehicle propulsion function, including both acceleration and deceleration (during regular operations and emergency), is performed by a linear propulsion system. Linear induction motor with U shaped armature (U-LIM) consists of power electronics systems that supply electrical energy, for operational traction/braking function, at variable frequency and voltage thanks to PWM inverter, including a low voltage DC power supply circuit with a reliable energy storage system for emergency braking. The traction braking assembly will include at least two completely independent systems to ensure degraded operation in the event of a failure.

This specific LIM includes two parts, one is the three-phase inductor embedded on the vehicle, second is the passive armature fixed on the track. Considering the U-LIM, the armature is designed with a U shape. The U-shaped armature is made of a sheet of steel 10 to 20mm thick, co-laminated with a thin layer of copper or aluminium 1 to 3mm thick.

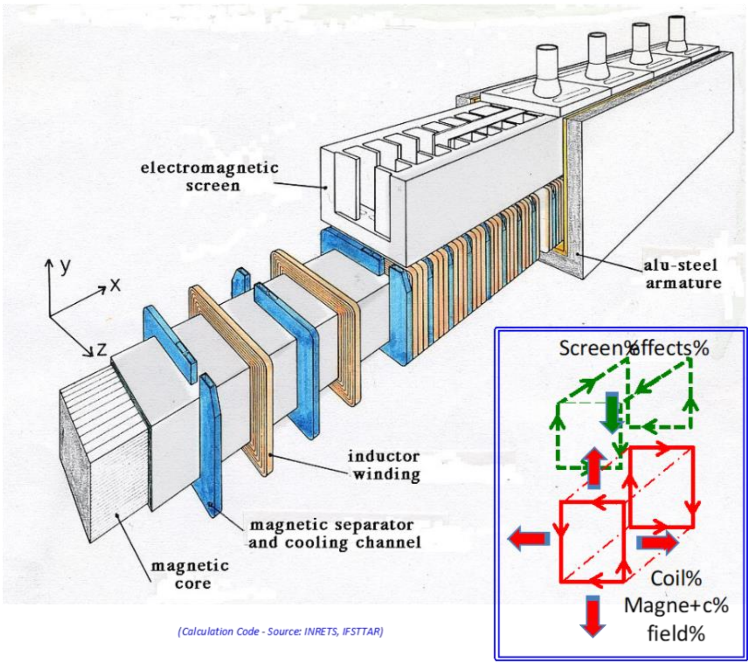


Figure 20 U-LIM - Linear Induction Motor with U shaped armature

This type of linear motor proposed for the applications defined in the use cases is an asynchronous linear motor embedded on the vehicle reacting with U shape armature fixed on the track.

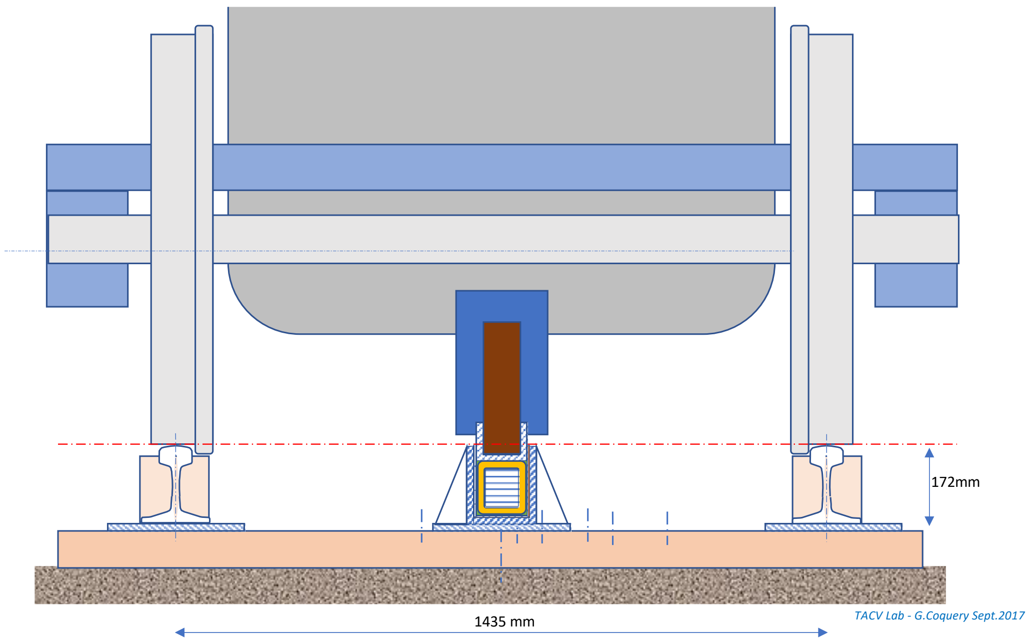


Figure 21 U-LIM – Interface vehicle track

The power converter delivers a three phases power supply at variable frequency from 0 to 100 Hz in order to control the vehicle speed. On the infrastructure side, a U-shaped armature is fixed on the sleepers which consists of a simple colaminated steel/copper profile (or steel/aluminium). The steel sheet allows to drive the magnetic flux, the conductive sheet allows the circulation.

The U-shaped armature allows to reduce drastically the generation of vertical and lateral parasitic forces.

The linear propulsion parameters defined to meet the operational requirements of the use-case 3 (Ref. §5.1.3) are listed in the next table.

Parameter	Value	Unit
Embedded Inductor (number x L x W x H, Weight)	2 x 3 x 0.15 x 0.25 (1200kg)	m
U-shaped armature on track (H x W X L)	0.26 x 0.21 x 12 (or 16)	m
Stator windings nominal voltage Pulsed air coil cooling technology	2000	Vrms

Parameter	Value	Unit
Peak acceleration force (design point) (requested 0,75m/s2 x 43 600 + Faero + Fslope = 32,7kN min.)	36kN	kN
Peak power (design point 90km/h) Compact PWM inverter IGBT or MOSFET-SiC techno.) Used for traction and regenerative braking	1800 (P.line) at ±200km/h 2500 (S.inverter)	kW kVA
Emergency Braking Force by using DC current injection with supercapacitor energy storage system. (requested 2.5m/s2 x 43 600 – Faero + Fslope = 109kN min.)	About 100kN max, Data Fbrake: f(V)	KN
Weight of U armature to be installed on the track Weight part of colaminated copper (or alu.)	103150 8820	Kg/km

Table 8 U-LIM - Basic linear propulsion parameters

This solution doesn't foresee the use of rare earth or magnet.

TACV Lab has pre-designed a U-LIM for the use case 3 and defined it with the characteristics illustrated by the next curves.

This design might be optimized for the geometric profile line taking into account the allowed speed and the time-schedule of the travel.

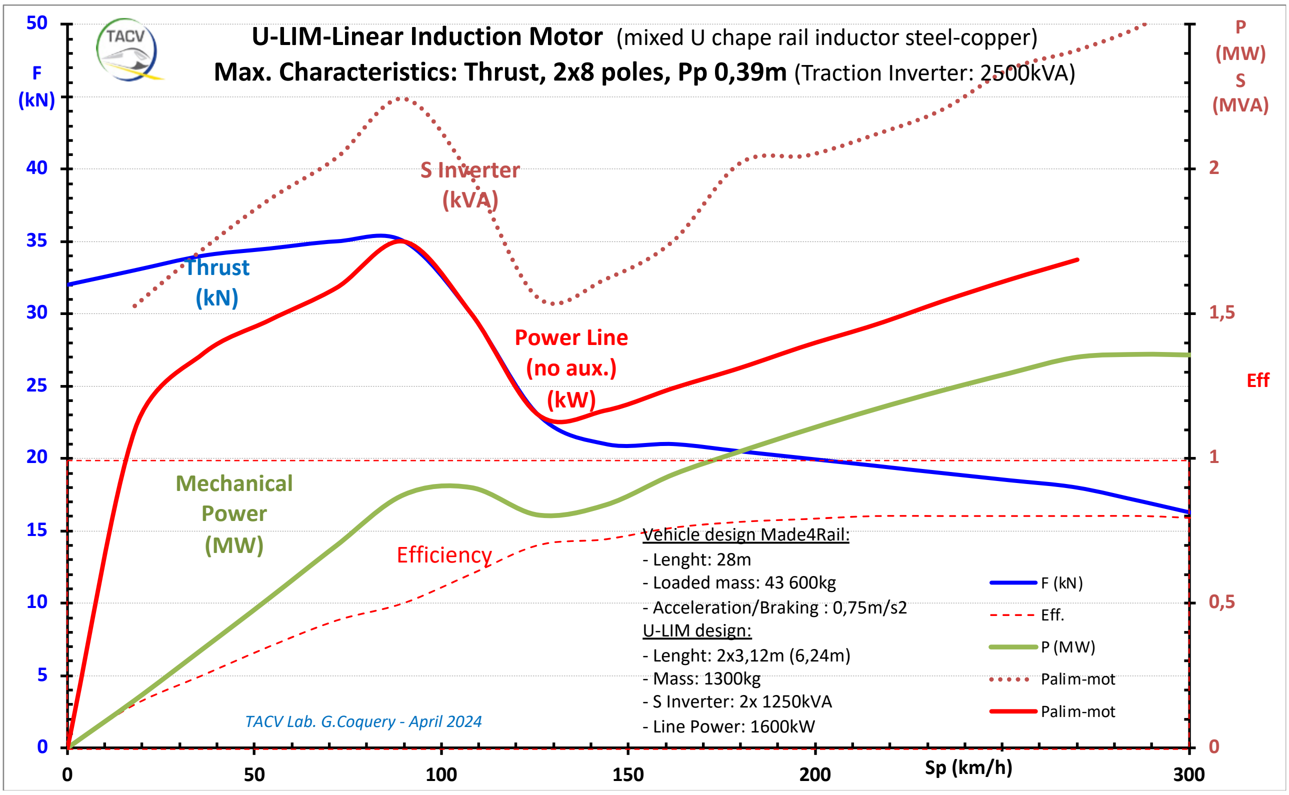


Figure 22 U-LIM characteristics for the use case 3 (Source TACV-Lab)

The previous curves show the maximum envelope of the thrust, efficiency and sizing power curves of the traction inverters. The maximum power requested on the power line is then 1800 kW for a voltage of 1500V DC.

Each U-LIM unit is powered by an on-board vehicle inverter of the PWM type with variable frequency from 5 to 80Hz for a speed of 200kmh.

9.2 Mode of operation

As reported above, the active part of the linear motor is installed on board the MDS vehicle and fixed under the coach.

The power supply to feed the ULIM will be taken from the catenary system using a standard pantograph, the voltage of 1.5 kV DC of the railway lines would make it possible to use converters with standard semiconductors, SiC technology is proposed for the greatest compactness of the systems.

The power requested is limited to about 1800 kW. If it is accepted by the catenary line, U-LIM can be controlled in the braking regenerative mode.

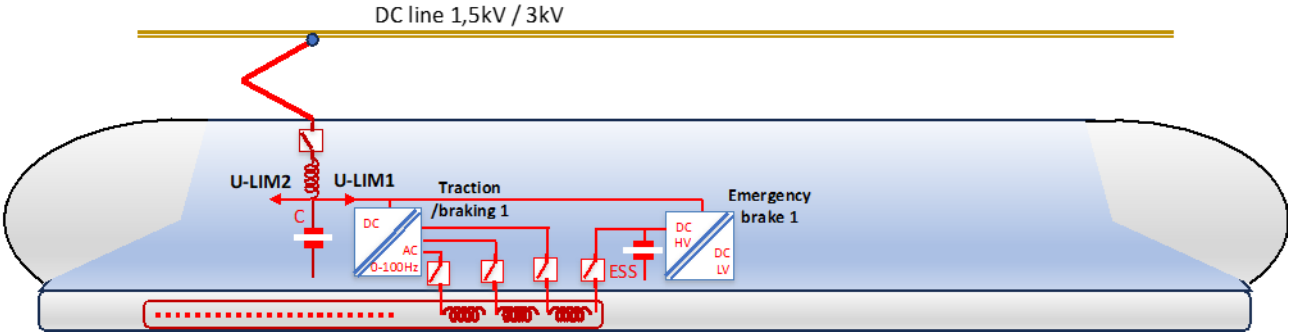


Figure 23 U-LIM - Traction/braking system on board of the vehicle (Source TACV-Lab)

The power supply taken from the catenary (3kV DC for the line of the use case 3) will be converted by three phases inverters in 2kV RMS with frequency variable between 5-100Hz to supply the three-phase inductor embedded on the vehicle.

It can be used also on AC line 25kV-50Hz and 15kV-16.7Hz. In this case, it is necessary to install on board at least one transformer and one rectifier controlled by PWM to reduce the reactive power. This solution makes the onboard electrical system heavier, which is not optimized for levitation vehicles. A new solution under study tested since few years consists of using a higher frequency than 16.7Hz and 50Hz transformer to get a lighter system. It seems now possible with the new generation of power semiconductors.

The variable current in the three-phase inductors generates an electromagnetic field which interacts with the U-shape armature on the track to create the propulsion of the vehicle.

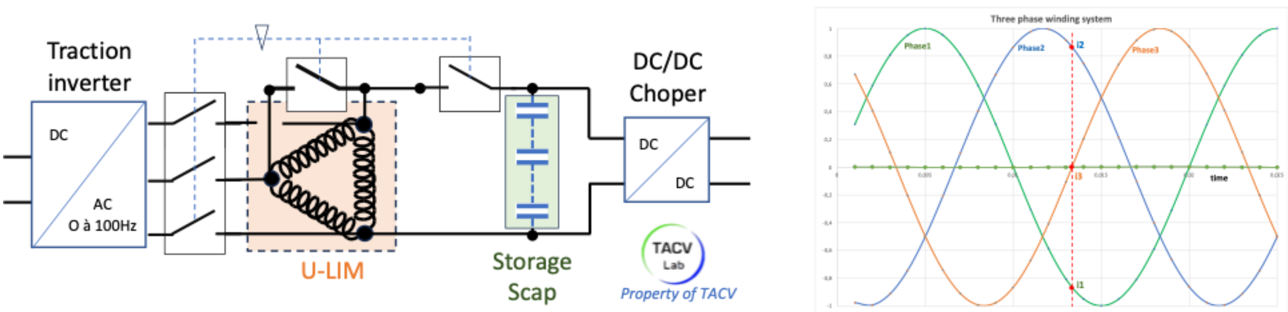


Figure 24 Simplified electrical diagram of the power system in traction mode and regenerative braking, and emergency braking mode by direct current injection by means of an independent stored energy system by supercapacitors (example for 3 phases Δ connection).

The U-LIM system offers a very high level of security:

- regarding traction and regenerative braking, the system is made of two completely independent circuits. This allows redundancy, offering degraded operation with two possibilities: either the end of the transport mission at reduced speed, or reaching a safety point for travelers.
- considering emergency braking, the direct current injection braking mode offers extremely powerful and very reliable braking. The electrical circuit is completely independent of the traction chain and energy capture by the catenary, it integrates a low-voltage energy storage module by supercapacitor which requires very little maintenance.

Due to the very high braking force during the emergency brake using DC injection, research works were done to establish the parasitic forces applied to the track and/or the levitation systems.

The next figure presents a synthesis of these studies which are in the frame of TACV Lab competences.

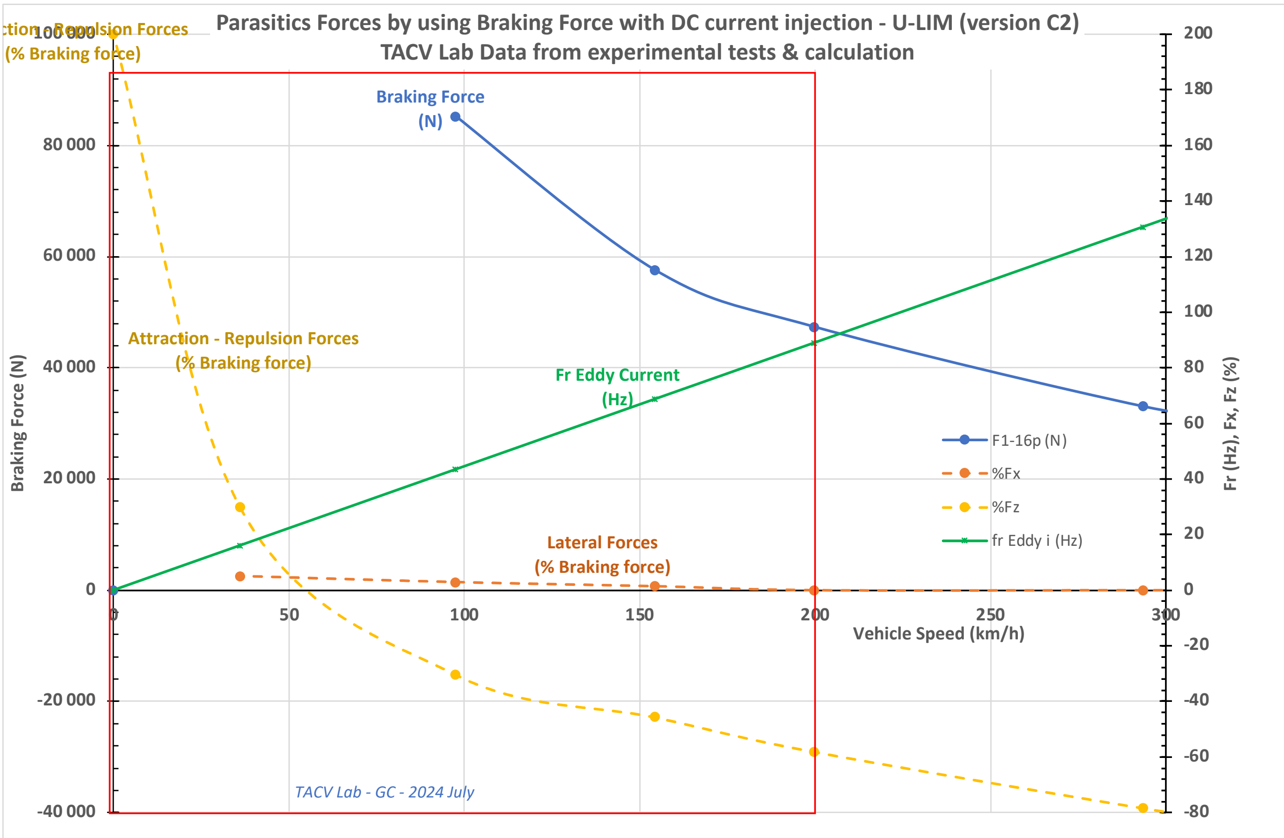


Figure 25 U-LIM – Parasitic Forces by using Braking Force with DC Current injection (Source TACV-Lab)

Considering the curves in Figure 25, the blue curve shows the maximum braking forces delivered using the DC powered U-LIM with appropriate connection of the phase windings (see the previous electrical diagram).

The dotted line curves show the maximum values of the parasitic forces with the maximum DC injection current authorized by the windings:

- the orange curve indicates the lateral forces which can influence the guidance, we see that the impact is very low, the U shape contributes to the cancellation of the forces (right and left),
- the red curve indicates the vertical parasitic force, we see that this parasitic force to the braking effort is a repulsive force at high speed which decreases with the reduction in speed, to cancel itself out (around 60km/h in the example), to become a very high attractive force at very low speed.

This characteristic can be kept to stabilize the vehicle on the track and complete braking on appropriate “landing” pads, or to stop the vehicle using a parking brake system. However, the parasitic force Fz, of repulsion at high speed and attraction at low speed, will influence the lift forces in the case of a MAGLEV system. Of course, it is possible to regulate this DC current for a correct braking force by reducing the parasitic force of attraction.

10 Signalling concept

10.1 Introduction

This chapter aims to highlight the implications for the signalling system due to the introduction of the MDS. After a short description of the existing signalling system, a concept of the signalling system is defined to ensure the interoperability between conventional and MDS vehicles on the same line and applicable to the use case 3.

The main goal is to ensure, where feasible, that the ETCS/ERTMS system which is currently under deployment in all countries can be used as signalling system on the line with mixed traffic (conventional and MDS vehicle).

10.2 Existing signaling system

The CCS system in Europe is based on the ETCS system. Control, Command and Signalling (CCS), refers to the on-board and trackside (or wayside) facilities and equipment designed to ensure the safe operation and movement of trains, direct rail traffic and keep trains away from each other.

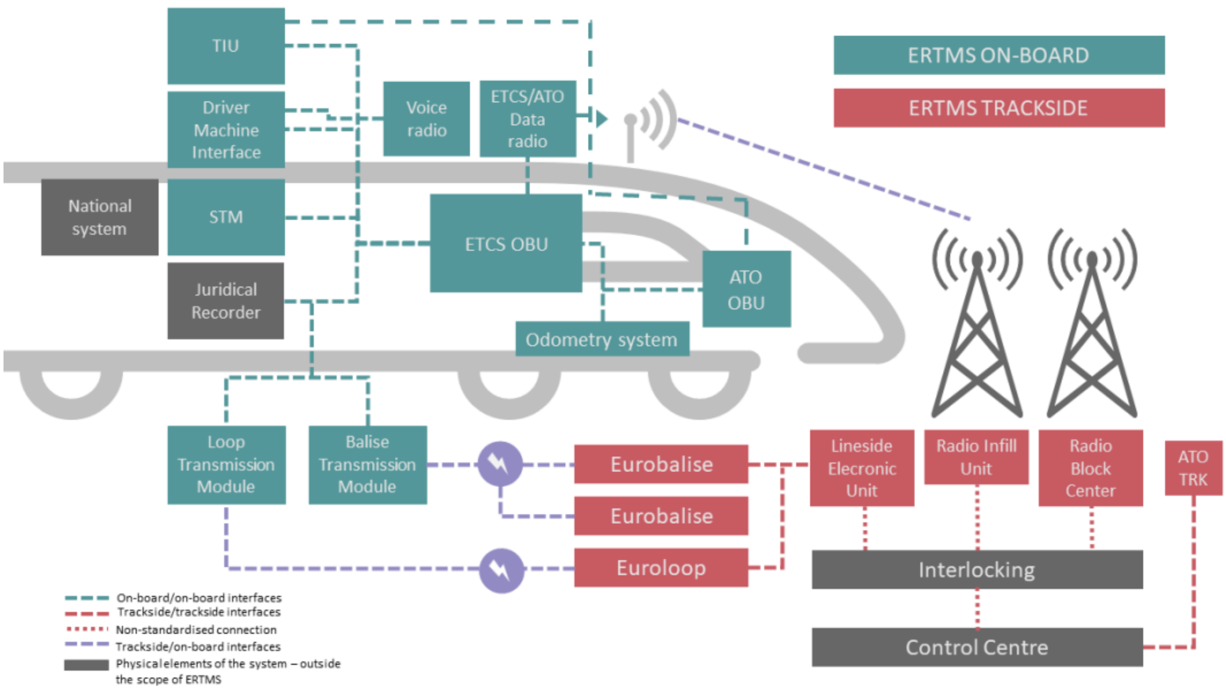


Figure 26 ERTMS Architecture (Ref. [52])

The Traffic Management System (TMS) is an integrated real-time system that offers monitoring and control of train movements. TMS imports the status of signals, track circuits, points, etc. from the station interlocking system in real time. The TMS implements the current timetable by promptly requesting the assignment of the appropriate section of track. Starting from these generic definitions it is necessary to address how systems designed mainly for the conventional vehicle can also be used in the management of MDS vehicle.

The first consideration is that these systems are composed of two main families of systems that interact with each other. These are the wayside systems and the on-board systems. The exchange of information between these systems takes place via specific radio channels, currently managed by systems related to GSM-R, but in the near future FRMCS (Future Railway Mobile Communication System) will be deployed.

Currently, the main wayside systems are:

- Interlocking with its field devices, which safely manages the configuration of the line, manages the status of the switches, detects the occupation status of the track by the rolling stocks and pilots the light signals when present.
- RBC (Radio Block Center) which receives information from the interlocking on the status of the line and via radio the information from the connected rolling stocks, safely defines their distance.
- TMS which defines the route and priorities of the trains circulating in the area of its competence. In the event of disturbances, it has the task of resolving the conflicts that arise to make the movement of trains as fluid as possible.
- The Eurobalise system that is known as a punctual communication device. It is a transponder system. The Engine is equipped with a transmitting system that wakes up the balises on the track with a transmission at 27.095 MHz. The balise is then able to send the relevant information at 4.234 MHz to the train. Innovative concept for balise using Ultra Wide Band communication have been also proposed in the literature and could be of great interest in the case of electromagnetic compatibility problems due to MDS technology (Ref. [31]).
- In the very near future, there are already applications on some lines, there will be a predominant introduction of ATO (Automatic Train Operation) systems which, as regards wayside systems, collect the information coming from the TMS and the RBC to make it increasingly fluid and the movement of trains along the lines of competence is repeatable. The wayside ATO component sends the running information to all the systems connected

on board the train and receives from them at least the indication of the position and instant speed of each train.

For the counterpart of the CCS installed on board the main actors are:

- The EVC (European Vital Computer) which interacts directly with RBC and receives authorization from it to move along the line. The EVC uses the EUROBALISEs installed along the tracks to have a unique reference along the line and communicate it to the RBC which controls the movement of all trains. The EVC has the task of creating the braking curves to respect the speed limits and stopping points imposed by RBC. The TCMS (Train Control Management System) has the responsibility of managing the rolling stock regarding the traction parts and for other operational functions such as the management of door openings. It interacts with the on-board EVC and ATO. The on-board ATO, which currently optimizes energy consumption, and the implementation of braking curves supervised by the EVC system. ATO interacts with the TCMS for the management of rolling stock and with EVC for aspects related to signalling. In the future ATO will include further automation functions up to GoA4 which provides for the complete absence of a driver in the cab. The Wayside and On-Board systems exchange by radio communications vital and non-vital information. Currently, the target is to introduce the MDS vehicle over an existing ETCS Level 2 Signalling System.

10.3 Signalling concept for mixed traffic operation

The purpose of this section is to highlight, regardless of the specific MDS technology used, which signalling system based on ETCS Level 2 solution could be better adopted in the scenario of mixed traffic where traditional trains and MDS vehicles are present at the same time on the line.

The following aspects shall be considered in the definition of the signalling concept for mixed traffic with MDS vehicle:

- The signalling system shall be resistant to EM interference introduced by MDS technology.
- MDS vehicle based on levitation cannot be detected by the existing track detection system as axle counter or track circuit. A new solution shall be foreseen to detect the passage of a MDS vehicle and declare a section of the line occupied or not.

The concept of the signalling system for a mixed line starts from the assumption that existing ERTMS system can be used at least by conventional vehicles. This assumption is not obvious because the effects on the ERTMS system due to the introduction of the MDS technology must be deeply studied. However, to reduce the impacts on the existing infrastructure due to the introduction of MDS technology, solutions aiming to conserve the ERTMS system are preferable.

As described in chapter 16, the introduction of MDS technology impacts the signalling components installed on the track such as balises and train detection system.

Some solutions are proposed in the following paragraphs to ensure mixed traffic operation and identify alternative solutions to balises and train detection system for MDS vehicle. Even if these two systems are not going to be used for MDS vehicle, the objective is to find alternative solutions that minimize the impact on the other components of the signalling system as RBC and interlocking.

10.3.1 Balise

If proved that the existing balises continue to work properly with MDS technology, they can be used by MDS vehicle. In this scenario, the MDS vehicle shall be equipped with a Balise Transmission Module.

However, due to EM field generated by the linear motor during the passage of the vehicle over the balise, there are high chances that they will not work.

In this scenario, other solutions shall be studied to allow the mixed traffic operation. The following options are proposed:

1. New balises are introduced for conventional and MDS vehicle. This option aims to develop a new type of balise that can be used by conventional and MDS vehicles. This solution has:
   - The advantage that conventional and MDS vehicles will use the same technology.
   - The disadvantage that infrastructure and conventional vehicles must be upgraded to operate with the new type of balise. The time needed for consolidate the solution of these new balises could be greater.
2. Existing balises are used for conventional vehicles and virtual balises are used for MDS vehicle. The 'virtual balise' concept has been under development and consists of providing positioning information to the train by means of GNSS signals, instead of the physical balises required by ERTMS, as proposed in the ETCS Level 2 with moving block concept.
   For this purpose, the onboard equipment will consist of a new module called Virtual Balise Reader (VBR) where will be preloaded the list of virtual balises and their position corresponding to the position of the physical balises used by conventional vehicle. This module will process the GNSS signals and compare the GNSS coordinates with the list of coordinates of the balises preloaded.

When the Virtual Balise Reader recognises that the vehicle is in the precise point where a real balise is installed, it will use the position of the vehicle to send to the EVC the telegram of the corresponding virtual balise stored in the memory.
This solution avoids the introduction of new hardware along the line, however it requires to know the position of the vehicle along the line. This information can be obtained with adequate reception of the GNSS signal or taking advantage of the introduction of the linear motor from which the position of the vehicle can be derived knowing the segment active along the line (Only for LSM solution, ref. §8).
The virtual balises must be triggered when the train is in the same position as the corresponding real Eurobalise.

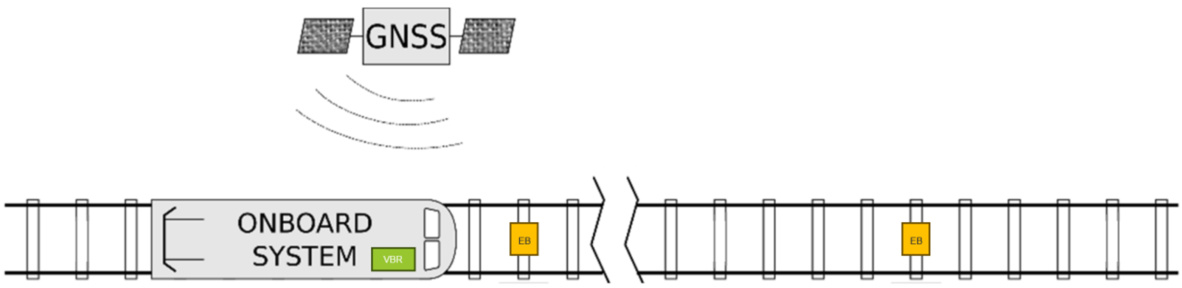


Figure 27 Virtual Balise (Ref. [53])

This "dualism" certainly has a non-negligible impact on existing Interlocking and RBC systems.
On the interlocking side, the field devices must be able to recognize that an MDS vehicle has activated a linear motor segment and in which section of the line. At the same time the track circuit are used for checking the presence of the conventional train when no MDS trains are in that area.
It is clear that, there can be no situation where a section is considered to be in use when it is not, or, even worse, where a section is actually in use and is not recognised by the system.

10.3.2 Train Detection System

The Train Detection System detects if a section of the track is currently occupied by a train and provides that information to the train control system.

Train Detection System is currently realized using axle counters or track circuits.

- An axle counter is a system used to detect the clear or occupied status of a section of track between two points. The system generally consists of a wheel sensor (one for each end of the section) and an evaluation unit for counting the axles of the train both into and out of the section.
- A track circuit is an electrical device used to prove the absence of a train. The passage of the train above the system generates a short circuit between wheels and rails.

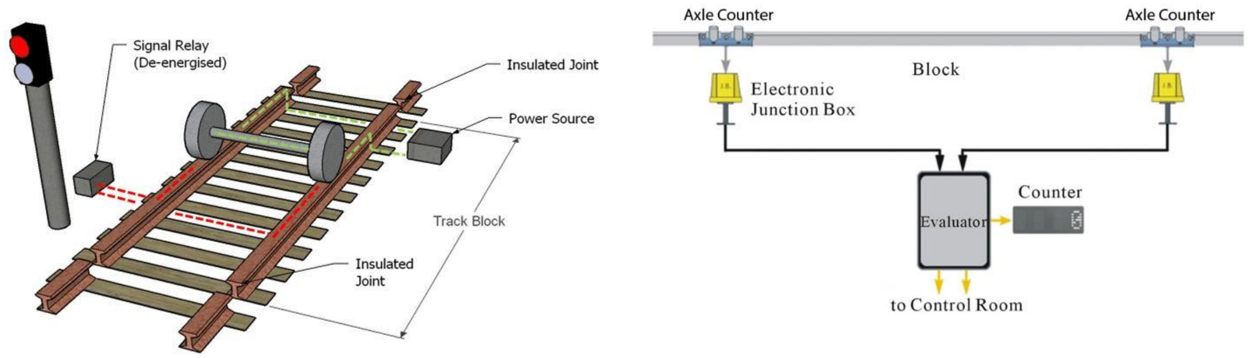


Figure 28 Train Detection System: Track Circuit and Axle Counter (Ref. [54], [55])

The existing train detection systems such as axle counters and track circuits can't operate with MDS vehicle based on levitation:

- The axle counter presents a physical interface (encroachment) with the magnetic sliders allowing the levitation and guidance of the vehicle on the existing rail. For this reason, the use of the axle counter can't be considered in line with mixed traffic (Ref. Figure 73).
- The operation of the track circuit is based on the contact between wheels and rails to create a short circuit and detect the passage of the trains. They may still be used for conventional vehicles if they are not affected by the EM field generated by linear motor and magnetic sliders.

  However, the passage of MDS vehicles can't be detected by the track circuits due to the missing contact between the magnetic sliders and rails. It must also be verified whether the effects of the electromagnetic field produced by the vehicle towards the track circuits produce side effects.

For this reason, a new solution shall be developed for the detection of the MDS vehicle.

The solutions proposed are the following:

1. If detection of conventional vehicle can be done with the existing track circuit, a new system shall be developed to detect MDS vehicle along the track.
   A first option is to use the linear motor to detect the position of the vehicle along the line and consequently define which section of the line is occupied by the MDS vehicle. Solutions based on this concept are already considered in pure magnetic levitation systems (Ref. [27]).
   With the use of the LSM, the position of the MDS vehicle along the line can be given by the position of the linear motor segment active.
   More precise solution can be studied to evaluate the position of the MDS vehicle based on the current in the linear synchronous motor.
   This solution must ensure that the information provided by the linear motor and the track circuit are aligned. This information will then be provided to the interlocking.
2. Develop a new train detection system that can be used for detection of conventional and MDS vehicle. This solution has the advantage to use the same technology for both vehicles, however, it requires an upgrade of the existing infrastructure.

10.3.3 Wayside Signalling Upgrade for MDS Vehicle

Considering that MDS technology requires the introduction of new signalling solutions on the track side for MDS vehicle, these modifications impact the existing central signalling system which shall be upgraded to manage at the same time MDS and conventional vehicles.

The modifications required depend on the solution adopted on the track side (Ref. §10.3.1, §0).

The interlocking must be modified to deduce the presence of a train in a given section, taking the information from one of the two systems depending on the type of train occupying it:

- If it is a conventional vehicle this information is obtained from the track circuit.
- If it is an MDS vehicle this information can be obtained from the newly introduced system, for example the active segment of the linear motor indicating whether the train is present in the section.

The section must be declared occupied if at least one system is detecting a presence of a vehicle. Using two different systems to detect the track occupancy has an impact on the availability, as the number of components and failure increases. The status of the sections, as it is currently done, would be sent to RBC.

On the RBC side, the management of the virtual balises should be added, which will correspond to the physical EUROBALISE ones. In any case the RBC will have to know whether it is a physical or a virtual balise, so a double management will have to be implemented. It doesn't currently exist in the RBC.

10.3.4 On-Board Signalling Upgrade for MDS Vehicle

With the assumption that ERTMS system can be kept as it is for conventional vehicle, no changes are foreseen on the signalling system of conventional vehicle.

For MDS vehicles, instead of the BTM, a Virtual Balise Reader (VBR) may be foreseen on board to replace the functionality of the physical balise. VBR will have preloaded the list of virtual balises and their position. As reported above, the position of the virtual balises correspond to the position of the physical balises used by conventional vehicles.

The VBR can use the information of the position given by GSNN or by the linear motor to recognise on which section of the track the MDS vehicle is.

When the VBR recognises that the vehicle is in the precise point where a real balise is installed, it will use the position of the vehicle to send to the EVC the telegram of the corresponding virtual balise stored in the memory.

This aspect has a major impact on safety, because a new function is needed to recognise on which segment of the linear motor the MDS vehicle is, and then linking this information to the map that will be on board the MDS vehicle defining the position of the virtual balises.

On the other hand, this is a major innovation which, once the solution is found, would make the MDS system extremely reliable.

In the context of virtual coupling, it is essential to guarantee the secure exchange of position and speed data between trains. To this end, the TDS must be modified to meet these requirements. Therefore, we must consider new communication technologies that offer this functionality, enabling direct communication between vehicles with high data rates and low latency, thus requiring FRMCS.

Virtual coupling needs train-to-train (T2T) communication for sharing information between the different train units and receiving the reference signals from the infrastructure. According to this information, the onboard system is responsible for the safe tracking of the speed profiles, and it should also respect the spacing policy between trains and allow the follower to safely follow the lead train.

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.

In conclusion, following the approach described above, functional requirements must be derived for the sensors and communication systems for virtual coupling. Sensors are needed to determine the absolute position, relative position (or distance) between trains, relative and absolute velocities, and acceleration. Regarding communication, it is necessary to define how often this information must be exchanged between trains, as well as the type of information and the amount of data.

10.4 Train Management System

According to the scenario described in the D4.1 (Ref. [17]), the operation of the MDS vehicle shall be performed at least in GoA3.

In any case, MDS vehicles will be equipped with driver panels connected to the signalling system for the manual operation of the vehicle. It will be mainly used in stations and depot for maintenance.

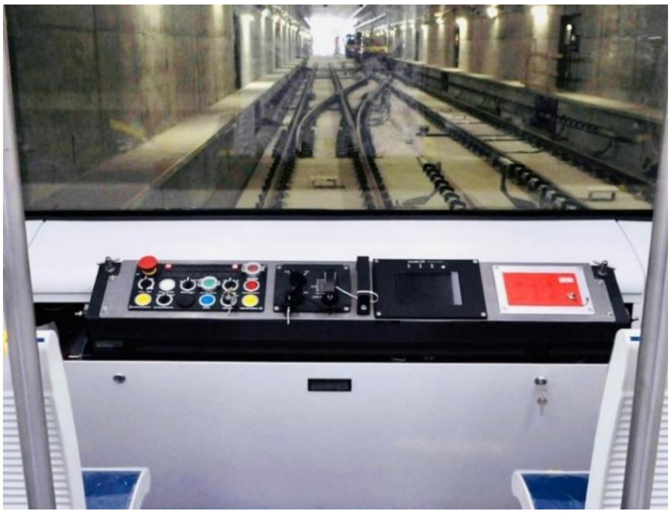


Figure 29 MDS Vehicle - Driver panel (Example from metro vehicle, Ref. [56])

11 Communication concept

11.1 Railway communication systems

Communication between railway vehicle and wayside system are ensured by radio communication systems which can provide three types of communications:

- safety-related services to support train movement,
- non-safety related operational services, and
- internet access by onboard passengers.

Radio communications ensure safer movements of trains at higher speeds with increased passenger capacity, a better quality of services, and a reduced number of trackside equipment. Radio communication systems are a key component of rail and metro control systems for several decades.

In the rail domain, ETCS system has been introduced for European high-speed lines since the end of the 90s. It relies on two main components: the radio system GSM-R and the ERTMS balises also based on wireless transmissions at low frequencies.

The GSM-R is based on GSM phase 2+ cellular standard. A specific short frequency band is allocated for Rail in Europe in the 900 MHz band (876-880 MHz and 921-925 MHz). It is deployed on 150,000 km of railway lines where only 23,000 km are high speed line (HSL).

The main components of GSM-R are the Network part composed by the Mobile Switching Center and the Radio Base Station deployed along the tracks

Railway vehicles are equipped with GSM-R radio to communicate with the wayside equipment.

The architecture is similar to the classical GSM phase 2+ and provide some additional features, called advanced speech call items, such as group calls, broadcasting of calls, pre-emption of channels and priorities.

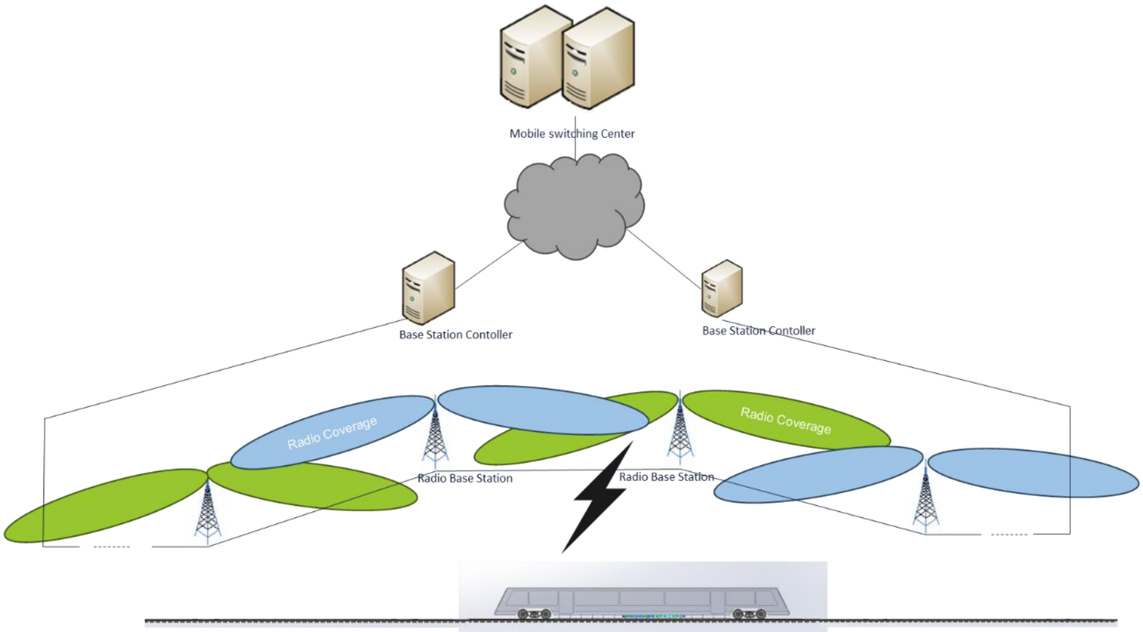


Figure 30 Wayside Radio Communication System – GSM-R Architecture

GSM-R will become obsolete in 2030 and the Future Railway Mobile Communication System (FRMCS) based on 5G NR standard is under development at European level to answer the railway needs in terms of services, quality of services, data rate, low latency, etc. (Ref. [31], [33]).

It will be IP based, multi-bearer and resilient to technology evolution and interference. It has the ambition to bring bearer flexibility to the railway telecommunication essential services using the capabilities of 5G NR standard. It will be the system that will offer a full migration towards 5G for the railway industry. The 5G based FRMCS system will replace GSM-R in the ETCS system. The allocated bands at European level known as RMR bands are 2 x 4 MHz as GSM-R bands and 10 MHz in TDD in the 1900 MHz band. As part of 5G NR standard, the millimetric Waves band from 34 to 70 GHz is also investigated in various projects (Ref. [34]) as well as the complementarity between FRMCS and LEO Satellites systems (Ref. [36]).

The architecture of the FRMCS remains similar to GSM-R, however the Radio Base Station will be upgraded with 5G transceiver to allow the 5G communication. The modification is required on the railway vehicle where GSM-R radio will be replaced by FRMCS radio.

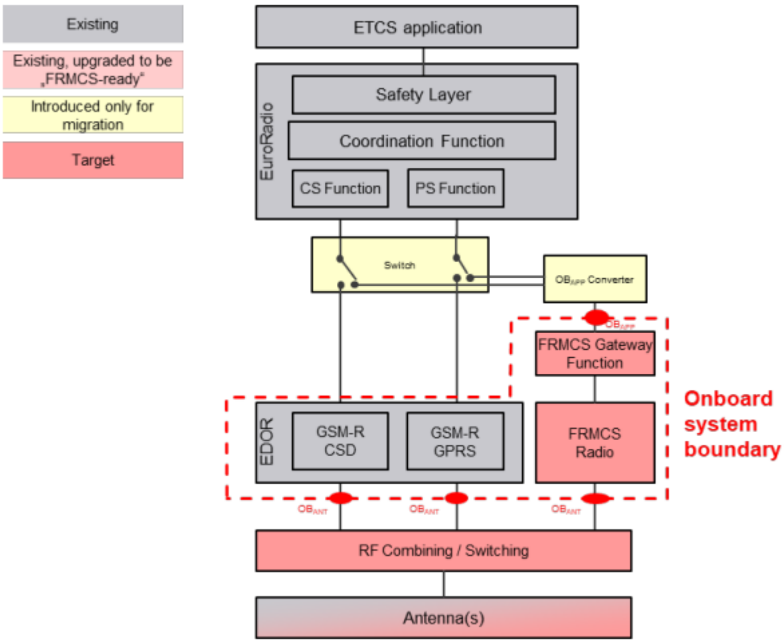


Figure 31 Vehicle Radio Communication System: Migration from GSM-R to FRMCS (Ref. [57])

Table 9 recaps the main physical layer characteristics of GSM-R and 5G-R (FRMCS).

Parameter	GSM-R	5G-R (FRMCS)
Frequency	Uplink: 876 – 880 MHz Downlink: 921 – 932 MHz	1.9 GHz
Bandwidth	0.2 MHz	≥ 100 MHz
Modulation	GSMK	16- QAM/OFDM/NOMA
Cell Range	8 km	1.5 – 5 km
Peak Data Rate, Downlink, Uplink	172/172 Kbps	20/10 Gbps
Peak Spectral Efficiency	0.33 bps/Hz	20 bps/Hz
Latency	400 ms	≤ 1 ms
Mobility	Max. 300 km/h	Max. 500 km/h

Table 9 System Parameters: GSM-R vs FRMCS

For metro and mass transit applications, radio communication systems known as CBTC (Communication Based Train Control systems) are also considered since several decades and driverless systems rely on CBTC. Systems based on IEEE 802.11 Wi-Fi has been developed by major industry players (Alstom, Thalès, Siemens, etc.) as the radio technology for CBTC (Ref. [37]). There is not yet European standards for these systems. Industry refers generally to IEEE 1474 standard (Ref. [38], [39]). The frequency band considered is the ISM band. Metro operators have requested at European level the allocation of a specific band in the band allocated for safety in the ITS band: 5.8 GHz.

These systems may be used in case of MDS application in urban environment. For the use case under analysis the FRMCS is considered as radio communication system for the implementation of the MDS technology. The time needed for the development of the MDS technology (about 10 years) will allow the deployment of the FRMCS along the existing line to replace the GSM-R.

In addition to the vehicle wayside communication, vehicle to vehicle communication is required to implement the virtual coupling as described in the D6.1 (Ref. [19]).

The coupling of two trains will be composed of three logical phases: "approaching phase", "final approaching phase" and "virtual train phase" (Ref. [19]) These phases imply the combination of train-to-infrastructure and train-to-train data exchanges. One train will be defined as the master and the other ones as the slaves. Virtual coupling of trains implies the connection of the embedded communication networks. Indeed, the wireless communications between the two vehicles must be able to offer very high data rate with very high reliability and low latency.

Several technologies have been envisaged and evaluated such as ITS-G5, LTE, 5G and millimetric waves (Ref. [40], [41], [42], [43], [44], [45]). No choice has been yet made within the EU-Rail Projects program (X2RAIL-3 project from Shift2Rail JU) and many technical challenges remain to be solved. In the FRMCS functional specifications, the case of virtual coupling of trains is considered. 5G NR can answer the needs in terms of data rate, reliability (Ref. [46]). The 5G device to device communication standard can be considered when available. The combination of two technologies to answer the needs of long range and short-range communication is also considered. Research is ongoing on this topic in IAM4RAIL project (Ref. [47]).

11.2 Vehicle communication system design

The communication system of the MDS vehicle is considered to be similar to the system installed on conventional vehicle, except that the communication onboard - wayside will be performed with FRMCS technology.

However, in addition to the vehicle-wayside radio link, to allow the virtual coupling, as described in the chapter 10, the MDS vehicles inside the same platoon require point to point communication between them. The point-to-point communication between vehicles is currently being developed. For the MDS vehicle prototype, a dedicated radio has been considered to allow point to point communication between vehicles. However, it may not be needed if the communication among vehicle may be performed using the FRMCS radio.

The MDS Vehicle communication system is composed by two subsystems:

- on board fibre communication system
- on board radio communication system

The fibre optic network allows to guarantee the communication among all subsystems installed on board and the radio communication systems.

The on-board radio communication system is mainly composed by the FRMCS radio and antenna. They ensure the communication between on-board and wayside systems.

As reported in the previous, the communication can be split in:

- safety-related services to support train movement,
- non-safety related operational services, and
- internet access by onboard passengers.

A common solution for the implementation of the vehicle communication system is the segregation of the data between safety and non-safety related. The main goal of data segregation is to enhance the security and privacy of the data by limiting access to it.

Using this approach, different on-board fibre communication system can be foreseen based on the type of data to be transported.

Another aspect to consider in the design of the communication system is its availability. This point is crucial in driverless system where the movement of the vehicle is based on the availability of the communication system. For this reason, two solutions are envisioned for the MDS vehicle:

- Fibre communication system architecture based on ring topology
- Redundant radio communication system.

Based on the consideration above, the topology of the communication system of the MDS vehicle is shown in Figure 32:

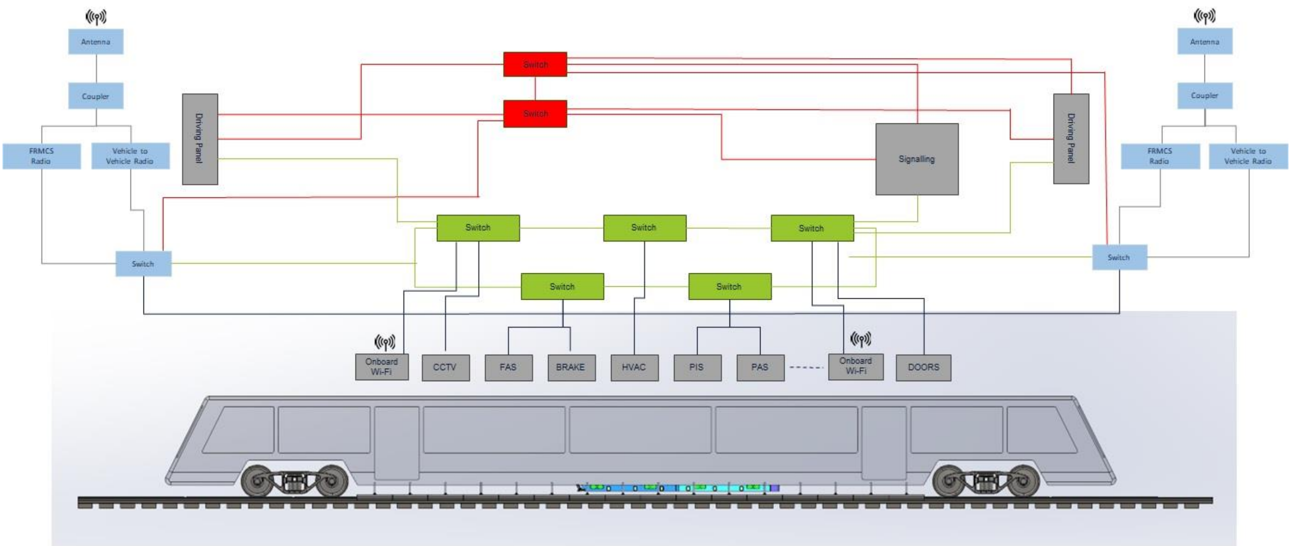


Figure 32 MDS Vehicle - Communication System Architecture

The communication system of the MDS vehicle is composed by:

- On board fibre communication system for critical communication, in red. This system allows the communication of the signalling components and the transmission of the safety critical data.
- On board fibre communication system for non-critical communication, in green. This system allows the communication of all on board systems.

For both systems a ring topology network has been foreseen. This configuration is tolerant to single point of failure. If a failure occurs, the ring is open in two sections and the communications are guaranteed.

The switches are connected by optical fibre while the connection between the switches and different subsystems can be realized with optical fibre or copper cables. All communication will be based on ethernet protocol, except specific cases where different protocols are needed.

The number of switches will depend on the number of ports needed to connect all on board systems. Each system can be connected to one or more switches.

A network management system (NMS) shall be foreseen to manage the network, report the failures, reconfigure the network, provide statistics on network usage, etc.

The fibre communication system is connected to the radio communication system with redundant switches. The advantage of the FRMCS is that all data (signalling, voice, video, etc) can be transmitted over radio using the same protocol and taking advantage of the performance (throughput, low latency, etc) of the FRMCS.

Two radios in configuration Master-Slave are foreseen on the MDS vehicle to ensure the communication with the wayside systems. They will be installed on the opposite sides of the vehicle to avoid common cause failure.

A Wi-Fi system for passengers is also foreseen on-board.

12 Vehicle Auxiliary system

12.1 Introduction

The objective of this chapter is to provide a short description of the auxiliary systems needed for the MDS vehicle prototype. In general, the auxiliary systems required for the MDS Vehicle prototype are very similar to those installed in a conventional vehicle.

A short description of each system is reported in the following paragraphs.

12.2 HVAC system

The heating and ventilation system aims to provide a comfortable climate in the vehicle interior to achieve the following:

- comfortable temperature in the compartment.
- no draughts, no cold radiation, no condensation on interior surfaces and interior surfaces warm to the touch
- balanced ventilation and uniform air circulation with no hot or cold spots in the passenger area.
- adequate supply of fresh air at an acceptable temperature.

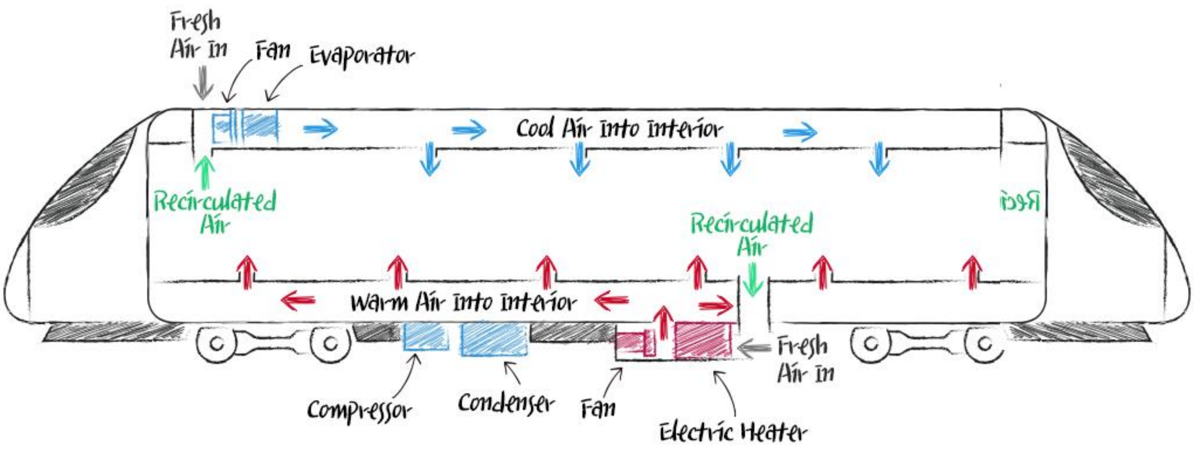


Figure 33 MDS Vehicle – Example of HVAC system from conventional train (Ref. [58])

The system is also used to ensure adequate environmental conditions such as temperature to the equipment.

The heating system shall have sufficient capacity to ensure a minimum air temperature of 20°C at an ambient temperature of 0° C at maximum vehicle speed. The inside temperature of each coach shall be adjustable automatically and manually using a control panel. The temperature shall be set to regulated automatically using temperature sensor and stay in a range of ± 1.5˚C of the reference temperature.

The system shall be designed to enable automatic pre-heating and pre-cooling of passenger compartments of a parked train before entry into service to be achieved in the shortest possible time. The temperature inside a parked train shall be controlled not to drop below 5˚C or dew point +3˚C, whichever is the higher.

The HVAC system shall provide positive pressurization up to at the maximum vehicle speed. The HVAC system shall include a pressure protection system to avoid sudden pressure variations within the coach and an efficient air filtration system for the fresh air intake with self-cleaning capabilities to evacuate dust and sand.

The MDS vehicle shall be equipped with redundant HVAC units.

The system shall provide emergency ventilation for at least 60 minutes in case of loss of the main power supply. Emergency ventilation shall be set at three (3) air changes per hour.

The HVAC system must be interfaced with the fire alarm system and automatically stop in case of fire to prevent natural migration of smoke and toxic fumes.

The HVAC system shall comply with EN 13129 for coaches. The MDS vehicle shall comply with the internal air quality requirements (CO2 levels) for passengers and staff defined in TSI 1302/2014 Section 4.2.5.8.

12.3 Vehicle Information system

All vehicles shall be equipped with an information system. The vehicle information system provides the following functions:

- Public Address
- Emergency call points
- Passenger Information

The Public Address is in charge of all internal communications in the vehicle. The main functions of the Public Address and Intercom system are:

a) To broadcast audio announcements from staff onboard or OCC to passengers. A Crew Intercom Panel installed on board the train, the staff onboard can transmit live announcements to passengers.
b) To broadcast pre-recorded announcements from the Passenger Information System. These messages can correspond to:
    - Route announcements,
    - Useful information (Mind the gap, beware of belongings, etc.),
    - Tourist information
c) To broadcast emergency alarms and warnings. In the presence of an event (handle activation, fire alarm) the system can broadcast acoustic signals in order to advice the train attendant, the crew members and the passengers. Events can be configured according to customer specifications.

To guarantee a high level of safety, different levels of priority are set to audio messages to guarantee no important or relevant information is missed.

Figure 34 MDS Vehicle – Example of emergency call point

Communication between passengers and OCC are performed with the emergency call points. One emergency call points will be foreseen close to each door. They can be also used for remote listening from OCC.

The passenger information system is composed by monitors, visible from all seats, which show general information to the passengers such as:

- Current train location
- Train stops
- Time
- Outside temperature
- Train number
- Train speed
- Remaining time to next station and to last station stop

Figure 35 MDS Vehicle – Example of passenger information system (Ref. [59])

The vehicle will be equipped also with exterior information display near each exterior door of each coach. The exterior information display is intended to show relevant information to the passengers to ease the access such as destination, departure time and intermediate stops.

The free height below the Passenger Information Displays (if installed in the ceiling) and measured in centre line of the vehicle shall be a minimum of 2100 mm.

12.4 CCTV

Cameras (Video surveillance system) shall be installed in the MDS vehicle and ensure the full coverage of the passenger compartment. CCTV system plays an important role in case of driverless system, since it supports remote operation from OCC to observe passengers' behaviour and support them in case of emergency.

On-board CCTV system will be composed by cameras over IP and on-board digital video recording equipment. The capacity of the equipment shall allow recording of the last 7 days of activity of all cameras at a rate of at least 25 pictures per second. The date, time and location of the camera shall be included in the pictures. Thanks to the introduction of the FRMCS, video streaming can be transmitted live to OCC operator (Ref. Figure 32).

12.5 Lighting system

The lighting system of the rolling stock is composed of the following sub-systems:

- Normal internal lighting aims to provide a lighting level for a comfortable journey for the passengers in the rolling stock.
- Emergency internal lighting aims to provide the minimal lighting conditions to guarantee the passengers' safety
- External lighting: aims mainly to provide sufficient lighting in the vicinity of the rolling stock for operational purposes (visibility for the driver, signal the direction of the train, lighten reflecting signals, …)

The emergency internal lighting and the external lighting will be fed by the emergency power supply system. Luminous guiding strips will be integrated within the interior to guide passengers towards doors in cases of reduced visibility caused by smoke or dust.

The number of luminaires will be defined to ensure that the illumination level in normal and emergency conditions fulfil the values requested by the standards.

It will be possible to automatically adjust the lighting level and the colour temperature in normal operation. Adjustment of lighting levels will be controlled during normal operation and varied by the time of day and stopping sequences. E.g. When a train is taken out of service light in the train is dimmed when arriving at the final platform to indicate that this is no longer a passenger carrying train.

The ends of the vehicle shall have white LED headlights and red LED taillights. These can be arranged in any formation such that they comply with the operational requirements.

Operational needs for lighting shall include capability for the visual inspection of the railway infrastructure. The external lighting shall be controlled from the driver cab.

The passenger lighting (normal and emergency) shall be compliant to standard EN 13272 (Ref. [10]). External lights shall be compliant with in TSI 1302/2014 Section 4.2.7.1 (External lights, ref. [7]) and standard EN 15153-1 (Ref. [12]).

12.6 Fire detection and alarm system

The fire detection aims to detect the ignition of fire on board the vehicle. Onboard fire detection is required by TSI LOC&PAS (Ref. [7] §4.2.10.3.2) to cover equipment and areas on rolling stock that intrinsically have a fire risk.

MDS vehicle will be equipped with smoke detectors in the passenger's compartment and the electrical cabinet. Smoke detection will be also foreseen within the ventilation air inlet ducts to detect smoke external to the vehicle.

When a fire is detected, an alarm shall be transmitted to OCC operator and the vehicle will be stopped when the vehicle reaches the appropriate stopping point. In addition, the following automatic actions shall be implemented:

- Activation of CCTV
- Activation of bidirectional communication with the local emergency call point
- Activation of the fire suppression system
- Deactivation of the ventilation to prevent natural migration of smoke and toxic fumes.

All railway vehicles shall be fitted with fire detectors in accordance with the requirements for category 2-A trains in EN 45545 (Ref. [14]) and with national standards where applicable.

12.7 Fire Suppression System

The vehicle will be equipped with a fixed fire suppression system according to the requirement of the EN 45545-6 (Ref. [14]) and the applicable national standards. The system will be activated automatically when a fire is detected. Visible status indication shall be provided to indicate that the system is operative, both to the operator at control room and on any activated emergency driving panel.

The fire suppression system will utilise water as the extinguishing medium, discharged under air pressure fed from the vehicle supply. The water tanks shall be installed on the coach underframe, with appropriate measures in place to ensure that the system operates consistently throughout the range of ambient temperatures encountered in service. The water flow rate at each nozzle during activation and the area of coverage shall be sufficient to extinguish any credible fire (up to 0.5 MW ignition source) at any location in the passenger area. The vehicle and fire suppression system shall be designed such that operation of the system does not cause critical damage or failure to any part of the vehicle.

Two portable fire extinguishers shall be provided in MDS vehicle. An alarm to the operator shall be raised if a portable fire extinguisher is removed from its location.

12.8 Windshield wiper

The windshield shall be equipped with externally mounted windshield washer / wiper units (on each windscreen) to guarantee an adequate visibility from the driver's panel. They shall be activated automatically and possibly bypassed (manual operation). The driving panel shall be equipped with a control for operating the windscreen wiping and washing equipment. The control shall enable the operator to select the following options:

- 'PARK' – windscreen wiper switched off and retracted to the 'PARK' position, invisible from inside the vehicle.
- 'WIPE' – windscreen wiper operating.
- 'WASH' – windscreen wiper and washer both operating. The controller shall be required to be manually held in this position to operate the windscreen washer and shall automatically return to the 'WIPE' position when released.

The washers and wipers shall be capable of efficient operation under all specified environmental conditions and speed (up to 200 km/h). The wipers shall clear the largest possible area such that the driver's field of view is maximised.

The wipers shall not be visible from inside the vehicle when in the parked position. The washer reservoir shall have sufficient capacity to ensure that no topping up is required between preventive maintenance intervals. The reservoir shall be refillable from the exterior of the vehicle at track and at platform levels.

13 Vehicle interior

13.1 Exterior Doors

As stated in TSI 1302/2014 (Ref. [7], Section 4.2.10.5.1 item 12): The number of doors and their dimensions shall allow the complete evacuation within three minutes by passengers without their baggage. It is permitted to consider that passengers with reduced mobility are to be assisted by other passengers or staff, and that wheelchair users are evacuated without their wheelchair.

The MDS vehicle will be equipped with two doors, one on each side of the vehicle. They will be of sliding door leave type, electrically driven equipped with a window.

The door operating mechanism shall be configured so that the door leaves remain parallel to the longitudinal axis of the cab at all times during opening and closing.

The base of the doors will be at the same height of the station (550mm from the TOP according to TSI).

An external step will be provided, which will extend from the door step outwards from the coach body as far as the kinematic vehicle movement allows without fouling the platform edge under all circumstances, including under suspension failure conditions. The external step will extend across the full width of the door throughway. The difference in level between the upper surface of the step and the vehicle floor will be minimised as far as is reasonably practicable and shall not exceed an absolute limit of 15 mm. The external step shall have an anti-slip surface covering the whole usable area.

To make it easier for visually impaired people to identify the position of the doors, the interior surface of each door leaf shall be finished in a contrasting colour or shall carry a visually distinctive marking. The edge of the doorstep shall be identified using a contrasting-coloured edge strip. The opening and closing of the vehicle doors shall be accompanied by visual and audible warnings.

Figure 36 MDS Vehicle – Example of external door on a train with external step, and external access device (Ref. [60])

The operation of the doors will be handled by the train control system. All the doors will be locked by the train control system before train movement. When the vehicle is in the normal (driverless) mode of operation, the train control system will activate the trainlines to automatically control door opening and closing.

The door control circuit shall be interlocked with the traction power circuit and braking system. The interlock circuit shall confirm that all doors (including any which are locked out of use) are closed before traction power can be applied and if a door opens whilst in motion apply the emergency brake and remove traction power. The door interlock circuit status shall be notified to the ATC. The doors shall also be locked and notification provided to the ATC if the lock is not engaged.

The doors will be equipped also with safety device for emergency egress. An emergency door handle will be located inside the cab on the right-hand side when facing the door opening from inside. Activation of the emergency door handle shall be notified to the train control system. An alarm shall be reported to OCC operator. Action to be taken after the activation of the shall be evaluated by safety point of view, considering the driverless operation of the vehicle.

Each door will be provided with an external access device operated by a door access key. This access device shall be located to permit staff access to the coach from the platform, tunnel walkway and track, regardless of the state of the power supplies to the door or whether the door is locked out of use.

Exterior door system shall be compliant with TSI 1302/2014 (Ref. [7], Section 4.2.5.5) and standard EN 14752 (Ref. [11]). Exterior Passenger door system accessible by the PRM shall be compliant with TSI PRM (Ref. [4], Section 4.2.2.3.2).

13.2 Passenger's compartment

A coach of 25m (+ 3 metres for tail and head) allows to host 70 seats, including space for the PRM and the toilets. It can also host the different systems that in conventional vehicle may be distributed on the different cars, while for the MDS vehicle all systems shall be installed on the pod. The height shall be equivalent to a car with single floor (minimum 2.2 m).

The arrangement of the seats inside the vehicle is an aspect that must be defined with the agreement of the railway operation, to consider the level of service that it would like to offer.

For example, the pod can be a single area with different type of seats or divided in two areas with different level of service (1st class and 2nd class).

Independently by the organisation of the seats, the MDS vehicle will comply with the TSI PRM (Ref. [4]).

Figure 37 Example of wheelchair space (Ref. [61])

It will foresee 1 place for wheelchairs close to the doors and at least 7 priority seats (minimum 10% of the total) for the use of persons with disabilities and persons with reduced mobility. These seats will be identified by signs.

Priority seats can be positioned face-to-face or in configuration face to back. The width of the aisle by the seat configuration shall be a minimum of 450 mm, increased to 700 mm in the wheelchair accessible areas near the vestibule. Additional space can be reserved to bike, prams, luggage.

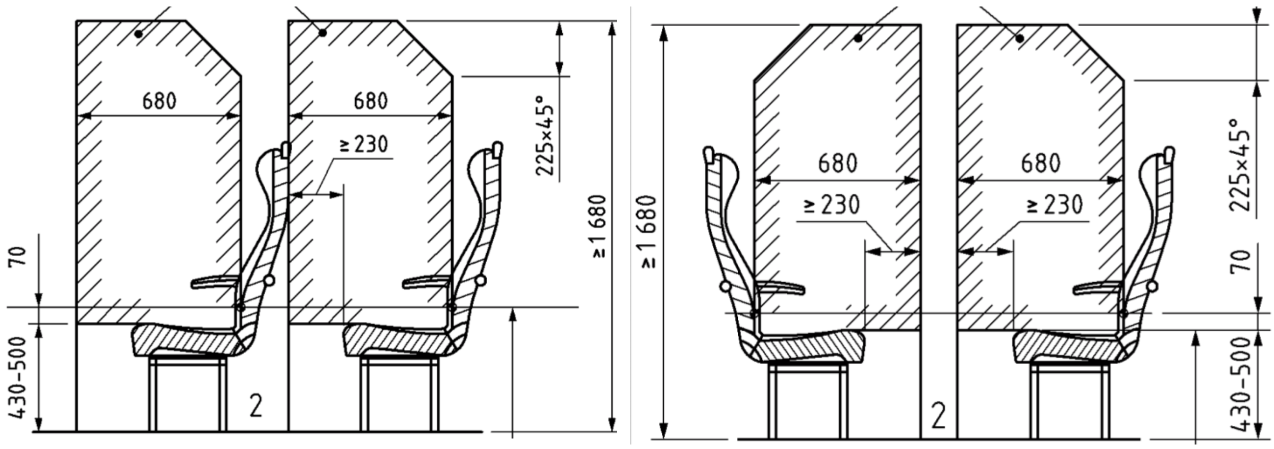


Figure 38 Arrangement of the priority seats in the train (TSI PRM, Ref. [4])

All seats are equipped with a socket. The corridors between the seats shall have a minimum width of 450mm. Considering the acceleration defined for the vehicle (Ref. Table 4) use of seat belts is not foreseen.

All seats arrangement and wheelchair area shall follow the guidelines of the TSI PRM (Ref. [4]). The attachment of the seats to the vehicle body shall meet the load cases and fatigue load cases in accordance with EN 12663 (Ref. [9]).

13.3 Toilets

MDS vehicle will be equipped with 1 PRM toilets accessible for persons in wheelchairs as required by the TSI PRM (Ref. [4]). The toilet space shall be compliant with the requirement for person with reduced mobility. Sliding doors will be foreseen to save space, with manual lock.

Fresh water tank shall be filled through the standard openings installed on the side of the coach. Water level in the tank will be checked by means of an indicator.

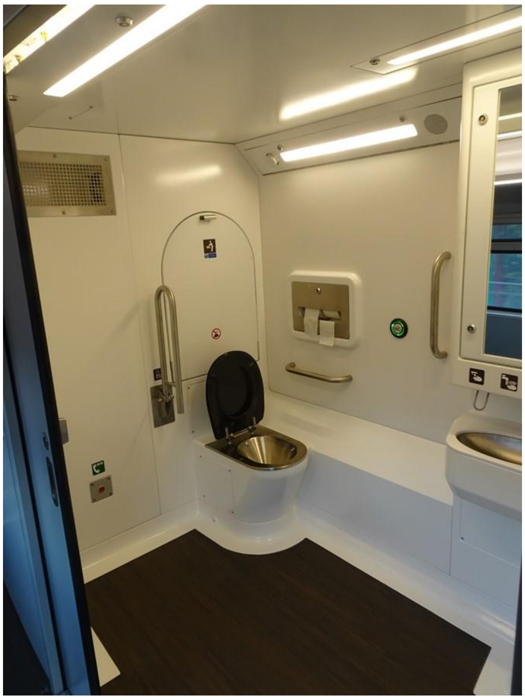


Figure 39 Example of toilets in a train (Ref. [62])

The grey and/or black water tanks shall be modular.

14 Vehicle Auxiliary Electrical system

14.1 Introduction

The vehicle's electrical system aims to provide electrical power supply to two electrical subsystems of the vehicle, consisting of:

- Traction power system, high voltage, to feed the propulsion motor moving and running the train
- Medium and low voltage system, used to feed the auxiliary systems for train control and passengers' comfort.

The electrical power required by the conventional vehicle is distributed along the line via the contact line (catenary system) through different delivery points represented by the electrical substations.

The architecture of the vehicle's electrical system for conventional vehicle is represented as in Figure 40.

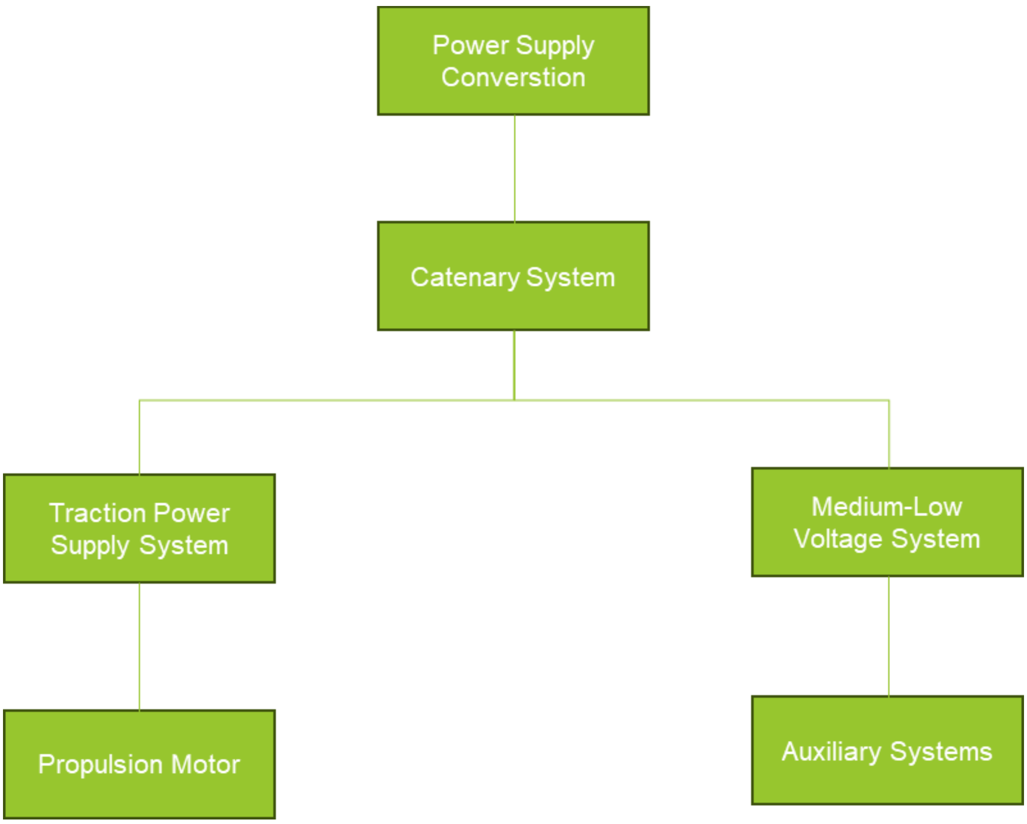


Figure 40 Conventional Vehicle - Electrical System Architecture

The architecture of the electrical system for MDS vehicle changes to consider the replacement of the onboard electrical motors for propulsion with the linear motor.

As described in the chapters 8 and 9, the linear motor is composed by two parts: motor and stator. Depending on the solution adopted, the active part of the linear motor can be installed on the track (LSM, Ref. §8) or onboard (U-LIM, chapters 9), then the architecture of the vehicle electrical system shall be adapted accordingly.

The following paragraphs aim at defining the power consumption of the MDS vehicle auxiliary systems and the architecture of the electrical auxiliary system for LSM and U-LIM configuration.

14.2 Electrical System for Auxiliary Systems

The electrical system for auxiliary services which aims at providing the power supply to the systems for train control and passengers' comfort is composed by two different subsystems supplying different loads:

- MV system (Medium Voltage) – 400 VAC
- LV (Low Voltage) system – 24 VDC

The MV - 400 VAC system distribution, three-phase + neutral, supplies the MV loads consisting of:

- Air conditioning units (HVAC), motorized compressors and fans
- Compressed air production unit
- Electrical sockets of passenger seats
- Trolley and electromagnetic pad handling system for emergency braking

The LV system – 24 VDC, two-phase, supplies LV loads consisting of:

- Driving command and control system
- Passenger telecommunications system, sound system
- Telecommunication system for service communications, radio
- Train door system
- Fire detection system
- Interior lighting system
- Interior lighting system
- Auxiliary systems
- WC system

A preliminary evaluation of the power consumption of the vehicle auxiliary systems has been performed considering the operating scenario described in the paragraph 6.2.1.

Considering the characteristics of the auxiliary systems, most of them work continuously with a constant electrical absorption during all the various phases of operation.

On the other hand, some of them such as sound system, radio service, train door system and toilet are not always in operation, with constant electrical absorption during all the various phases of operation. These systems are operated on demand and the power consumption can be calculated as the sum of the two components: power consumption when the system is in standby plus the power consumption when the system is active.

To evaluate the power consumption of the systems working on demand, the following parameters have been defined:

Parameter	Value
Stopping time at intermediate station	1 min.
Number of stops per hour	4

Table 10 Additional Operating parameter for battery capacity evaluation

The power consumption of the MV and LV systems is evaluated in Table *11* and Table 12 respectively.

Subsystem	Load (kW) - Active	Load (kW) - Stand-by	Active Time (Min)	Load for Round / Trip (kW)	Remarks
Signalling System	1	-		1	
Passenger Information system (video)	0.25			0.25	
Passenger Address system (audio)	0.25	0.05	4	0.06	Activated 1 min per stop (4 min per hour)
CCTV	0.4			0.4	

Subsystem	Load (kW) - Active	Load (kW) - Stand-by	Active Time (Min)	Load for Round / Trip (kW)	Remarks
Radio Communication System (Radio FRMCS)	0.25			0.25	
Virtual Coupling Communication (Radio)	0.25			0.25	
Doors	0.6	0.01	0.67	0.02	Activated 10 sec per stop (40 sec per hour)
Fire Detection and Alarm System	0.2	-		0.2	
Internal Lighting	0.8	-		0.8	
External Lighting	0.2	-		0.2	
Auxiliary system (relays, etc)	0.8	-		0.8	
Toilet	2	0	10	0.33	Activated 10 minutes per hour
TOTAL	**7**			**4.75**	

Table 11 *Analysis* of the load for Low Voltage - 24 VDC

Subsystem	Load (kW) - Active	Load (kW) - Stand-by	Active Time (minutes)	Load for Round / Trip (kW)	Remarks
Refrigeration	21	-		21	
Heating	16	-		16	
Compressed air production group	10	-		10	For pantographs and others system
Passenger seat electrical outlets	2	-		2	
Bogie lifting/lowering system	8	-	2.667	0.36	Activated 40 sec per station (160 sec per hour)
Total Medium Voltage Load - refrigeration				**33.36**	
Total Medium Voltage Load - heating				**28.36**	

Table 12 Analysis of the load for Medium Voltage - 400 VAC

Note: the loads of the different subsystems have been derived from rolling stock used in railway and metro systems.

Considering the total for LV and MV, the total power consumption of the vehicle for one day operation (15 hours) is calculated in Table 13.

Summary	
Total MV Load	33.36 kW
Total LV Load	4.75 kW
Total	38.11 kW
Total hours of operation	15 h
Total power for operation	571.58 kWh

Table 13 Summary of MDS Vehicle Power Consumption

14.3 Architecture of the electrical system for auxiliary system.

The vehicle auxiliary systems are supplied by two different types of systems:

- MT systems (Medium Voltage) – 400 VAC.
- LV (Low Voltage) systems – 24 Vdc.

The architectures of the proposed power systems are described in the following paragraphs for the two different configurations of linear motor considered for the MDS vehicle, LSM and U-LIM.

14.3.1 Electrical system for LSM configuration

In this case the synchronous linear motor provides the active part of the traction system on the track; the on-board traction power system is not necessary and the installation of the catenary contact line is not envisaged.

To guarantee the power supply of the on-board auxiliary service systems, the installation of a Battery Group with adequate autonomy to cover the daily service of 15h service is envisaged, which constitutes the primary power source for the loads fed by:

- Medium Voltage (400 VAC, 50 Hz, 3f + N)
- Low Voltage (24 VDC)

Based on the value of the energy of 571.58 kWh required in the daily service by the auxiliary systems (Ref. Table 13), a lithium-type battery group can be foreseen. It should have an energy density of 220 Wh/Kg, which corresponds to about 2400 kg for a volume of about 1.6 m3. Other type of batteries can be evaluated to optimize weight and performance, as well as different recharging points along the track.

The power supply system, see Figure 41, consists of the following components:

- Input module consisting of a DC converter to adapt the voltage of the battery pack to the input values of the three-phase inverter module
- Three-phase inverter module with MV output terminals (400 VAC, 50 Hz, 3f + N)
- Rectifier module derived from the three-phase inverter module with BT output terminals (24 VDC)

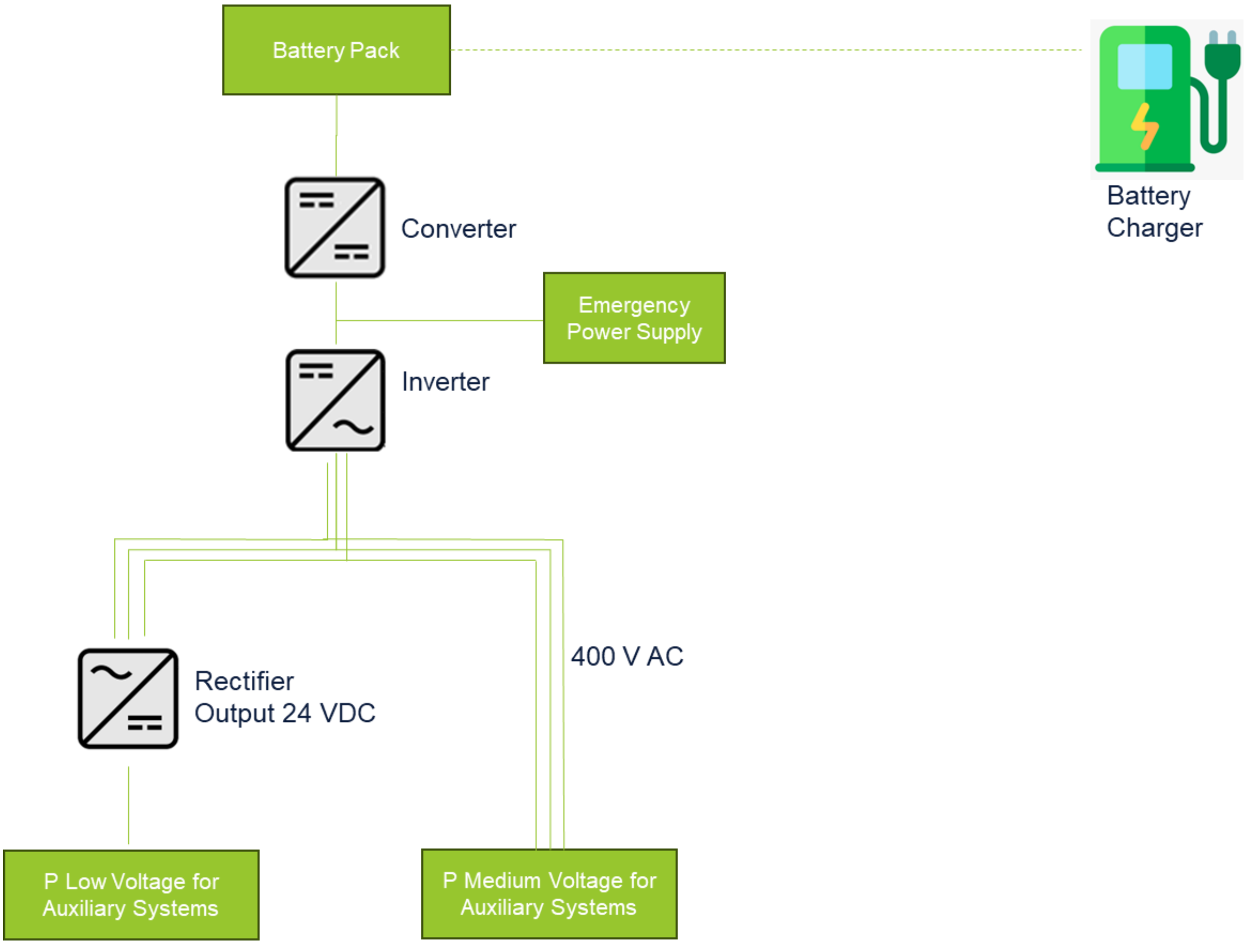


Figure 41 MDS Vehicle - Electrical System Architecture for Auxiliary System (LSM configuration)

14.3.2 Electrical system for U-LIM system

The U-LIM system includes the active part of the linear motor on board. In this case, the electrical system architecture of the MDS vehicle does not change much compared to a conventional vehicle, since the main energy source will be taken from the catenary system and used to power both the linear motor (as propulsion systems) and the auxiliary service systems.

In this case the MDS vehicle must be equipped with two pantographs to avoid a single point of failure.

The architecture of the auxiliary electrical system is shown in Figure 42. It consists of the following components:

- Input module consisting of a DC converter to adapt the contact line voltage to the input values of the three-phase inverter module
- Three-phase inverter module with MV output terminals (400 VAC, 50 Hz, 3f + N)
- Rectifier module derived from the three-phase inverter module with BT output terminals (24 VDC)

The architecture of the traction power supply system, see Figure 42, consists of the following components:

- Input module consisting of a DC converter to adapt the contact line voltage to the input values of the three-phase inverter module
- Three-phase inverter module, redundant, with output terminals to generate 2kV RMS 5-100Hz.

An alternative solution is the installation of a battery on board to provide the power supply to the linear motor and the systems. This solution is catching on in conventional vehicles, which are equipped with hydrogen cells that can guarantee an autonomy up to 2000 km. This solution is mainly oriented for lines that are not equipped with catenary system.

The use of on-board battery to provide traction power to the linear motor of a MDS vehicle should be investigated more in detail to evaluate pros and cons, such as additional weight of the vehicle introduced by the battery, simplification of the vehicle and infrastructure, and removing dependency from pantograph and catenary.

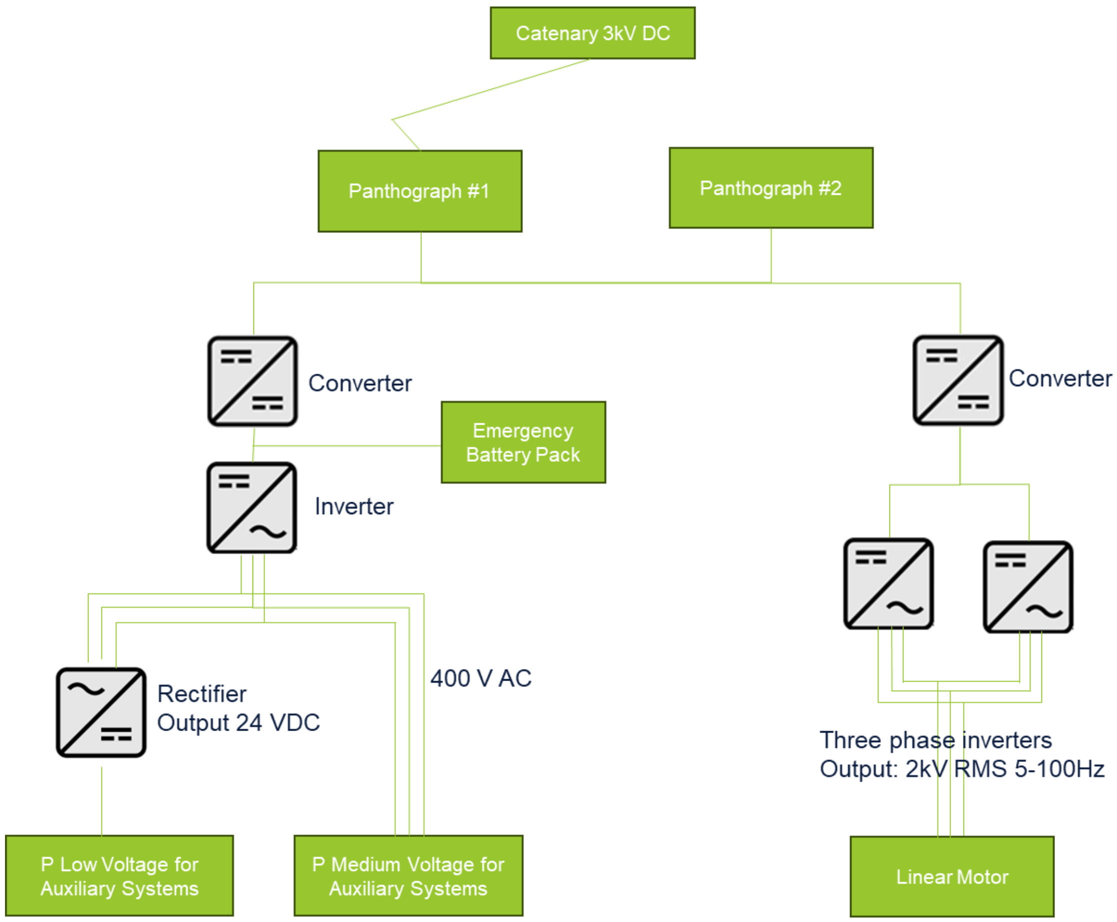


Figure 42 MDS Vehicle - Electrical System Architecture for Auxiliary System (U-LIM Configuration)

14.3.3 Power system in case of emergency.

In case of emergency, such as 3 kV DC power failure or failure of the battery group, an independent battery group installed on the MDS vehicle is foreseen in parallel to the three-phase inverter module of the auxiliary system, see Figure 43, to ensure the regular operation of all MV and LV loads for one hour.

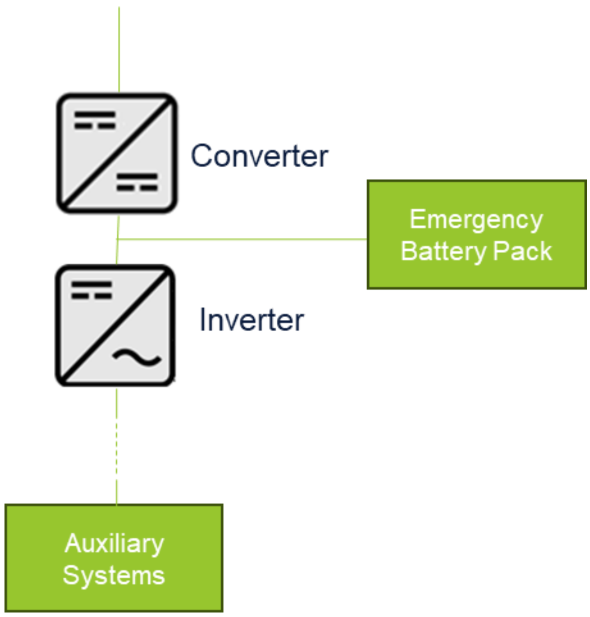


Figure 43 MDS Vehicle – Emergency Power Supply System for Auxiliary Systems

15 Air Levitation Vehicle

15.1 General vehicle description

The solution proposed foresee the installation of a track slab in the middle of the existing railway ballasted track. The track slab will be used as a platform to allow the levitation, guidance, propulsion and brake of the new MDS vehicle based on air levitation.

The MDS vehicle is in size and dimensions the same as the ETR421 composed by 4 coaches, but the bogie is replaced by a bogie which carry the load by air levitation and propelled by rotating permanent magnetic wheels.

Parameter	Value	Remarks
Length total	109.6m	4 coaches
Height	4.3m	
Width	2.8m	
Weight	267914 ton	4 coaches
Operation Speed	160 km/s	Max speed
Normal Acceleration	1.1 m/s2	
Power Supply	3kV DC	
Max Power	3400 kW	

Table 14 ETR421 Vehicle Parameters – Summary (Ref. [48])

This ensures that the new vehicle not only meets capacity needs but also fits within the established parameters of existing rail systems. By adhering to these design principles, the Airlev MDS vehicle promises to offer a practical and efficient solution for modern rail transport, balancing innovation with existing infrastructural constraints.

The technical features of the MDS train based on air levitation and its corresponding track are detailed in the following Figure 44. The principle of air levitation is based on creating a pressure differential between the air inside and outside an air chamber, generating sufficient mechanical force to lift a vehicle off the slab base that is foreseen in the middle of the existing track. This proven technology is used already on several lines in the past, please refer to the review of air levitation in D2.1 (Ref. [15]). A significant improvement of the concept proposed is the new propulsion method, namely, electro-dynamic wheels (EDW, rotating magnets), as depicted in Figure 44. The EDW can create thrust force and provide braking when rotated in the opposite direction.

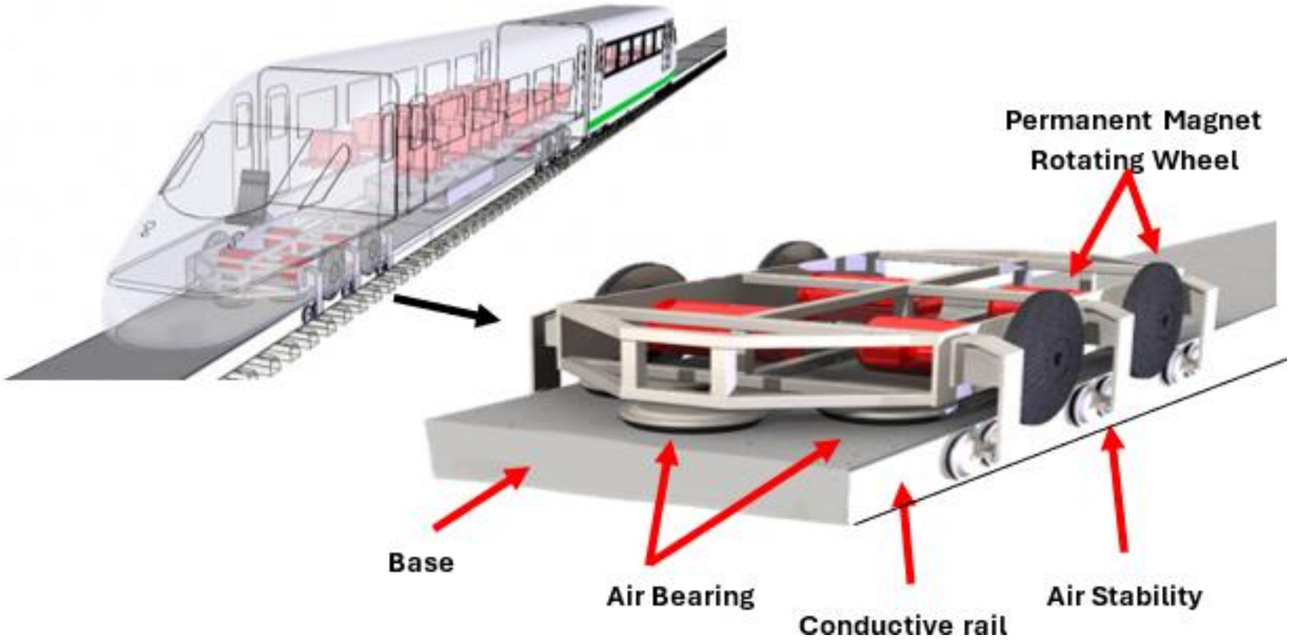


Figure 44 AirLev Train. Load carrying by air levitation and rotating permanent magnet wheel for propulsion/braking.

The aim is to develop a bogie (demonstrator) that contains both the air levitation method for load carrying and guidance as well as the propulsion/braking method by using the rotating permanent magnetic wheel principle. The track specifications of the proposed use-case 2 will be used as input in engineering the proposed bogie. Later, the engineered and build bogie (demonstrator) will be tested on an adapted track (adding slab containing balises and other signalling devices) at the Rail Center, Amersfoort, the Netherlands. The tests consist of acceleration and braking tests (using acceleration sensors, tachometers, etc.) as well as the effectiveness of the shielding of the magnetic fields with respect to signalling devices.

15.2 Track

The air levitation train runs on top of a slab, see Figure 45. The slab with stator strips for propulsion and braking is placed in between the existing rail. So, the conventional and the air levitation train can use the same track. In Figure 46 a track is depicted that could be made when the existing track has to be replaced after a certain service life.

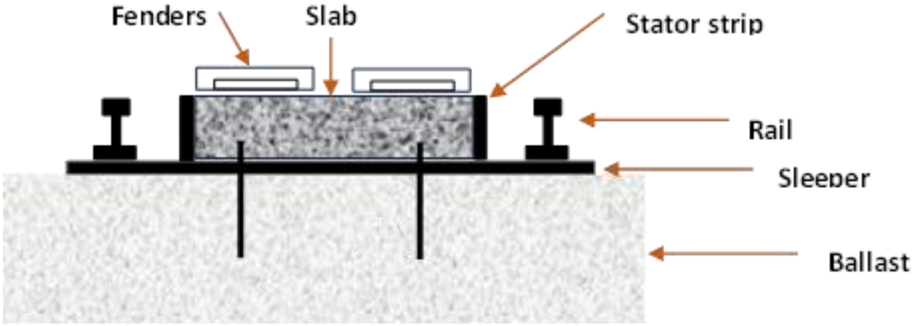


Figure 45 Track for conventional trains and air levitation trains

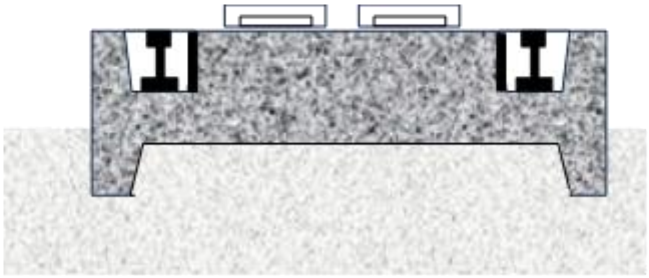


Figure 46 Future track for air levitation trains that also allows conventional trains to run on.

The air levitation principle in combination with rotating permanent magnet wheel propulsion is a feasible option to improve public transport due to more frequent and faster trains. Due to non-contact train-track, wheel-rail noise is eliminated as well as rolling contact fatigue (and maintenance). The technology for propulsion and braking proposed here could be very well used/compared with the proposed technologies that will be developed/implemented in the other use-cases within the MaDe4Rail project.

15.3 Levitation and guidance system

To carry the load by air, air fenders are used (see Figure 47). This technology has proven to be effective for several air levitation transportation systems, see summary of air levitation air cushion in deliverable D2.1 (Ref. [15]). Instead of using for instance a fan, an air compressor in combination with an accumulator (for a stabilized air pressure) will be placed in a sound isolation chamber, see Figure 47. Air compressor installed onboard can be supplied with power supply from the existing catenary system or with battery installed on board. The guidance of the train will be realized by air fenders as well, see Figure 44.

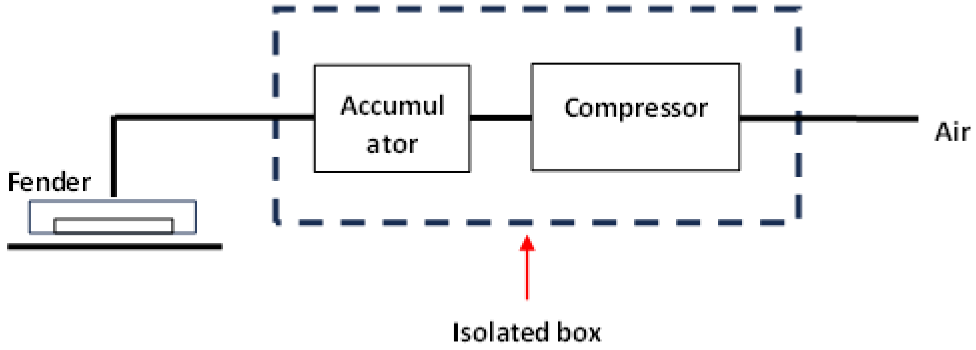


Figure 47 Air fender – compressor system

15.3.1 Levitation

The air fenders can be used for the levitation of both the pods and the conventional trains with bogies replaced by Airlev bogie. The following discussions focus on the conventional train with bogie replaced. The mass per coach is 67 ton, i.e. 33.5 tons per bogie. The normal force per bogie is therefore 335 kN. With an air pressure of the order of 5 bar and the train as defined in the hybrid MDS based on air levitation configuration, the total surface area of the fenders per bogie needed for lifting the train is:

$$A = \frac{F}{p} = \frac{335 \cdot 10^3}{5 \cdot 10^5} = 0.67m^2$$

In [26] several options are given for fenders that are suitable. The arrangement of the fenders can be chosen such that passing balises are not an issue (for instance 2 rows of 4 to 5 fenders with a total load area of about 0.9 m^2, i.e. fenders with a diameter of 27 cm).

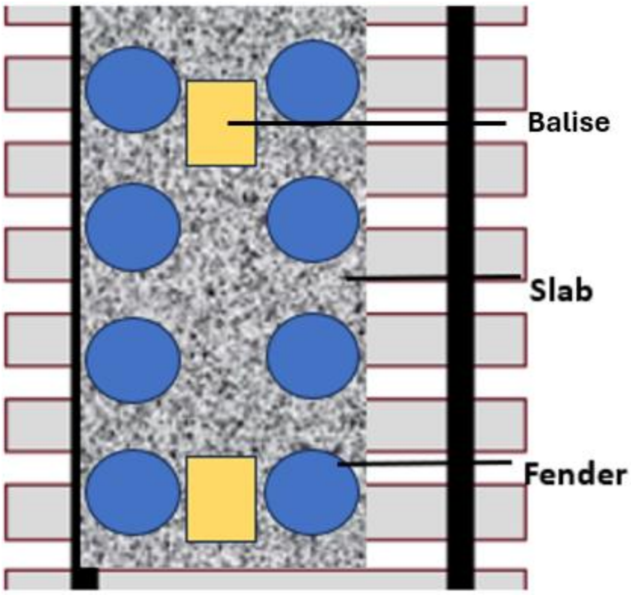


Figure 48 Arrangement of fenders for carrying the train

Furthermore, it has been chosen to carry the whole load by the fenders (and not partially) in order to avoid possible derailment (hunting of the train at high speed on straight tracks, switches or in curves).

15.3.2 Guidance

The modified Airlev train velocity of 180 km/h results in a centrifugal force in a curve with track radius of 400 m given by:

$$F = \frac{mV^2}{R} = \frac{67 \cdot 10^3 \cdot 50^2}{400} \approx 420\ kN, i.e. 210kN\ per\ bogie$$

The surface area of the guidance side fenders is:

$$A = \frac{F}{p} = \frac{210 \cdot 10^3}{5 \cdot 10^5} = 0.42\ m^2$$

Using 4 sides fenders at each side of the bogie results in fenders with surface area of 0.11 m^2 each.

15.4 Propulsion and braking system

Next to the load carrying capacity, a reliable propulsion and braking is necessary, not being dependent on friction, to be able to increase the number of (faster) trains on a track. It has been chosen to use magnetic propulsion and braking with a wheel containing permanent magnets rotating contactless along an aluminium conductor (stator) installed on the side of the slab (Ref. Figure 49). A Lorentz force is generated for propulsion (rotational velocity wheel larger than train velocity) and braking (rotational velocity lower than the train velocity), see Figure 50.

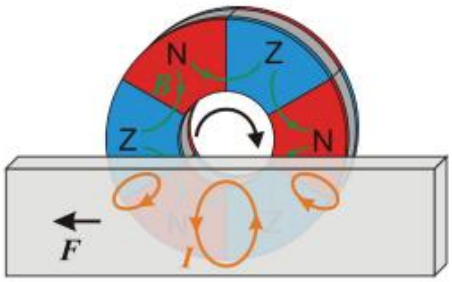
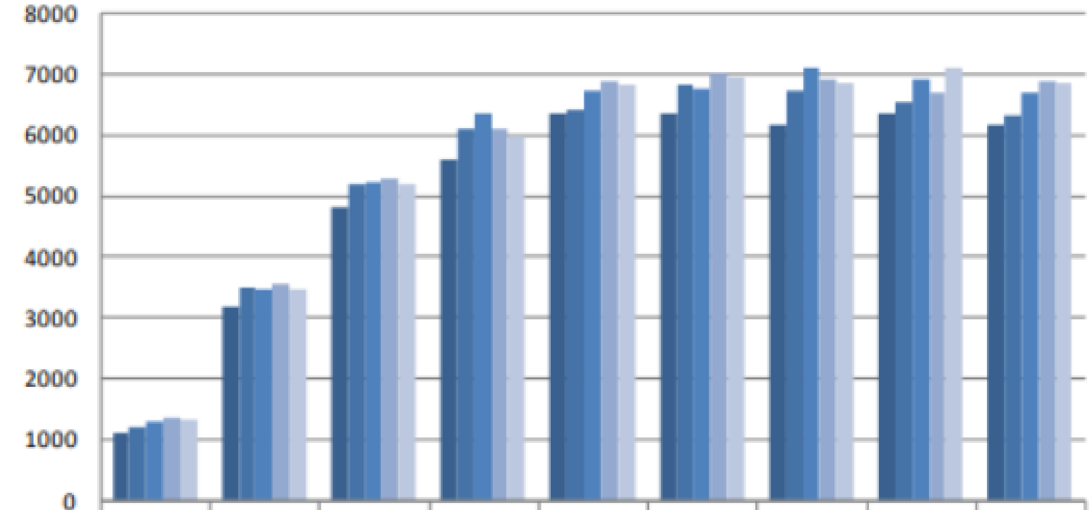


Figure 49 Propulsion and braking by rotating a wheel with permanent magnets along a stator. This principle is proven, see, for instance, J. Bird, PhD thesis 2006, University of Wisconsin-Madison, USA.

This propulsion and braking system is studied (modelled) and on a small scale tested (diameter wheel 200 mm). A rotating wheel with permanent magnets (diameter 700 mm) generates a Lorentz force of the order of 9 to 10 kN (an optimized and larger wheel may generate 10 kN or more), see Figure 50.

Considering the data of a carriage/coach as used in the hybrid MDS based on air levitation configuration, the maximum acceleration and deceleration is of the order 1.2 m/s^2 and a slope of a track of about 4-5 degrees can be overcome. With the available propulsion force a train velocity over 300 km/h is possible.



schil ->	0,5	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5
n=12	1135	3208	4839	5602	6367	6357	6168	6368	6168
n=14	1220	3519	5211	6119	6438	6839	6753	6571	6348
n=16	1319	3473	5229	6355	6746	6791	7118	6937	6709
n=18	1389	3561	5299	6114	6903	7012	6923	6706	6905
n=20	1354	3477	5195	6000	6836	6962	6864	7116	6881

Figure 50 Propulsion force (N) as a function of velocity difference between rotating wheel and strip (stator), varying from 0.5 m/s till 8.5 m/s, and number (n) of magnets for a certain rotating wheel configuration.

16 Compatibility between MDS and existing infrastructure

16.1 Introduction

The main objective of the hybrid MDS technology is to ensure the compatibility with the existing railway infrastructure to ensure that existing lines can be used by conventional train and MDS vehicles.

However, the introduction of MDS technology has an impact on the existing infrastructure. During the concept design of the vehicle and its subsystems, different aspects have been identified and investigated to evaluate the impact of the MDS technology on the existing line where mixed traffic with conventional vehicles must be ensured.

The main points of attention raised during the design of the MDS vehicle prototype related to the compatibility between MDS technology and existing infrastructure are the following:

1. MDS components for propulsion and levitation have different impacts on the existing infrastructure, such as:
   a. MDS components introduce new loads on the existing infrastructure.
   b. MDS components have geometrical conflicts with existing track elements.
   c. MDS components impact the existing track maintenance activity.
2. MDS components impact the operation of the existing signalling components installed along the track.

These points are described more in detail in the following paragraphs.

Please note that the issues identified for the magnetic levitation MDS vehicle are also applicable to the to the air levitation MDS bogie described in the chapter 15.

16.2 Interference between existing infrastructure and levitation system

16.2.1 Loads and load distribution

Passive ferromagnetic levitation sliders offer a significant improvement in load compatibility compared to traditional wheel-based systems as described in the paragraph 7.2.1. No special issue has been observed on the load distribution due to the introduction of the magnetic levitation.

16.2.2 Interference between levitation and guidance system and track components

The main interferences between levitation and guidance system and track components are physical and represented by:

- Rails fastening.
- Switches and check rails
- Level crossings

Considering the solution described in the chapter 7, the clearance between the magnetic sliders and the rail fixations shall be ensured.

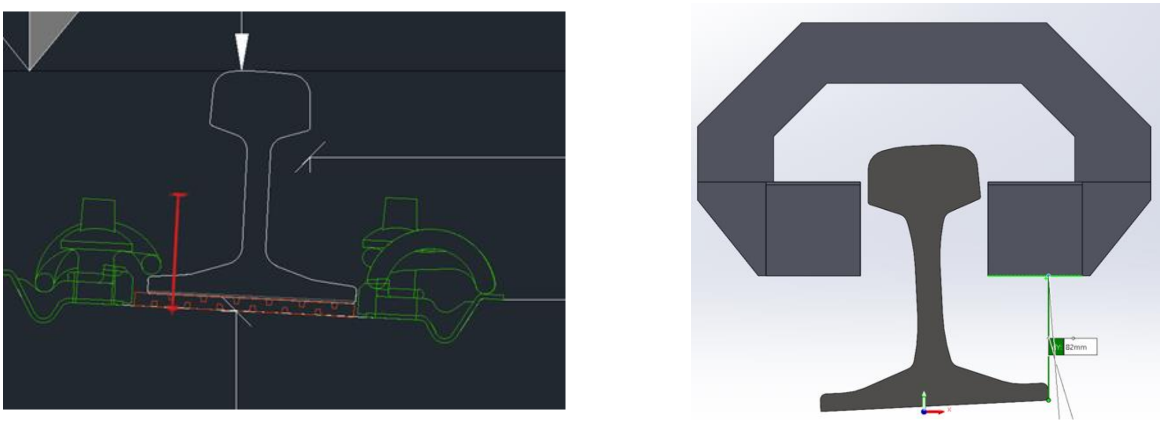


Figure 51 Interface between rail fixations and magnetic sliders (minimum distance)

Rail fastenings depend on the type of rails and sleepers used. The height of the fixation can vary from 75mm to 100mm for current standard fastening.

For the use case under analysis, the line is equipped with rail UIC60:

Dimensions of UIC60 Rail:

Type of Rail	Standard	Dimensions (mm)					Section S	Mass m
		H	B	C	D	E	cm²	kg/m
European standard EN 13674-1								
60E1 (UIC60)	EN 13674 - 1	172,00	150,00	72,00	51,00	16,50	76,70	60,21

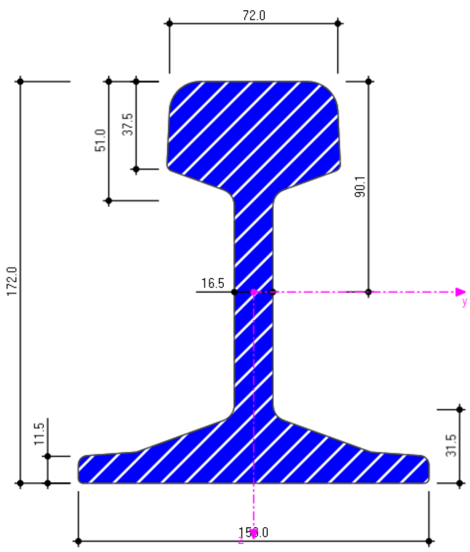


Figure 52 Geometry of the rail UIC60 used on the line for use case 3

According to the simulation performed, the space under the slider available for the installation of the fixation to avoid interference with the sliders is 82 mm.

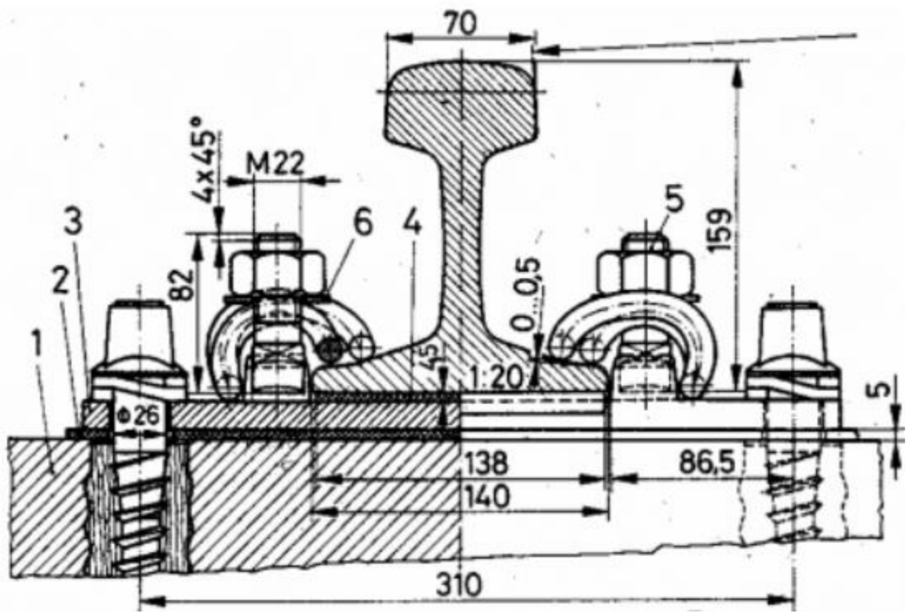


Figure 53 Geometry of the fastening with a rail UIC60

Some type of rail fastenings can be used to avoid the interference with the fastening and ensure also a safety gap between them and the sliders. A replacement of fastening may be necessary in case of conflict. This aspect must be studied case by case to ensure that the clearance is always guaranteed and adjustments to the current fastenings could also be studied to better integrate the new technologies.

The magnetic levitation system proposed in chapter 7 foresees the use of magnetic sliders levitating on the existing rails. This solution allows to reuse the existing rails. However, it presents the following limitations:

1. The magnetic slider can't pass over the switches;
2. The magnetic slider may create conflicts with other track components such as check rails.

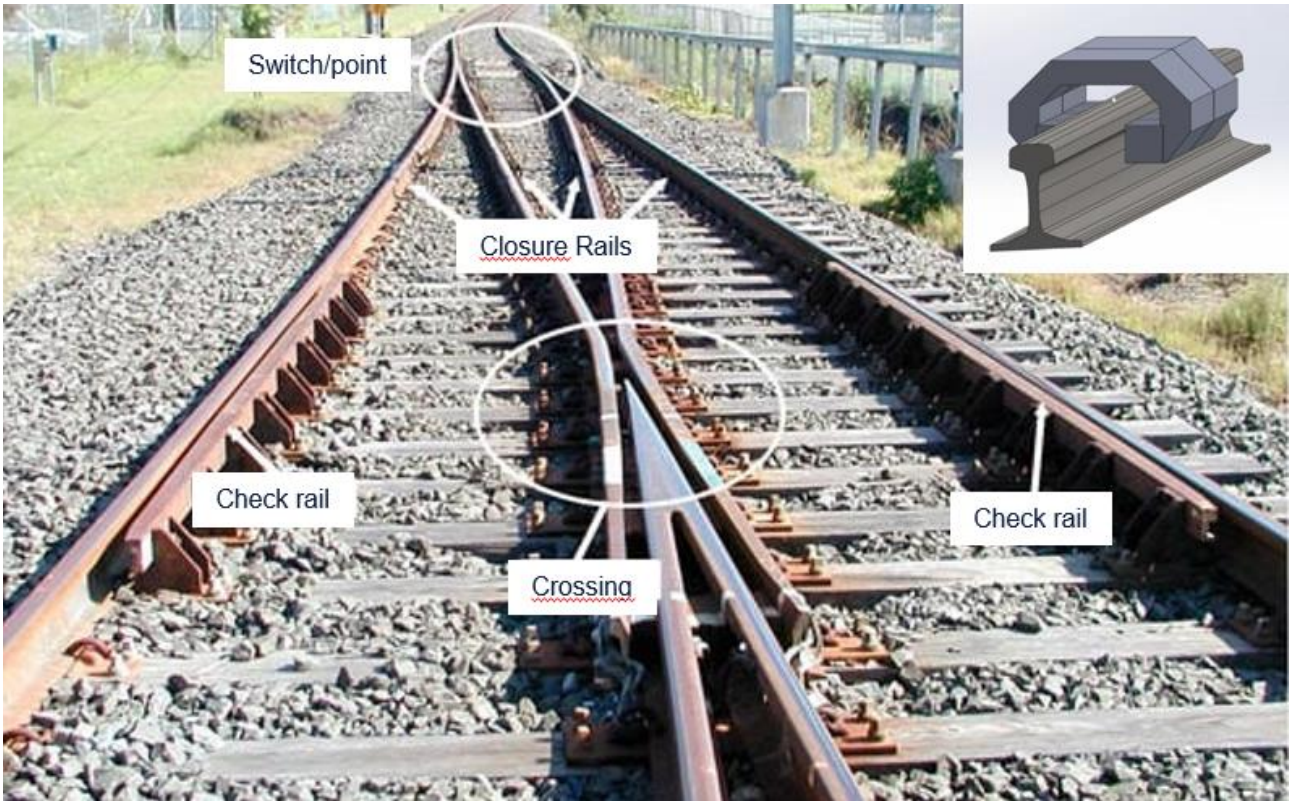


Figure 54 Interference of magnetic sliders with switches and check rails

Switches and check rails are essential components in the existing infrastructure. To introduce MDS technology, additional investigations must be performed to find adequate solutions in order to integrate MDS technology in existing infrastructure and guarantee compatibility with the conventional vehicles.

The interference with the switches may be solved investigating two options:

a. The first solution is to design a vehicle able to switch from magnetic sliders to standard bogie and vice versa when passing over the switches. This operation shall be safely done during the race of the vehicle, to avoid any increase in travel time. It will be subjected to very restrictive requirements in term of safety because the switching operation may lead to mechanical interference between the components.
b. The second option is to modify the switches and make them compatible for conventional train and MDS vehicle based on levitation. This solution would require switches similar to those used in the MagLev or steep grade line, where they allow to maintain the continuity of the track.

MagLev line Pilatus Bahn

Figure 55 Example of switch for MagLev line (Source: youtube)

In this case, the components of the switches shall be united in movement.

Another aspect that should be investigated is the conflict between the magnetic sliders and other components installed along the track such as check rails.

The check rails are laid parallel to a running track to guide wheels through sharp curves, slope, bridges, and near structures critical during a derailment. They allow to reduce wear and the risk of derailments. The function of the check rails is essential to ensure the safety of the conventional vehicle.

The magnetic sliders (See dimensions in Figure 10) may collide with the check rails.

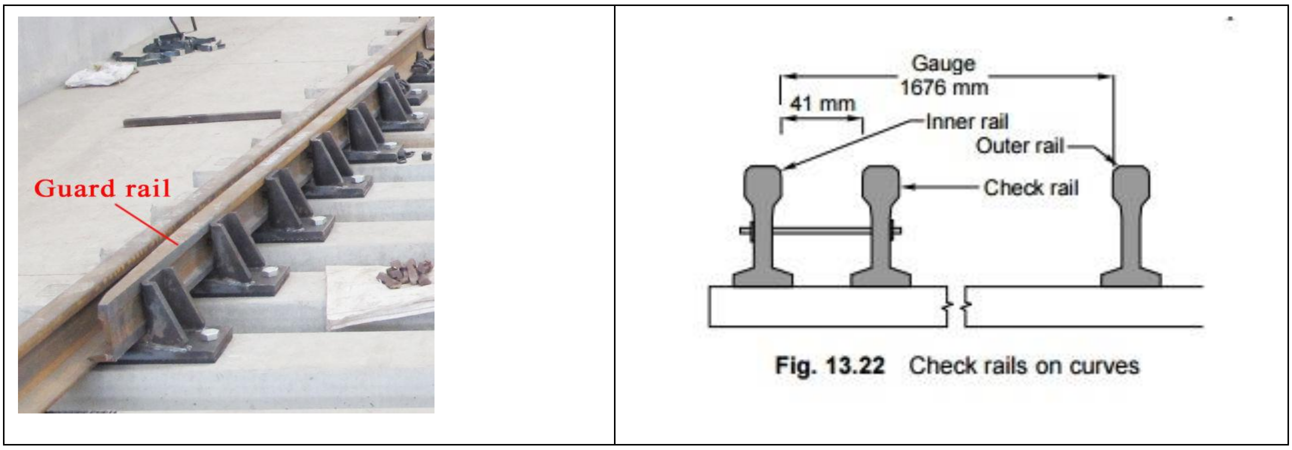


Figure 56 Example of check rail installation

Possible solutions to avoid interference with the check rails are:

- The introduction of motorized check rails that can be moved from a position to another depending to the type of vehicle along the line. The operation of motorized check rails will be similar to the existing switches.
- Use of external beams for the levitation of the MDS vehicle. This is completely a different and demanding solution than the one studied in the chapter 7, where the levitation and guidance of the MDS vehicle is ensured by the external beams. Even if this solution solves the interference with the track components installed between the existing rails, some new interfaces require further investigation such as fixations, loads and forces on sleepers and superstructure, and compatibility with the switches (similar to those already described for the linear motor in the previous paragraphs). In addition, this solution is subject to verification for geometrical compatibility.

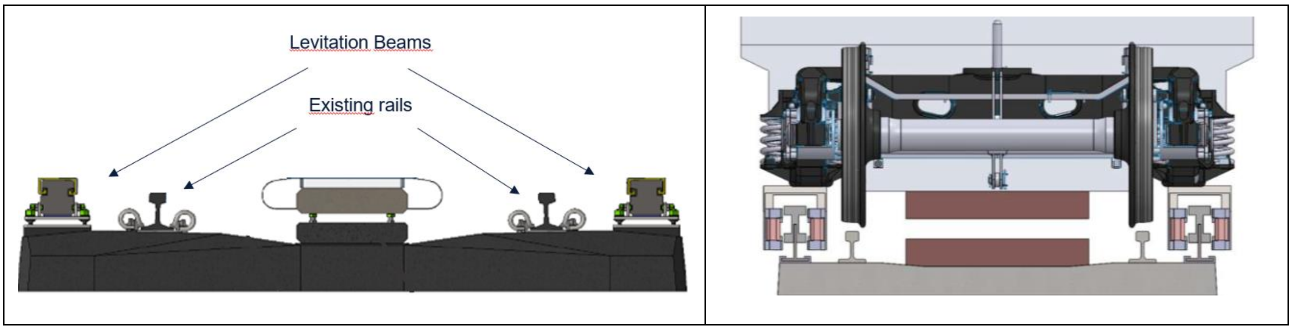


Figure 57 Solution with external beams for levitation

Finally, the magnetic slider interferes with the rubber level crossing panels which do not allow the passage of the sliders.

Figure 58 Example of level crossing.

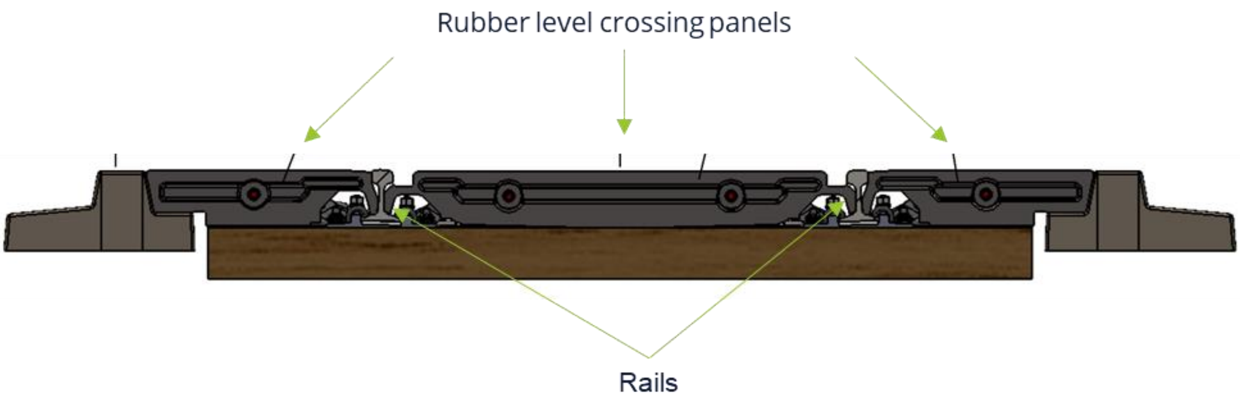


Figure 59 Example of level crossing section

Where feasible, the suppression of the level crossing with the construction of underground passage for the road vehicles is the preferable solution which improves the safety of both conventional and MDS vehicles.

Otherwise, the use of the conventional bogie installed on the MDS vehicle shall be used for the passage above the level crossing.

16.3 Interference between linear motor and existing infrastructure

16.3.1 Installation and load distribution

The installation of the linear motor on the track introduces a new interface with the existing track components having an impact on installation, operation and maintenance.

The solution proposed in the chapters 8 and 9 foresees the installation of the linear motor in the middle of the track (between the existing rails). This solution raises the following compatibility issues:

a. A solution must be studied to fix the linear motor segments along the existing track;
b. The linear motor introduces new loads in the middle of the track, not present in the current configuration;
c. The linear motor may interfere with the maintenance activity periodically performed on the track (Ref. §16.4)

The current sleepers don't present any feature to fix the linear motor segments.

Figure 60 Concrete and wooden sleepers

A modification of the existing sleepers may affect their structural properties, therefore a different solution should be studied.

In addition, Figure 61 shows that the installation of the linear motor in the middle of the track introduces new forces on sleepers and superstructure which are currently not present.

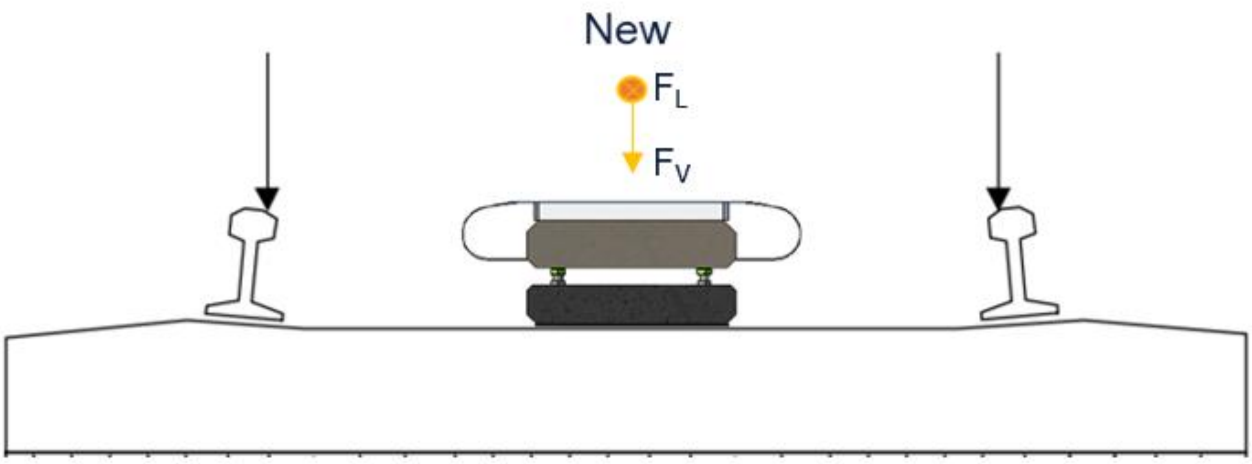


Figure 61 Linear motor force distribution

The conventional vehicles apply only a vertical load on the rails and sleepers at the contact point between the wheels and running rails as shown on the Figure 62.

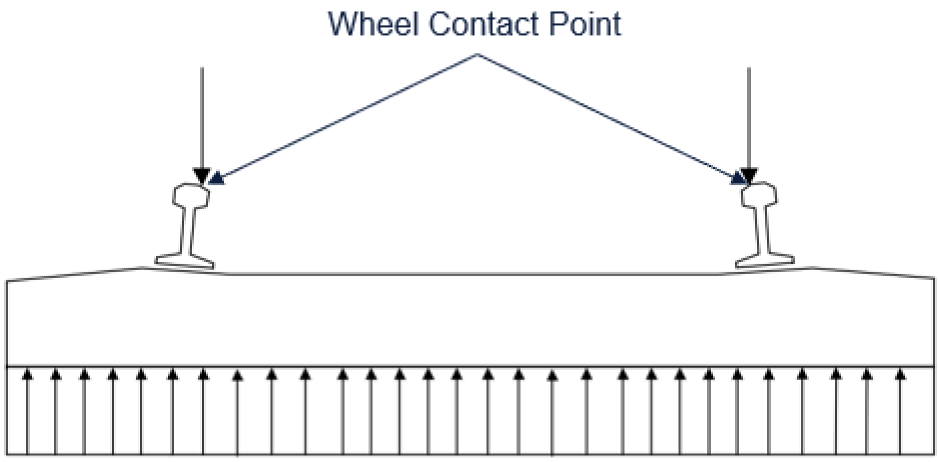


Figure 62 Conventional force distribution

The load generated by the linear motor in the middle of the track can be summarized as the two following contributions:

- Static load
- Variable load

These new forces will present a vertical and longitudinal component as shown on Figure 61. The latter may lead to displacement of the sleepers and impact on the rail fixations.

The worst-case scenario of variable load is during the acceleration and deceleration of the MDS vehicle which are at 0.75 and 2.5 m/s^2 respectively. For LSM, the maximum longitudinal load is proportional to the max braking force from the linear motor. For 2.5 m/s2 (standard deceleration) it is 109 kN. The vertical force in the worst case in full desynchronization is also ca. 109 kN in both sides.

The mechanical properties of the existing sleepers and rails shall be assessed against the new forces introduced by the linear motor. Where the existing sleepers are not suitable for the fixation of the linear motor segment and the new loads introduced by it, new solutions shall be investigated, and they may require major upgrade of the existing track.

It would be worth mentioning that concrete sleepers are built with internal reinforcement. The position and nature of those reinforcement must be modified to adapt to the new loads.

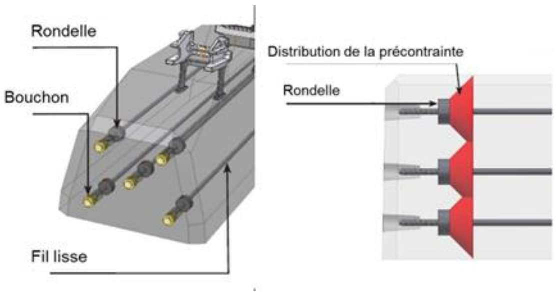


Figure 63 Example of sleeper with reinforcement

Additionally, the impact of the electromagnetic field and possible eddy currents on the reinforcement shall be investigated. More details about the electromagnetic compatibility are reported in the paragraph 16.5.2.

16.3.2 Interference between linear motor and switches

The installation of the linear motor in the middle of the track shall guarantee the operation of the switches.

Figure 64 Example of simple swich (Wikipedia)

An interference between the switches and the linear motor may be present, depending on:

1) The space occupied by the linear motor in the middle of the track;
2) The length of the switch and the space needed to move the switch rails. Switches of high-speed lines can have a length up to 300m.

Where feasible, a simple solution for the integration of the linear motor in the switches is to create an interruption of the linear motor as shown on Figure 65.

Figure 65 Interruption of the linear motor in the switch in Metro Vancouver (Ref. [62])

This solution may be applicable in the case where the interruption required is shorter than the length of the linear motor on the vehicle. In this case, a part of the linear motor on the vehicle can still interact with the linear motor on the track installed on one of the two sides of the switch.

If the interruption is greater than the length of the linear motor on the vehicle, it may happen that the vehicle stops above the interruption and remains without any propulsion, blocked in the middle of the switch.

In this case, an alternative solution shall be studied:

- One option is to modify the switches like those used in the steep grade railway as shown on Figure 66.
  The linear motor can be installed and operated just like the toothed track rail laid between the tracks. This solution allows to guarantee the continuity of the linear motor along the switch.

Figure 66 Cog rail switch used in steep grade railway (Source: youtube)

- A second option is to modify the MDS vehicle to cross the existing switches without the presence of the linear motor. As described in the section 16.2.2, the magnetic sliders can't pass over the switches and the use of standard bogie has been considered as a possible solution to cross the existing switches. Fitting the vehicle with motorized bogies and additional battery pack for traction, the current switches can be crossed by MDS vehicle without the need to install a linear motor. This solution avoids modification to the existing switches to integrate the linear motor. However, it increases the complexity and the mass of the MDS vehicle, since motorized bogies are between 2-3 tons heavier than non-motorized bogies. Additional mass is also added by the batteries needed for the propulsion.

16.4 Track Maintenance

The tracks, especially ballasted tracks, are subjected to periodic maintenance:

- Track tamping: Every 2-5 years
- Rail grinding: Every 8 years

Track tamping refers to lifting and correcting the longitudinal and vertical alignment of the track by squeezing ballast stone into the void created under the sleeper due to the lift.

Rail grinding and milling is a method to remove the surface flaws at initial stage itself and to re-profile the rail head making the profile more favourable to the wheel profile and thus control the stress on rail.

The execution of these activities is performed by dedicated maintenance vehicles, which may have major impact on the components installed on the track. Today, the signalling system components, such as balises, track circuits, etc., are removed before the execution of the maintenance activity.

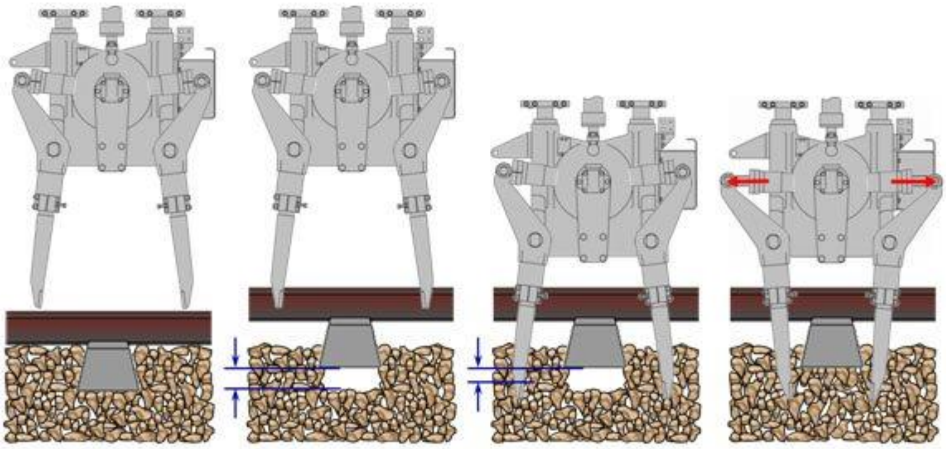


Figure 67 Track Tamping Procedure

The introduction of the linear motor impacts the execution of the tamping activity, since:

- It can interfere with the tamping machine shown in the Figure 67.
- It can be damaged during the tamping activity if maintained on the track.

Two solutions can be investigated in the detailed design of the linear motor:

a. The linear motor is removed from the track before the execution of the tamping activity. This option increases time and cost for the execution of the maintenance activity; however the fixation of the linear motor can be studied to ensure a quick and easy removal and re-installation of the linear motor segments.
b. The linear motor can be designed to resist the load and vibration generated by the tamping machine. This solution aims to maintain the linear motor on the track during the tamping activity, therefore saving time. This solution may increase the complexity of the linear motor.

The execution of the rail griding impacts less the components on the track. However, they shall be designed to not be influenced by the external effects generated the rail griding activity such as temperature and sparks.

An additional effect of the MDS on the maintenance activity is related to the frequency of the task required on the infrastructure.

MDS technology as linear motor and levitation system may require more stringent tolerance to be operated than the existing infrastructure.

- The gap between the stator and the motor can vary between 10 and 50 mm. An increase in the gap leads to a degradation of the performance.
- The alignment of the rails shall be guaranteed to avoid any protrusions interfering with the magnetic sliders.

To ensure the performances and safety requirements for the operation of the MDS systems, more frequent inspections and works on the track may be required.

16.5 Compatibility of MDS with existing signalling system

In Europe, all the most modern lines are equipped with the ETCS Level 2 system. This signalling system is based on some consolidated concepts such as the use of train detection system for train identification along the line, the use of Eurobalise to verify that the train is traveling along the correct stretch of line and radio communications.

The introduction of MDS vehicles within the existing infrastructure may influence the operation of the signalling system. The main interferences identified in the project between MDS technology and existing signalling system are the following:

- Installation interference between signalling components on the track and MDS components, such as linear motor and levitation system;
- Electromagnetic interferences generated by the linear motor and levitation system on signalling components.

16.5.1 Installation interference

The installation of the linear motor in the middle of the existing track interferes with the balises. Several solutions have been identified.

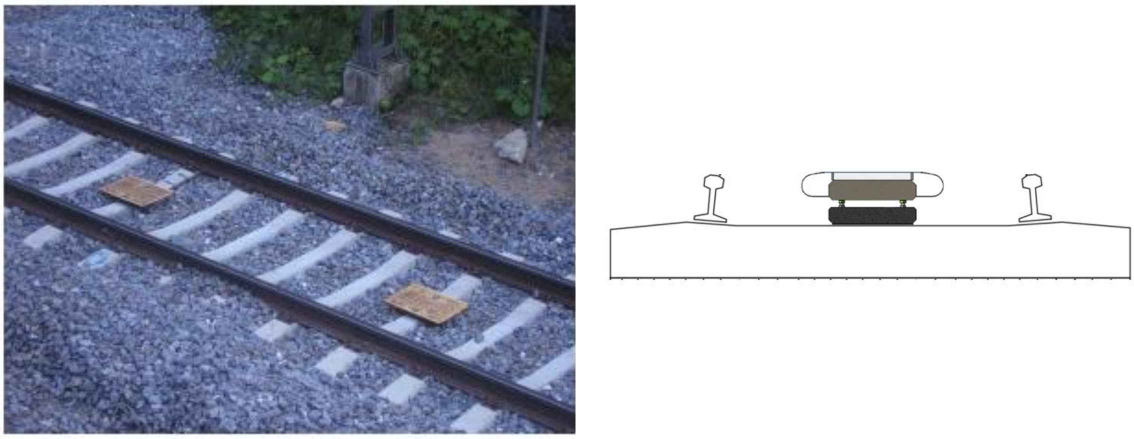


Figure 68 Interference between balise and linear motor in the middle of the track

1) A possible solution identified to avoid this conflict is the introduction of a gap on the linear motor installed on the track (stator). The maximum distance between two consecutive balises within the same group is 12 meters[2]. Depending on the distance between the balises, the linear motor can be interrupted for a short distance, ensuring that interaction with the mover is not lost and it doesn't interfere with the operation of the balise (Ref.16.5.2).

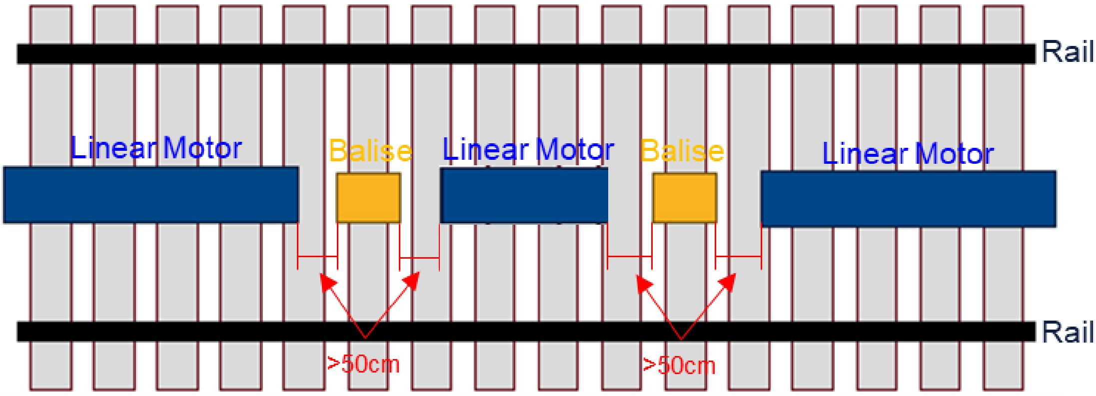


Figure 69 Solution 1 to avoid installation interference between linear motor and balise

2) The solution 2 foresees to split the linear motor in two parts. Each side provides half of the power needed for the traction of the MDS vehicle (Figure 70).

[2] https://www.era.europa.eu/system/files/2023-01/sos2_index013_-_subset-040_v330.pdf

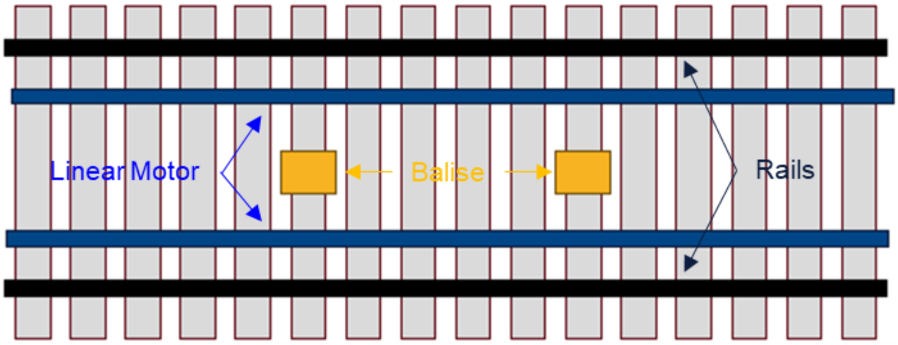


Figure 70 Solution 2 to avoid installation interference between linear motor and balise

3) The solution 3, applicable in the case where levitation rails are installed outside the existing track, foresees the integration of the linear motor in the lateral levitation rail avoiding interference with the balise (Figure 71).

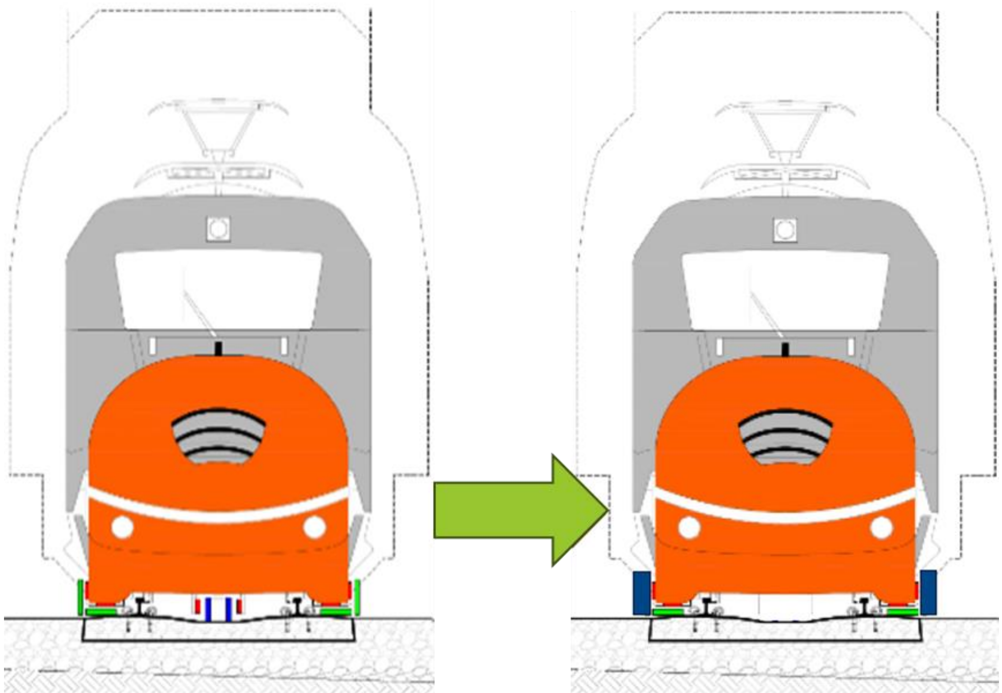


Figure 71 Solution 3 to avoid installation interference between linear motor and balise

Each of these solutions foreseen has pros and cons that should be widely investigated to find the good compromise between cost and performance.

	Solution 1	Solution 2	Solution 3
Pros	Easy to implement.	No mechanical interference with balise Better traction performance without interruption	No mechanical interference with balise Better traction performance without interruption
Cons	Interruption may still create EM interference with the balise Local degradation of traction performance Interference with switches	Increase of cost compared to solution 1 Solution may still create EM interference with balise Interference with switches	Renewal of the track for the installation of the levitation rails. Interference with switches

Figure 72 Summary of pros and cons option to avoid installation interference between linear motor and balise

The use of magnetic sliders for the levitation on the existing rails interferes with the axel counters.

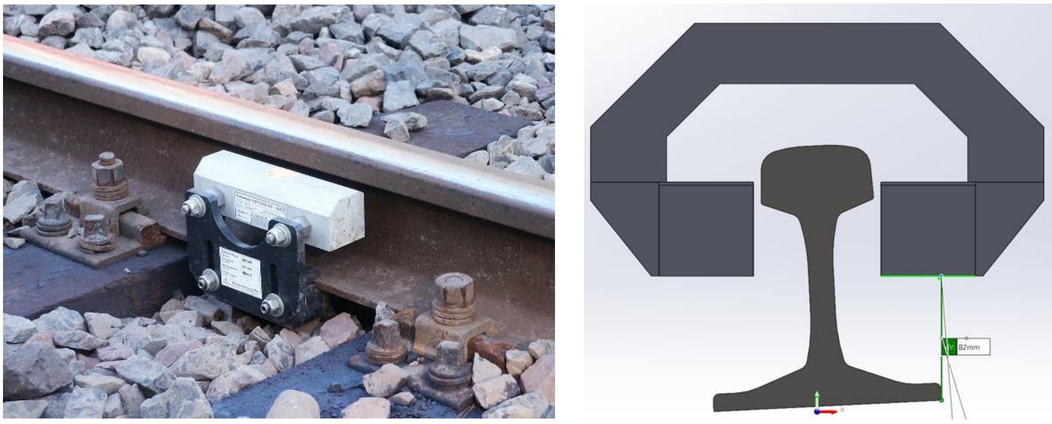


Figure 73 Interference between axle counter and magnetic sliders

In this case, the problem can be solved using track circuits instead of axle counters.

The track circuit guarantees the same functionality than the axle counters without interfering with the magnetic sliders. The track circuit is composed by a cable that connects the rails. The passage of the train generates a short circuit between wheels and rails. The installation of the cable can be adjusted to avoid the conflict with the magnetic sliders.

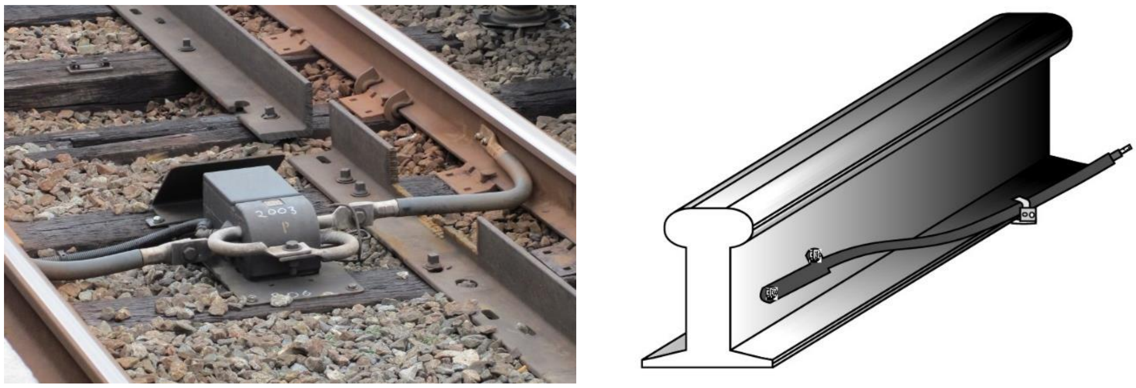


Figure 74 Example of track circuit installation on existing track

16.5.2 Electromagnetic interferences

As already indicated in D6.2 (Ref. [20]), some components of the signalling system could have side effects or malfunctions following the introduction of the electromagnetic fields generated by the linear motor or levitation system of MDS vehicles. These are the following:

- BTM-EUROBALISE
- Radio Communication System
- On-board Train Interface
- Train Detection System TDS (axle counter or track circuit).

In other documents of the MaDe4Rail project (Ref. [20]) the individual aspects and potential causes of malfunctions were addressed. This document aims at identifying which interventions can be made on signalling system or the MDS technology to mitigate potential interferences.

Studies performed on MagLev system shows that EM radiations by the linear motor and levitation systems are within the acceptable limits for passengers and in accordance with the international safety guidelines (Ref. [28], [29], [30]).

However, it doesn't guarantee that the solution adopted for Hybrid MDS won't produce EM interferences with the existing signalling components on the track. The absolute certainty of the impact can be obtained following a rigorous campaign of tests in all the required operating conditions.

In the meantime, some evaluations have been done in the project which are preparatory for future investigations and studies.

Two main sources of EM radiations are present in the H-MDS:

- EM field generated by the linear motor
- EM field generated by the levitation system.

The level of EM field generated by these two systems depends on the type of technology used.

Some considerations are reported in the following in relation to the solution proposed in this work package.

The Linear Synchronous Motor described in the chapter 8 is composed by consecutive segments installed on the track. Each segment is activated only during the passage of the MDS vehicle to provide propulsion. Therefore, the segments adjacent to the signalling components such as balise are those that can create EM interference. Preliminary calculation shows that Linear Synchronous Motor generates a magnetic field with a strength over 400 times higher than specified in Eurobalise regulations during transit. The effects of the EM field on the balise can be the following:

a. EM field generated by linear motor can damage the components of the balise making it unusable.
b. EM field generated by linear motor doesn’t introduce any damage to the components of the balise, however the EM field generated by linear motor interferes with the balise making it unusable to transmit the data (position, track geometry, speed restriction, etc) to MDS vehicle or conventional vehicle on adjacent track.

As shown in the previous paragraph (Ref. Figure 69), a gap should be created in the linear motor installed on the track to avoid any conflict with the balise.

The gap between the two LM segments adjacent to the balises can be adjusted to avoid that the EM field generated by the linear motor can damage the components of the balise.

Electromagnetic simulation studies indicate that the electromagnetic field 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 as shown in Figure 69. This aspect requires further research and validation.

In this way, the balise may still not be used by MDS vehicles, however they can be used by conventional vehicle. The effects of the EM field on balises installed on adjacent tracks should also be verified.

If the installation of the linear motor is done according to the solution 2 shown in Figure 70, the solutions measures shown in the Figure 75**Errore. L'origine riferimento non è stata trovata.** may be used to protect the balise from the EM field generated by the linear motor:

a. The first option foresees the interruption of the linear motor in correspondence of the balise from one side and the installation of an EM barrier on the other side. This solution guarantees the propulsion of the vehicle along the whole track.
b. The second option foresees the installation of an inactive part of the linear motor in correspondence of the balise (green block). This solution allows to minimize the interruption of the traction to the vehicle.

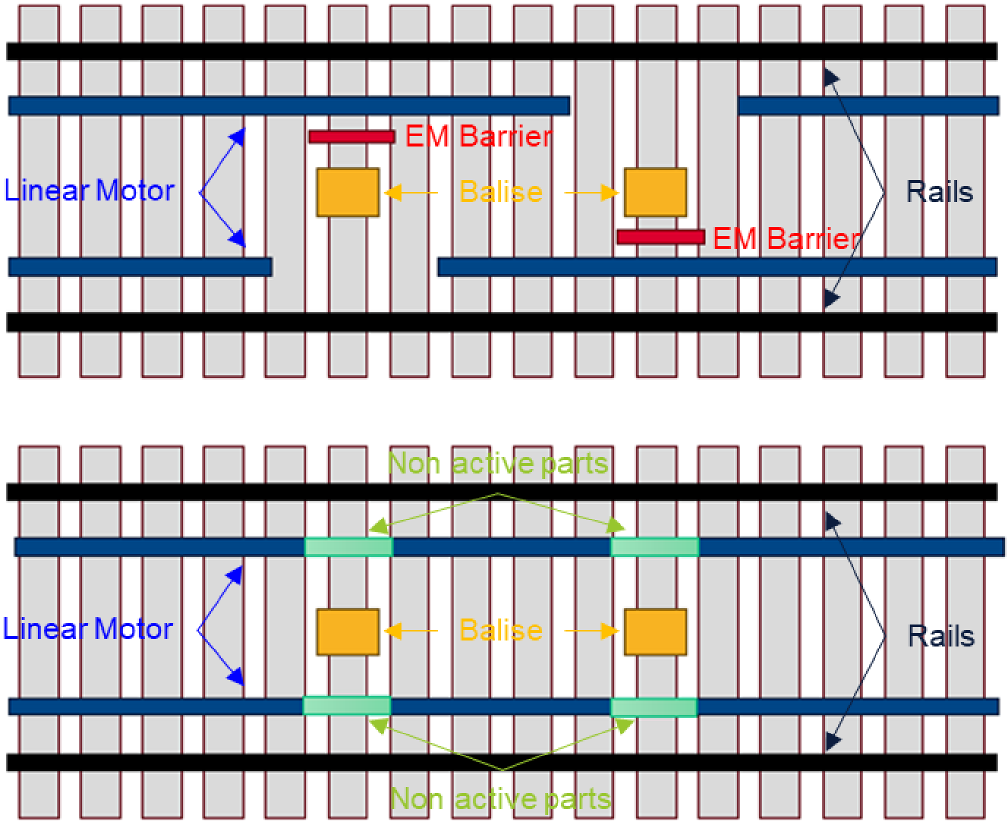


Figure 75 Proposal to limit the EM field generated by the linear motor on the balise

A second source of EM interference is given by the levitation system. In this study, a passive magnetic levitation system has been evaluated. As shown in the following picture, the EM field generated by the magnetic sliders is confined between the sliders and the rail.

Based on the magnetic simulations performed, no influence is expected from the EM field generated by the sliders on the balises which are in the middle of the track, however the influence of the field on the track circuit shall be studied more in detail.

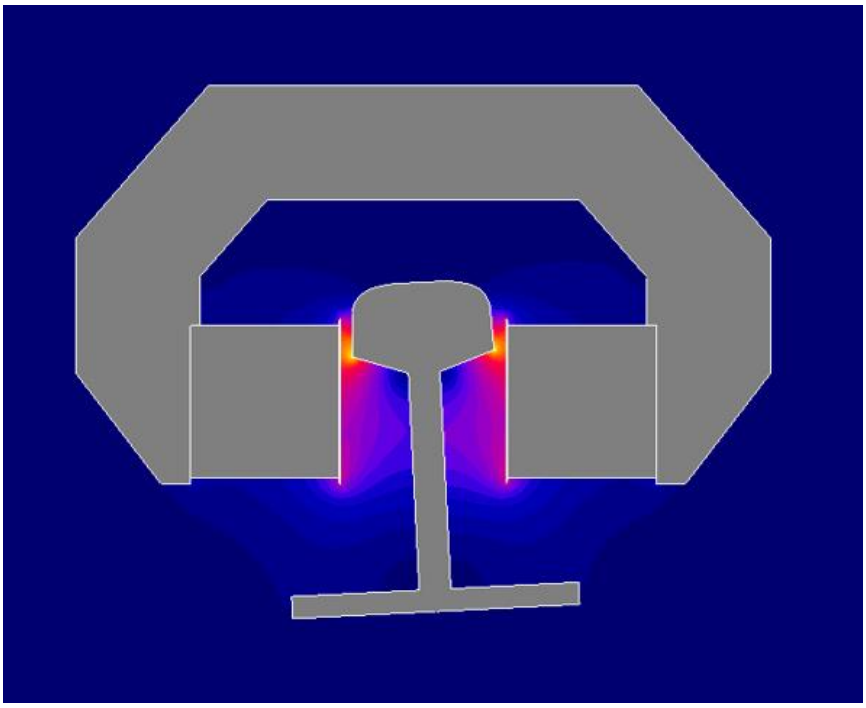


Figure 76 EM field generated by the magnetic slider

17 Conclusion

The concept design of a MDS vehicle based on magnetic levitation has been developed for the use case 3. The vehicle can be used for similar lines, suitably upgraded with MDS technology, to provide regional or intercity service.

The design of the different subsystems of the MDS vehicle has been developed, with special focus on levitation/guidance system and propulsion/braking systems which are strictly linked to the introduction of MDS technology on the existing lines.

The solution proposed for the levitation/guidance system foresees the use of passive magnets able to levitate on the existing rails (Ref. §7). This solution, taken alone, has minor impact on the existing infrastructure, however depending by the line, type of service, and the modifications requested to introduce MDS technology, other solutions as the levitation on external beams (Ref. Figure 57) may be evaluated.

Two different solutions have been investigated for the propulsion/braking system, the first based on Linear Synchronous Motor with active part on the wayside (Ref. §8), the second based on U-shape Linear Asynchronous Motor with active part on board (Ref. §9).

While the first solution based on Linear Synchronous Motor allow to derived position of the vehicle along the line that can be used by the signalling system, the second solution based on Linear Asynchronous Motor with the active part of the linear motor on board allows to reduce the impact of the infrastructure since it doesn't require any modification to the electrical substations and installation of additional cabling along the track.

The signalling system of the MDS vehicle has been analysed considering the interaction with the wayside signalling equipment and the compatibility with the existing ERTMS (Ref. §10).

The concept design of the vehicle communication has been based on FRMCS which will replace the GSM-R from 2035 (Ref. §11).

The electrical system of the vehicle, in particular the auxiliary system power supply has been adapted to the different solutions for the propulsion system (Ref. 14). Where the LSM is used for the propulsion with the active part on the wayside, the MDS vehicle has been equipped with dedicated battery group able to provide the power supply to the onboard auxiliary system. The vehicle equipped with U-LIM configuration will take the power supply from the catenary system to feed the auxiliary systems and the active part of the linear motor installed on-board, similar to the solution used in the conventional vehicle.

Finally, auxiliary systems and interior of the MDS passenger vehicle have been described. These systems are common to the those used in the conventional vehicle and are not impacted by the introduction of the MDS technology (Ref. §12, §13).

A concept design of the bogie for a MDS vehicle based on air levitation has been developed in the chapter 15. The concept design for the bogie has been developed considering a different use case than the magnetic levitation vehicle in accordance with the scenarios analysed in the WP7 (Ref [22]).

The design of the MDS vehicle prototype has allowed to identify new interfaces between the MDS components installed on board and on the track and the existing railway infrastructure. Compatibility issues related to the integration of MDS technology on existing infrastructure have been identified and investigated. They have been described in the chapter 16 and are related to:

- Impact on the existing track due to the installation of the linear motor;
- Interference between levitation system and existing infrastructure;
- Impact on track maintenance activity due to the installation of MDS components;
- Integration of MDS vehicles in the existing signalling system.

The solutions identified during the study require deeper analysis aiming to quantify the impacts of the MDS component on the existing infrastructure (e.g. loads, EM interference, etc) and make a trade-off of the different solution proposed or of new solutions.

This is an essential step to define more precise solutions allowing the integration of the MDS technology in the existing infrastructure and develop a detailed design for the MDS vehicle.

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