



# MaDe4Rail<sub>FA7</sub>

## Deliverable D4.1

**Document on the MDS vehicle subsystem including subsystem definition, system-level interface identification, and methods of integration into the overall common-architecture MDS**

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## 1 Executive Summary

The objective of Deliverable 4.1 is the definition of the Maglev-Derived Systems (MDS) breakdown structure at vehicle level (Chapter 5), the overview of the possible applications of the 3 types of MDS (Chapter 6) – Full MDS, Hybrid MDS and Conventional system upgraded with MDS technologies – and the technology concept descriptions, which consider the main subsystems as per Technical Specifications for Interoperability (TSI) guidelines, like propulsion, guidance, suspension and braking, together with the main interface identification (Chapters 7 to 10). These insights are possible thanks to the results of WP2, which identified the potential technologies to be implemented in the European Common Network.

This deliverable must be considered as a starting point and as an input for a thorough analysis of MDS implementation in the common European network, especially for what concerns the resolution of the possible incompatibilities due to the relevant interfaces between the MDS and the existing infrastructure, which need an in-depth study for each system and application. This deliverable takes in consideration only the technical aspects of the technologies and applications whilst the economical ones are excluded.

## 2 Abbreviations and acronyms

<b>Abbreviation / Acronym</b>	<b>Description</b>
<b>ATC</b>	Automatic Train Control
<b>ATO</b>	Automatic Train Operations
<b>BTM</b>	Balise Transmission Module
<b>CCS</b>	Command Control and Signalling
<b>EDS</b>	Electrodynamic Suspension
<b>EMC</b>	Electromagnetic Compatibility
<b>EMS</b>	Electromagnetic Suspension
<b>ERTMS</b>	European Rail Traffic Management System
<b>ETCS</b>	European Train Control System
<b>EVC</b>	European Vital Computer
<b>GNSS</b>	Global Navigation Satellite System
<b>GoA</b>	Grade of Automation
<b>LIM</b>	Linear Induction Motor
<b>LOC &amp; PAS TSI</b>	Rolling Stock - Locomotives and Passengers TSI
<b>LSM</b>	Linear Synchronous Motors
<b>MDS</b>	Maglev-derived System
<b>MTBF</b>	Mean Time Between Failures
<b>OBU</b>	Onboard Unit
<b>RBC</b>	Radio Block Centre
<b>SBS</b>	System Breakdown Structure
<b>TCMS</b>	Train Control Management System
<b>TTC</b>	Train Test Centre
<b>TSI</b>	Technical Specification of Interoperability
<b>V2V</b>	Vehicle-to-vehicle
<b>WP</b>	Work Package
<b>WPT</b>	Wireless Power Transfer



### 3 Background

The present document constitutes the Deliverable D4.1 “Document on the MDS vehicle subsystem including subsystem definition, system level interface identification, and methods of integration into the overall common architecture MDS” in the framework of the MaDe4Rail project within Flagship Area 7- Innovation on new approaches for guided transport modes as described in the EU-RAIL MAWP.



## 4 Objective/Aim

This document will define the generic MDS vehicle breakdown structure to provide a unified framework to create and compare different configurations of MDS vehicles. This activity will be possible by exploiting the results of the Work Packages 2 and 3, which identify the basic technologies supporting MDS and the associated risks and standard implementation.

The definitions of MDS and of the components enlisted in the MDS vehicle system breakdown structure (SBS) and the possible applications in the common European Network will be proposed.

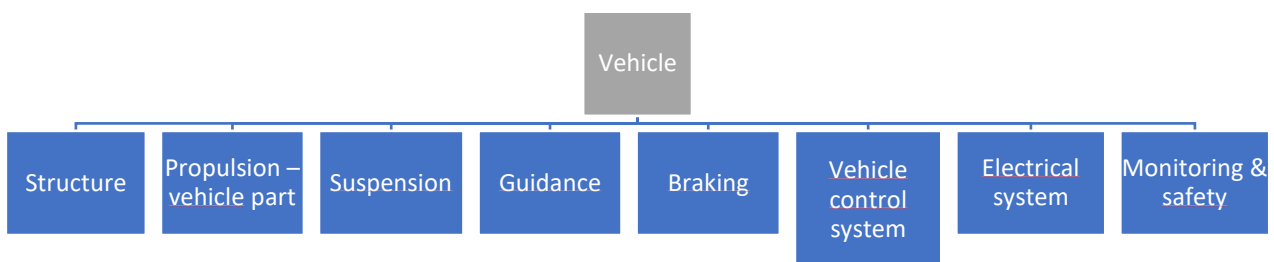
The description of the vehicle concept comprising its functional components and properties of 3 MDS configurations (Full, Hybrid and Conventional upgraded) will be developed, detailing the characteristics of the subsystems as defined in the Rolling Stock - Locomotives and Passengers TSI (LOC & PAS TSI).

Finally, the interfaces within the MDS and between the MDS (Hybrid and Conventional wagons upgraded with MDS technologies) and the existing infrastructure will be identified, to allow more detailed studies of the technologies implementation within the existing common European Network and the associated risks.

## 5 MDS Vehicle breakdown structure and definitions

### 5.1 Vehicle System Breakdown Structure (SBS)

The MDS vehicle breakdown structure has been created in WP2. The extract of this breakdown structure has been shown in Figure 1. The aim of the SBS is to provide unified framework to create and compare different MDS vehicles.



**Figure 1 - System Breakdown Structure for MDS vehicle**

The structure of the vehicle could be new or retrofitted, the propulsion component on the vehicle may be a linear motor primary in form of permanent magnets (LSM) or 3-phase windings with or without back-iron. Suspension and guidance of the vehicle could be based on wheels, levitation modules or air-cushions. Vehicle control system could be e.g., Train Control Management System (TCMS) or other dedicated systems used in MDS. Braking component may be inherent part of the linear motor, electrodynamic wheels or a wheel-based railway braking systems. Electrical systems could be onboard power sources, current shoe, pantographs, WPT or other. Monitoring and safety are vehicle management subsystems or measuring and protective devices e.g., anti-collision radars or vehicle “heartbeat” sensors.

### 5.2 Definitions

A Maglev-Derived Systems (MDS) can be defined as innovative, fast track-bound transportation systems for rail application that use maglev-based technologies, such as linear motors with magnetic/pneumatic levitation, as their foundation.

The definitions of the components enlisted in the MDS vehicle SBS are shown in Table 1.

**Table 1 - MDS breakdown structure – definitions**

Subsystem	Component	Definition
Vehicle		The MDS movable subsystem which is used to transport passengers and goods along predefined guideway.

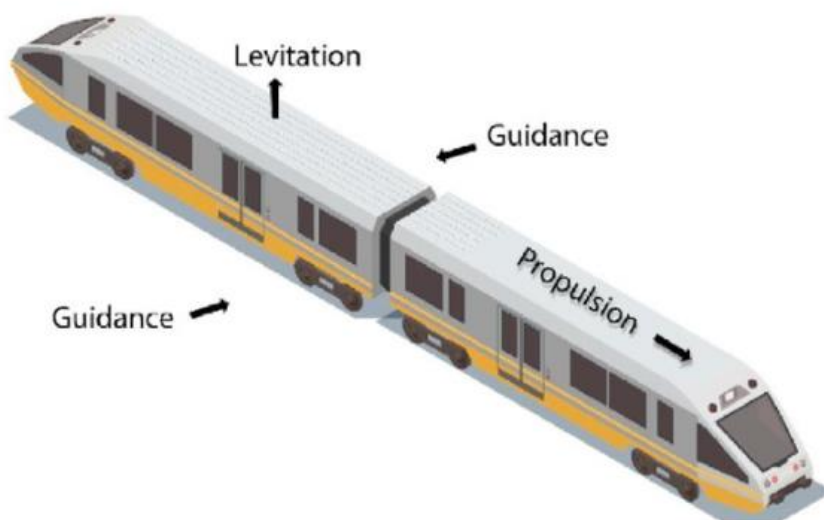
	Structure	Refers to the vehicle structure which could be frame or monocoque used to transfer the loads and mount other vehicle components. It may be new or retrofitted using existing rolling stock.
	Propulsion – vehicle part	System component that enables longitudinal movement of the MDS vehicle. It enables both acceleration and deceleration. It may be electromagnetic (LSM), electrodynamic (LIM), friction-based (wheels), or combined.
	Suspension	Component that enables counteracting vertical load and/or maintaining the vertical position of the MDS vehicle. It may be electromagnetic, electrodynamic, mechanical (wheels), pneumatic, passive or combined.
	Guidance	Subsystem that enables maintaining the lateral position of the MDS vehicle. It may be electromagnetic, electrodynamic, mechanical (wheels), pneumatic, or combined.
	Braking	Combination of parts that either progressively reduces the speed of the moving vehicle or brings the vehicle to a halt and/or holds it stationary or fulfils both functions. It may be integrated with the propulsion system or mounted as a separate subsystem.
	Vehicle Control System	Refers to the vehicle component that supervises electronically the vehicle movement, accelerations and deceleration curves, emergency responses and health checks. Usually connected to the Command and Control subsystem.
	Electrical system	Component essential to power all electrical and electronic devices in the vehicle which deals with the conversion, transmission, storage or switching of electric power with or without control of that power.
	Monitoring & Safety	Component or set of components that enables monitoring the vehicle state and condition, also preventing unwanted events (e.g., anti-collision system).

## 6 Overview and applications of selected MDS

Based on the methodology and the MDS reported in the deliverable D2.1, 3 configurations of MDS have been distinguished: Full MDS, Hybrid MDS (based on air levitation or magnetic levitation) and Conventional railway systems upgraded with MDS technologies.

### 6.1 Full MDS

A Maglev system, define as full MDS for the scope of the project, is a transportation system that uses magnetic forces for vehicle suspension and propulsion instead of standard wheels and rails. Examples of urban transit systems and high-speed trains linked to this technology can be found around the world, mainly in Asia. Figure 2 represents the working principles of a maglev train.



**Figure 2 - Working principles of a MDS vehicle**

Maglev systems use magnetic fields to overcome gravity by suspending carriages using the principles and techniques of magnetic levitation. The electromagnetic forces required to implement the technology in the transportation sector can be generated in a variety of ways; the common distinction includes:

- Electrodynamic suspension, where the electromagnetic forces are produced as a result of the relative motion between the conductive element and an electromagnetic field source (e.g., permanent magnets with an aluminium track, or permanent magnets' track and superconductive electromagnets).
- Electromagnetic suspension, where the forces are produced by electromagnets on a magnetically conductive track.

- Passive suspension, where alternative methods of force generation are available that are based on forces produced by passive elements, such as permanent magnets, rather than dynamic effects, such as ferromagnetic levitation.

## 6.2 Hybrid MDS

Hybrid Maglev Derived Systems (MDS) represent an innovative approach to enhance existing railway infrastructure. These systems can utilize either airlev or maglev technologies, and are designed to be fully interoperable and integrated with current railway systems, ensuring seamless operation and improved efficiency.

### 6.2.1 Based on air levitation system

A hybrid MDS system based on air levitation generally refers to a transportation system that relies both on wheel-based suspension and air levitation suspension in combination or during different operative conditions. An air-cushion vehicle, also named as airlev vehicle for the purposes of the project, is an important alternative for hybrid MDS development. Integrating airlev trains into existing railway systems as well as possible new railway infrastructures is the main idea behind the concept of hybrid MDS based on air levitation. The main contents of this section are based on the US patent and EU patent – Levitation system for a train (Grant No. US 10293803B2 and EP 2701960).

The principle behind air cushion suspension is rooted in creating a pressure differential between the air inside and outside an air chamber. This generates enough mechanical force to lift an object, such as a vehicle, a few millimetres off the ground. In parallel with maglev technologies and solutions, air cushioned technology for railways (or track way in general) has been studied since 1950s. Recently, air levitation for railway vehicles becomes worthy to study, since the air multiplier technology has enabled enough air levitation forces to train. This brings us to the threshold of the next potential leap in railway technology, the air levitation train, in short, the Airlev train. This technology will utilize a cushion of air to lift the vehicle, which was envisioned to further eliminate friction, reduce energy consumption, and enable even higher speeds similar to maglev trains but with much lower costs.

Instead of using wheels in direct contact with rails, airlev trains use powerful fans to create a cushion of air underneath them, effectively levitating the vehicle above the track. This not only decreases friction but also reduces wear and tear on both the vehicle and the infrastructure, promising greater longevity and lower maintenance costs.

The concept of air levitation technology for railway (or guide way) vehicles can be traced back to 1956, such as Tracked Hovercraft (United Kingdom) and Aerotrain (France). The original idea of levitating vehicle with air is from the hovercraft. Pioneers in this field envisaged a transportation system that would harness the power of air to lift vehicles and propel them at high speeds using air or linear induction motor (linear synchronous motor).



These early concepts laid the groundwork for what would eventually evolve into the airlev train technology. While there have been significant strides in the development of this technology, still under development.

Among the various airlev train technology systems described in the literature, the USA tracked air-cushion vehicle stands out with a more detailed account. This is due to its more complete prototype development history, extensive design and parameter details, comprehensive sub-system information, and documented test runs. Most importantly, the USA tracked air-cushion vehicle aligns closely with the purposes and use-cases of the MaDe4Rail project.

For instance, other airlev systems, such as the Cairo Airport APM – Minimetro, briefly introduced in Deliverable 2.1, serve as short-distance people movers driven by cable. This system is unsuitable for intercity or high-speed railway applications. Similarly, the French air-cushion technology, which utilizes an upside-down 'T' shaped track, cannot be integrated into conventional railway systems. Additionally, its propulsion method relies on a jet engine, producing unacceptable noise levels.

After evaluating all available technologies in conjunction with the use-case requirements of MaDe4Rail and the completeness of the literature information, the USA tracked air-cushion vehicle technology was selected for detailed description. This decision was based on its historical development, detailed design and parameter information, comprehensive sub-system documentation, and successful test runs, all of which provide a robust foundation for understanding and potentially implementing this technology in the MaDe4Rail project.

## 6.2.2 Based on magnetic levitation

A hybrid MDS system based on magnetic levitation generally refers to a transportation system that relies both on wheel-based suspension and magnetic levitation suspension in combination or during different operative conditions. As an example, the vehicle can operate on wheels during switch crossing or platform approaching and on magnetic levitation systems on dedicated maglev corridors. The propulsion can be wheel-based during wheeled operation while different technologies can be adopted during maglev operations. A proper choice of the propulsion technology must be done based on a compatibility study and an economic evaluation. The vehicle shall be designed in order to ensure the compatibility with the existing or upgraded railway infrastructure as well as the interoperability of the transportation system.

A detailed description of magnet levitation MDS and its subsystems are described in detail in chapter 8.

### 6.3 Conventional system upgraded with MDS technologies

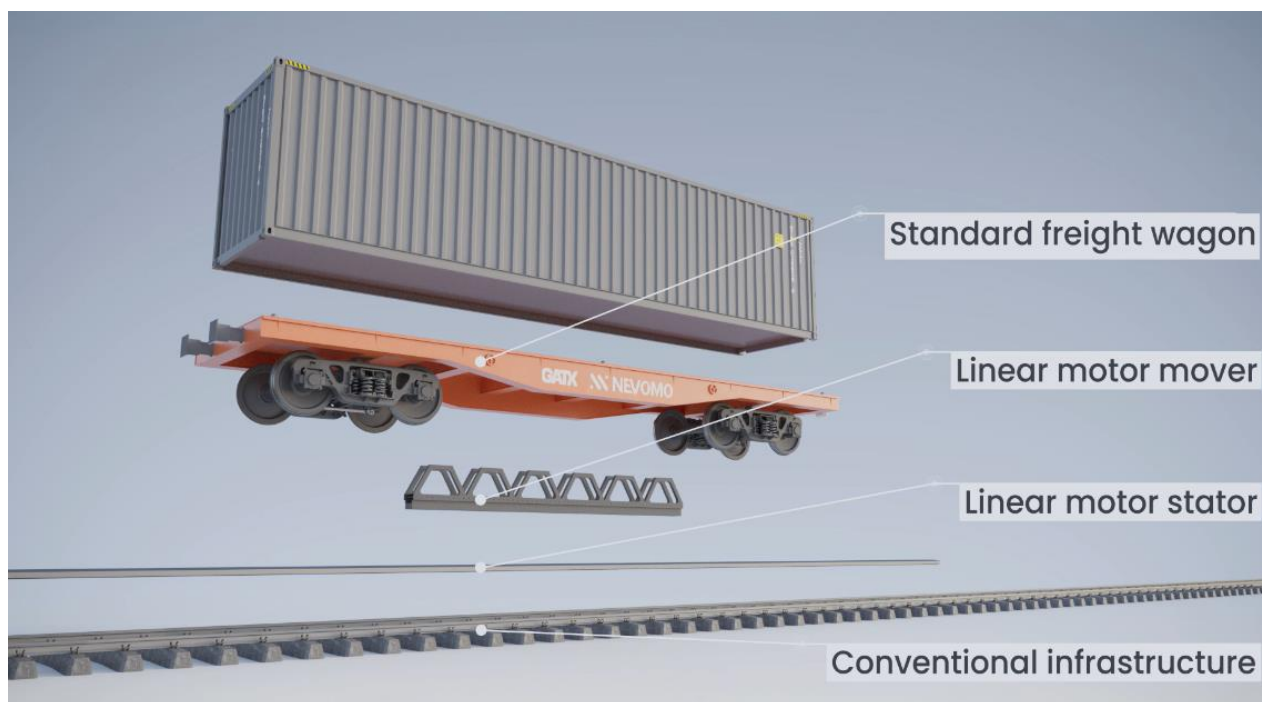
The following section refers to systems that take advantage of traditional wheel-rail contact as support means, while relying on other forms of propulsion technology, levitation, guidance derived from maglev systems. This “hybrid” configuration gives the advantages of:

- Increase in the allowable track slope,
- No limitation of traction due to adhesion between the wheel and the rail,
- Absence of rotating components,
- Compact wagon design (no overhead catenary required to power the electrified vehicles).

The electrical system in a maglev system constitutes components such as levitation, guidance, propulsion, input power transfer and control. This system generally derives power from linear motors for its propulsion and braking mechanism.

Technological enhancement of rail transportation technology requires either up-grade of the on-wheel railway infrastructure or construction of dedicated corridors for running maglev-based systems connected through passenger stations interoperability. Regardless of efforts to improve and upgrade conventional railway systems, they are limited in achieving speeds of more than 350 km/h with desired efficiency. Maglev technology has emerged as a breakaway from the conventional wheel-based technology for achieving higher speeds with better performance. On-wheel rail systems use adhesion between wheels and rails to move forward, while maglev systems use propulsion force generated by a linear electro-mechanical system, to move forward. This linear propulsion system replaces conventional rail wheels with electromagnets, by yielding sufficient force to levitate the train on the guideway. (Prasad, N., Jain, S., & Gupta, S. (2019)).

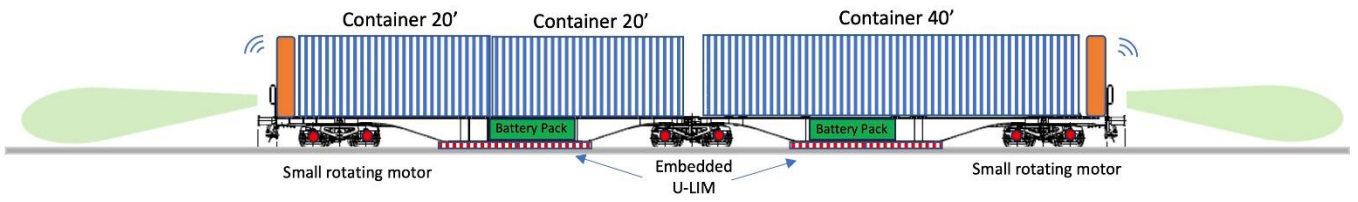
An example of such an upgraded system is MagRail Booster developed by Nevomo. The vehicles are retrofitted freight wagons equipped with linear synchronous motor mover and other necessary components like position sensors, pressure tank, onboard electronics, communication components, etc.. Railway wheels and rails act as a suspension and guidance for MagRail Booster. On the infrastructure side there is a linear motor stator. High-level description of this MDS configuration based on the system breakdown structure defined in 5.1 is presented in 9.3, and the relevant interfaces are shown in 10.3.



**Figure 3 - MagRail Booster system – retrofitted freight platform with linear synchronous motor installed**

An alternative solution of upgraded freight rail car is a container autonomous rail shuttle propelled by U-LIM (“U-CARS” designed by TACV Lab), based on standard articulated freight wagon (Sggmrss90) for low-speed short lines (port terminal, multimodal logistics platform or a train station...). It integrates adapted components, such as light axel electric drive for station shunting operation, supplied by onboard batterie packs using ground dynamic charging system (derived from tramway APS Alstom technology). It is equipped with an autonomous mobility system based on automotive technologies, and possibly integrates an automatic lateral transshipment (rail/rail or rail/truck) system. More detailed traction, braking and guidance description is presented in chapters 8.1, 8.2, 8.4, 8.5, 8.6 and 8.7.

The U-CARS does not require significant modification of the existing rail tracks, only adding the U shape armature in the centre of the track. Thanks to the LIM, high ramp can be overpassed, when the adhesion coefficient of the wheel/rail contact cannot assume this action.



**Figure 4 - "U-CARS" (TACV Lab design based on standard articulated wagon, mix propulsion by U-LIM and light axel electric drive).**

## 7 Description of the concept for vehicle subsystems – Full MDS

In this chapter, the vehicles' concepts (functional components + properties) have been described, starting from the common architecture based on the SBS defined in Chapter 5.

### 7.1 General overview

A first description of the main existing systems based on magnetic and air levitation is introduced in document D2.1 in chapter 5.3.

Magnetic levitation systems were classified according to the type of levitation into Electromagnetic suspension (EMS), Electrodynamic suspension (EDS) and Passive suspension. In order to contextualize this chapter, the main characteristics of the main systems are described below.

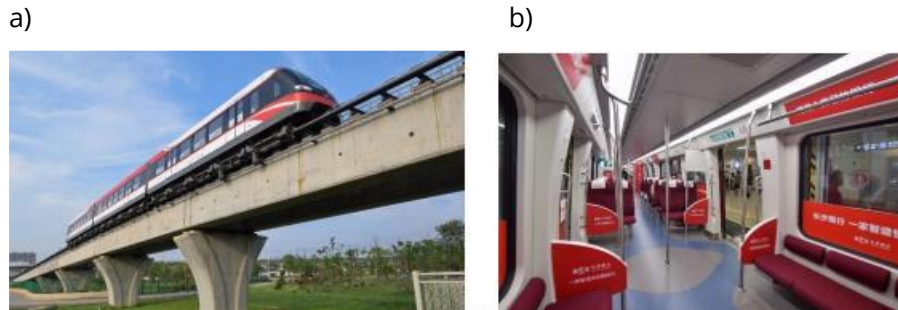
- Line S1 of the Beijing Subway [3] is a medium-low speed maglev line. It is operated by the Beijing Mass Transit Railway Operation Corporation Limited. The line was opened on 30 December 2017. It starts from Pingguoyuan in Shijingshan District and goes west towards Shichang in Mentougou District for a total length of 10.2 km. This system features a six-coach maglev train manufactured by CRRC Tangshan Co. Its basic principle of levitation is Electromagnetic Suspension (EMS).



**Figure 5 - The Beijing Line S1: vehicle and infrastructure**

- The first commercial urban maglev line in China became operational in Changsha in 2016 [4, 5]. Five 3-car, medium-low speed maglev trains are currently operating on the Changsha South Railway Station – Huanghua Airport Line in China. The line runs across 18.55 km. CRRC not only manufactures the vehicles, but also provides the majority of

related equipment for the line including power supply systems, signalling and BEL locomotives. Its basic principle of levitation is Electromagnetic Suspension (EMS).



**Figure 6 - The Changsha Maglev: a) vehicle and infrastructure b) interior structure.**

- Transrapid [10, 11] is a German-developed high-speed monorail train using magnetic levitation. Planning for the Transrapid system started in 1969 with a test facility for the system in Emsland, Germany completed in 1987. In 1991, technical readiness for application was approved by the Deutsche Bundesbahn in cooperation with renowned universities. The system is developed and marketed by Transrapid International, a joint venture of Siemens and ThyssenKrupp. Its basic principle of levitation is also Electromagnetic Suspension (EMS).

The only commercial implementation so far was in the year 2000, when the Chinese government ordered a Transrapid track to be built connecting the city of Shanghai to its Pudong International Airport. The Shanghai Maglev Train [12, 13] was inaugurated in 2002 and regular daily trips started in March 2004. The travel speed is 431 km/h, which the Maglev train maintains for 50 seconds as the short, 30.5 km track only allows the cruising speed to be maintained for a short time before deceleration must begin. The average number of riders per day (14 hours of operation) is about 7,500, while the maximum seating capacity per train is 440. The trains in Shanghai are of the Transrapid SMT type, which is based on the German Transrapid TR 08.



**Figure 7 - Outline (above) and picture (below) of the Transrapid SMT (Shanghai Maglev Transportation Development) vehicle**

- The first maglev utilizing electromagnetic suspension opened to public was HML-03, which was made by Hyundai Heavy Industries, for Daejeon Expo in 1993 after five years of research and manufacturing two prototypes: HML-01 and HML-02 [21 - 23]. The first urban maglev opened to public was UTM-02 in Daejeon on 21 April 2008 after 14 years of development and building one prototype: UTM-01. The urban maglev runs on 1 km track between Expo Park and National Science Museum. Meanwhile UTM-02 remarked an innovation by conducting the world's first ever maglev simulation. However, UTM-02 is still the second prototype of a final model. The final UTM model of Rotem's urban maglev, UTM-03, is scheduled to debut at the end of 2012 in Incheon's Yeongjong island where Incheon International Airport is located. As a continuation of the previous system, in 2016, a 6.1 km-long urban maglev line was inaugurated at Incheon airport, called ECOBEE [14]. Incheon International Airport and its surrounding area were selected by the Korean government as a maglev demonstration line for ECOBEE in 2007. ECOBEE is an EMS-based system, with U-shaped magnets and LIMs for levitation and propulsion. The operation scheme is almost the same as that of Linimo.
- The urban transit system known as Linimo [16, 17] is an EMS-based system and Linear Induction Motors (LIM), that has been in successful operation along the Tobu Kyuryo Line in Nagoya since 2005. The line is 8.9 km long with maximum inclines of 6% and minimum curve radii of 75 m. The vehicle run with maximum velocity of 100 km/h. The guideway infrastructure is composed of several essential components, including a U-shaped rail for levitation, a reaction plate tailored for the operation of the Linear Induction Motor (LIM), sleepers, girders, power rails, and signalling cables.

- The Sengenthal system [18 - 20] is also known as the Transport System Bögl (TSB). The TSB is an EMS-based system. This automated guided vehicle (AGV) system is designed to operate in urban areas over distances ranging from 5 to 30 km and is adaptable to operate worldwide. The trains for this system consist of two or more cars, each driven by a system of short-stator linear motors.
- Fenghuang Maglev [9] is a medium and low speed maglev rail line in Fenghuang County, Xiangxi Prefecture, Hunan Province, China. The first phase officially started operation on 30 July 2022 and connects the Fenghuanggucheng station on the Zhangjiajie-Jishou-Huaihua high-speed railway with railway with Fenghuangdengdai. It is an EMS-based system.
- The Tongji University Maglev system [29] uses the magnetic force of rare earth permanent magnetic material to realize a suspension, non-contact operation of a new air rail transit system, and it is a suspension maglev rail transit system which incorporates permanent magnet maglev, DC motor and intelligent transportation. The system has the advantages of lower building cost and lower maintenance cost, and can save more energy, protect the environment, and has less space occupation, high safety coefficient and less magnetic pollution.
- The Chuo Shinkansen [6 - 8] is a Japanese maglev line under construction between Tokyo and Nagoya, with plans for extension to Osaka. Its initial section is between Shinagawa Station in Tokyo and Nagoya Station in Nagoya, with stations in Sagami-hara, Kofu, Iida and Nakatsugawa. Following the completion of the Tokyo-Nagoya line, the line will extend to connect stations in Mie, Nara and Osaka. The line is expected to connect Tokyo and Nagoya in 40 minutes, and eventually Tokyo and Osaka in 67 minutes, running at a maximum speed of 505 km/h (314 mph). About 90% of the 286-kilometer (178 mi) line to Nagoya will be tunnels. The project was named MLX and the first prototype vehicle, ML100, was built in 1972. After this, a series of maglev trains have been built and tested. All the Japanese MLX models used superconductivity and the vehicle-guideway design is based on repulsive magnetic forces. The levitating force is generated between superconducting magnets on the trains and coils on the track. Currently, the last two series of vehicles (the "Series L0" and "Series L0 Improved version"), developed by JR Central, are operating on the Yamanashi Maglev test line. Series L0, started running in 2013, is the first-generation vehicle built with specifications for commercial services. On April 22, 2015, the Japanese superconducting maglev system L0 achieved a running speed of 603 km/h – a record for any guided vehicle. Series L0 improved version, started running in 2020, is the further brushed up version built based on various test data acquired from the original Series L0. The Series L0 improved version has fully adopted inductive power transmission method, which was developed as the specification for operational

vehicle. This has eliminated the use of gas turbines, installed in leading cars for the original Series L0. In fact, the Maglev Technological Practicality Evaluation Committee determined in September 2011 that the inductive power transmission technology used in the Superconducting Maglev has been established sufficiently for practical use as on-board power source. Moreover, the nose shape of the Series L0 improved version has been optimized, based on the results of running tests carried out with the original Series L0 train, to reduce air resistance by approx. 13%, thereby lowering power consumption and outside noise. The front vision camera and front light, installed at the nose section in the original Series L0, have been relocated to higher positions to improve front visibility. These vehicles are planned by the Central Japan Railway Company to be in service over the route between Tokyo and Nagoya in 2027, as the first phase of its entry into public service.

- Swissmetro [24] is a high-speed (500 km/h) magnetic levitation train project that differs from other existing systems, such as the German Transrapid, the Japanese MLX and the Japanese HSST, by its underground infrastructure of stations and tunnels under partial vacuum (8000 to 10,000 Pa). Swissmetro technologies have demonstrated the technical feasibility of the concept within a national and international network of industrial and academic partners. The Swissmetro project is a public transport system between the main cities of Switzerland, designed for speeds of up to 500 [km/h] in two tubes (tunnels) under partial vacuum. Every 6 [min], a vehicle carrying 200 passengers would travel without contact with the infrastructure through an application of linear motor technology, magnetic levitation and guidance. Low energy consumption is achieved by reducing drag. The system uses a partial vacuum maintained in the tunnels to reduce the energy required to propel the pressurised vehicles, which are based on the airframe principle; a propulsion system using linear electric motors that are interdependent with the tunnels themselves; and a magnetic levitation and guidance system allowing high speeds of around 500 km/h.
- Inductrack [15] uses passive induced-current system employing permanent magnets on the moving vehicle, in the Inductrack system repelling magnetic forces are produced by the interaction of a flux-concentrated magnetic field, produced by permanent magnets arranged in a Halbach array electromagnets, with an inductively loaded closed electric circuit.
- In mid-1971, the U.S. Department of Transportation (DOT) funded the development of a 60-passenger TACV capable of reaching speeds of 150 miles per hour (241 km/h), using linear induction propulsion and air cushion levitation. The Prototype Tracked Air Cushion Vehicle (PTACV) has a weight of 64,000 pounds (29030 kg), measures 95 feet (29 m) in length, 10.5 feet (3.2 m) in width, and 10.5 feet (3.2 m) in height. Designed as an all-electric vehicle, it can accommodate 60 passengers along with their luggage. The

Prototype TACV provides its passengers with an exceptionally smooth and quiet high-speed travel experience, maintaining a cabin noise level of 82 dB(A). Testing at speeds of 100 miles per hour on the Pueblo guideway has highlighted the vehicle's superior performance relative to other ground transportation methods.



**Figure 8 - Grumman Aerospace Corporation started design of their Tracked Levitated Research Vehicle (TLRV) in March 1970**

This analysis was based on the subsystem decomposition established in the MDS breakdown structure defined in chapter 7.1 of the deliverable "D2.1. Functional, technical, operational and economic overview of conventional rail systems, traditional magnetic levitation systems and innovative magnetic levitation derived systems" [2].

## 7.2 Structure

According to [2], the Structure refers to the framework of the vehicle, which can be a frame or a monocoque that is used to mount other vehicle components and transfer loads. It could be newly created or modified utilizing already-existing rolling stock.

The following is a description of the design and development of the structure of some of the identified maglev systems which are currently in operation:

## Changsha Maglev

The technical data of the Changsha Maglev Express (CME) vehicles [4, 5] are given in the following table.

**Table 2 - Changsha Maglev Express (CME): Technical data**

Train Marshalling	3-car Formation
Carbody	All-welded Aluminum Alloy V Structure
Rated Power Supply Voltage	DC 1,500 V
Gauge	1,860 mm
Max. Width of Train	2,800 mm
Carbody Length	15,510 mm (MC car) 15,000 mm (M car)
Vehicle Height (ToR to Vehicle Top)	3,700 mm
Clear Height of Saloon Height of Vehicle Floor to ToR	880 mm
Net Height of Passenger Compartment	2 100 mm
Distance between Centers of two Suspension Frame Modules	2,800 mm
Lateral Distance between Centers of two Suspension Frame	8,400 mm
Number of Suspension Frame Modules	5 per car
Rated Suspension Height	8 mm
Max. Operating Speed	100 km/h

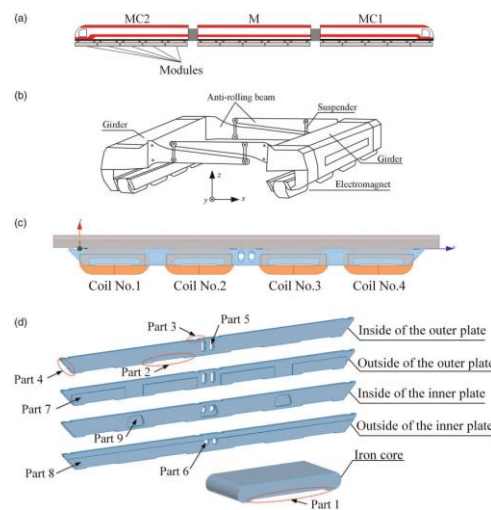
It has three vehicles, including two head carriages (MC1 carriage and MC2 carriage) and one middle carriage (M carriage), which can run in both directions.

Figure 9 (a) indicates the simplified model of CME's maglev train. Each carriage contains ten electromagnet modules, five on each side. One pair of electromagnet modules paralleled on both sides of the carriage is installed on a single mechanical bogie. In other words, five bogies will be installed underneath each carriage.

Figure 9 (b) shows the structure of the bogie. The anti-roll beam and the suspender are elastically connected to release some degrees of freedom of the girders, which is used to decouple the mutual mechanical coupling between the paired electromagnet modules. In this way, the control will become much easier as the control of each electromagnet module will

be hardly influenced by the control of others. An electromagnet module is the basic unit which consists of four coils for cooling, as shown in Figure 9 Figure (c). In CME trains, coils No. 1 and No. 2 are driven by the same controller, which is similar to No. 3 and No. 4. In other words, every electromagnet module has two levitation points controlled by the same levitation current. So, each vehicle has 20 levitation points.

Figure 9 (d) marks the details of CME's electromagnet module. On one hand, it accounts for the installation, where part 1 and part 2 are ventilation notches for the cooling of the coil, part 3 are notches of the slider, part 4 are sections for sensor mounting, and part 5 and part 6 are installation holes for braking equipment. On the other hand, it considers optimization, with part 7 and part 8 being the thickened portions of the plates (in order to meet the installation requirements, with part 7 partially thickened), and part 9 the weight reduction notches.



**Figure 9 – Electromagnetic suspension system of Changsha Maglev Express: (a) simplified model of a maglev train; (b) structure of bogie; (c) overall view of electromagnet module; and (d) partial view of electromagnet module.)**

### Chuo Shinkansen

The Chuo Shinkansen [6-8] will employ the SCMaglev technology, a maglev (magnetic levitation train) system which equips the last two series of vehicles (the “Series L0” and “Series L0 Improved version”) developed by JR Central.

The following table shows the technical data of the Series L0 Improved version vehicles in experimental service on the Yamanashi Maglev line.

**Table 3 – Series L0: Technical data**

Maximum operational speed	311mph
Passenger capacity	Up to 24 for leading cars and up to 60 for middle cars
Car length	91.8ft for leading cars and 79.7ft for middle cars
Car width	9.5ft
Car Height	10.1ft
Car material	Aluminium alloy
Weight	Approx. 25 metric tons (for one middle car)

### Transrapid 09

Figure shows the TR09 in operation on the TVE [10, 11]. The vehicle was developed in accordance to the requirements of Deutsche Bahn regarding an airport connector. The transformation of these requirements had influence on the technical realization of several onboard systems, e.g., door system, air conditioning, carriage body design and auxiliaries, like onboard camera systems, fire detection and fighting system or the interface architecture concerning the passenger information systems. Also, the levitation guidance system had to be adapted regarding the requirements of higher payload.



**Figure 10 - TR09 in operation on TVE**

Table 4 shows the comparison of the relevant data concerning the transport capacity between TR09 and TR08.

**Table 4 - Number of transport capacity (3-section vehicle)**

	<b>TR08</b>	<b>TR09</b>
Seats	310	156
Standing room	-	82.1 m <sup>2</sup>
Max. Passenger capacity	310 people	449 people
Payload	27.9 t	40.4 t

Apart from the technical and optical design of the TR 09, development also focussed the attention on the passenger-relevant comfort criteria such as the headrooms inside the vehicle, the pressure tightness, the air-conditioning and the sound level inside the passenger compartment.

The main dimensions of the vehicle are summarised in Table 5 and Table 6.

**Table 5 - Vehicle configuration**

<b>Dimensions of the vehicle sections</b>	<b>E1/E2 in mm</b>	<b>M in mm</b>
Section lengths (referred to the centre of the section coupling)	25500	24768
Outer width of carriage body	3700	3700
Length of triple-section vehicle	75768	

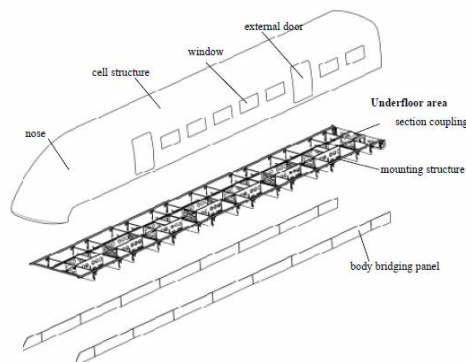
**Table 6 - Carriage body dimensions**

Height of the carriage body above guideway gradient (without antenna)	3350 mm
Height of carriage body above finished floor level on the outside	2400 mm
Height of carriage body above finished floor level on the inside	2330 mm

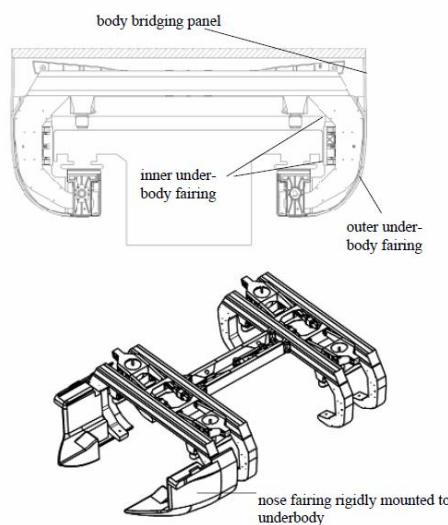
## Shanghai Maglev

The train consists of five sections, each section consists of a car body and running gears which connects the levitation and guidance magnets [10 - 13]. The running gear is also called Magnetic Wheels.

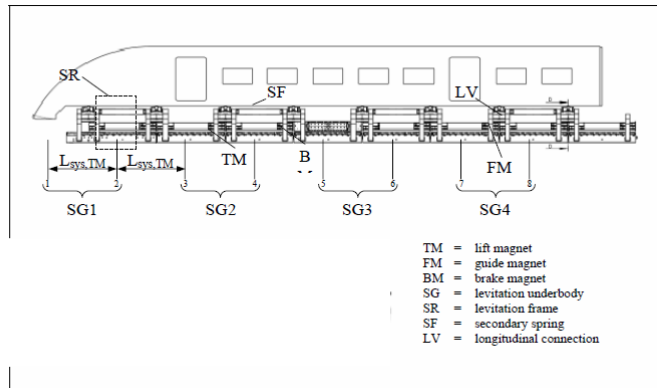
Two adjacent Magnetic Wheels are connected to form a so-called levitation bogie. There are four such levitation bogies under a car body. The levitation bogies are designed to enable transmission of vertical forces to support the car body and to transmit lateral forces to guide the train, transmission of longitudinal forces provides for braking and traction forces. Consequently, it is a very important component in the vehicle for both safety and comfort.



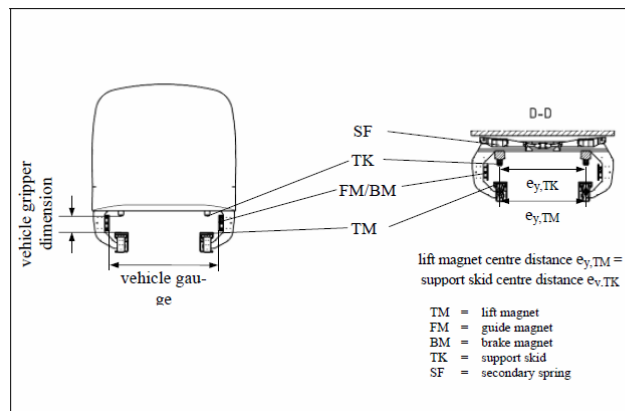
**Figure 11 – Designations of essential body structure assemblies (examples)**



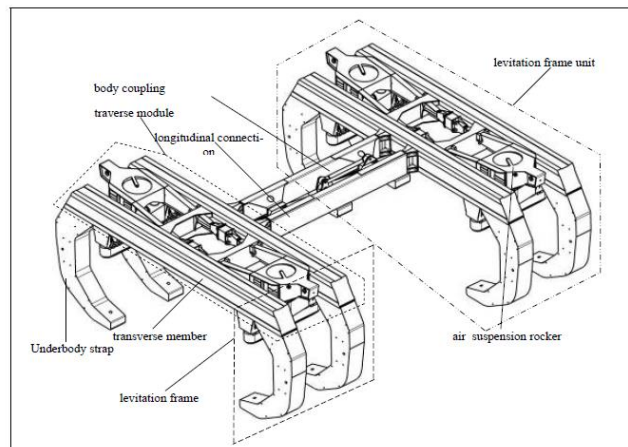
**Figure 12 – Designation of fairing elements of body and support/guidance system (schematic diagram)**



**Figure 13 – Designation of essential assemblies of the support/guidance system (schematic diagram side view)**



**Figure 14 - Designation of essential assemblies and dimensions of the support/guidance system (schematic diagram cross section)**



**Figure 15 - Designation of essential assemblies of the underbody structure (schematic diagram)**

### Incheon Airport Maglev (Ecobee)

The track gauge is 1850 mm. The lightweight of the vehicle has been obtained by mean of aluminum [14].

### Linimo

Car Body Structure is of semi-monocoque construction, consisting of welded aluminum alloy structure with two emergency end doors, 2 entrance doors/side/car, air suspension system as the secondary suspension. The Linimo vehicle comprises five bogies. The fleet consists of eight three-car trains [16, 17].

### Sengenthal

The individual sections are 12 meters long, empty load of 18 tonnes, have a payload of up to 9.5 tonnes and offer space for up to 127 people with a space requirement of 4 people per m<sup>2</sup>. The structure of the case is made of aluminium [18, 19, 20].

### Daejeon Maglev

The train consists of two cars and the top speed is 100 km/h with a maximum acceleration of 3.6 m/s<sup>2</sup>. Table shows major specifications of UTM-02 compared with those of UTM-01 [21, 22, 23].

**Table 7 - Comparison between UTM-01 and UTM-02**

Major Spec.	UTM-01	UTM-02
dimension	13.6 m *3 m *3.96 m	13 m*2.8 m*3.6m
empty weight	22 tons	14 tons
maximum capacity	80 persons	64 persons
max. speed	100 km/h	100 km/h
Levitation gap	11 mm	10 mm
No. of bogies	3/car	3/car
max. acceleration /deceleration	0.8 m/s <sup>2</sup> , in emergency 1.25 m/ s <sup>2</sup>	1.0 m/ s <sup>2</sup> , in emergency 1.25 m/ s <sup>2</sup>
vovf switching frequency	500 Hz	2000 - 2500 Hz
dc/dc switching freq.	400 Hz	2000 Hz

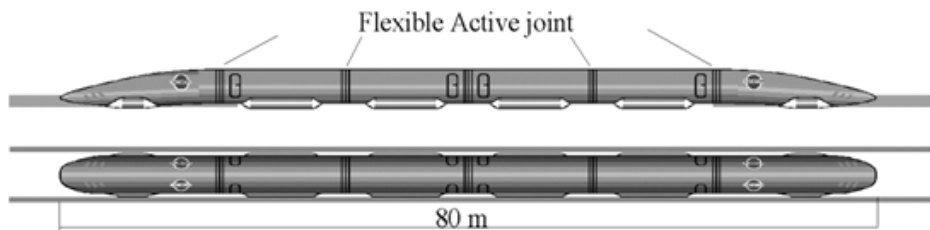
curve negotiability	60 m radius of curvature	less than 30 m of radius of curvature
power supply	DC 1500 V	DC 750 V
ATO	no	yes

### Swissmetro

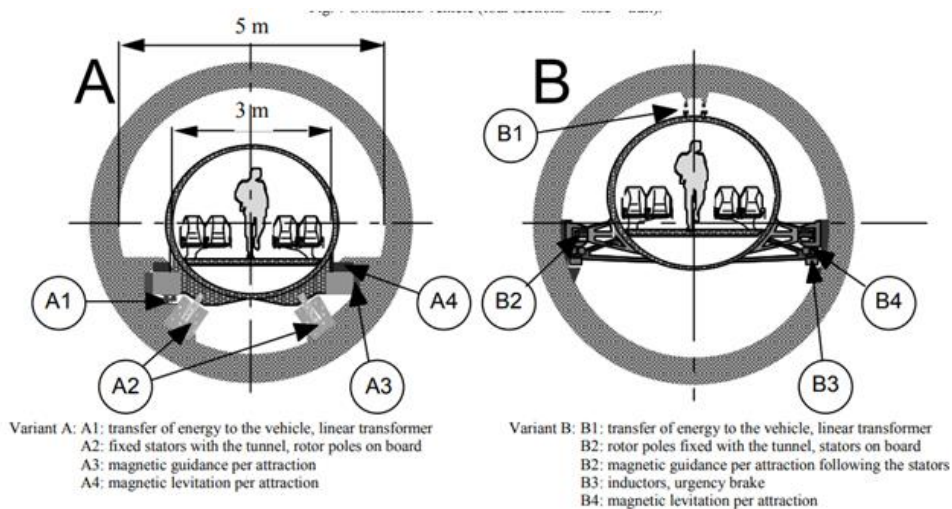
The train consists of six sections, each section consisting of a car body with all integrated components [24].

The vehicle operates in a partial vacuum (8000 to 10000 Pa) within the underground infrastructure of stations and tunnels. The magnetic system, called a levitation bogie, is placed under or to the side of the body (Figure ). The levitation bogies generate the forces necessary to support the body vertically, to guide the train, to pull the train and to brake the train.

The passenger compartment is a very important part of the car, both in terms of safety and comfort.



**Figure 16 - Swissmetro vehicle (four sections + nose + trail)**



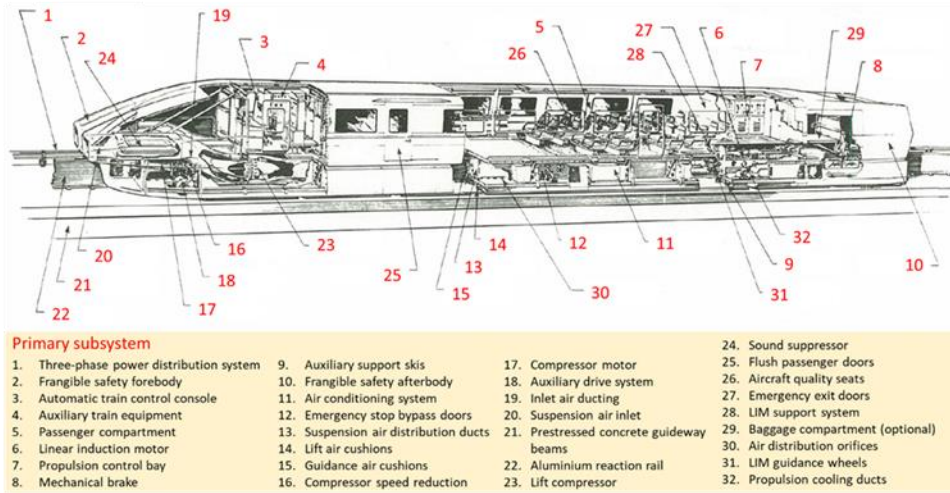
**Figure 17 - Swissmetro Cross Section of the Vehicle**

## **USA tracked air-cushion vehicle (TACV)**

Detailed illustrations of the USA TACV structures are concisely outlined in Figure below [25 - 28].

The primary subsystems shown are:

- Three-phase power distribution system
- Frangible safety forebody
- Automatic Train Control (ATC) console
- Auxiliary Train Equipment (ATC Rack)
- Passenger Compartment
- Linear Induction Motor (LIM)
- Propulsion Control Bay
- Mechanical Brake
- Frangible Safety Afterbody
- Auxiliary Support Skis
- Air Conditioning System
- Emergency Stop Bypass Doors
- Suspension Air Ducts
- Lift Air Cushions
- Guidance Air Cushions
- Air Compressor System
- Fire Detection/Suppression
- Auxiliary Drive Hydraulic System
- Emergency Batteries
- Battery Power Supplies
- 120 VAC Output Inverter
- Power Distribution Switchboard
- Auxiliary Power Transformer
- Power/Propulsion System Auxiliaries
- Communication Subsystem
- Brake Hydraulic System
- Variable Voltage Power Conditioning Unit (VVPCU)
- Power Collection Subsystem



**Figure 18 - Structure of primary subsystem**

The performance of the primary subsystems is given in the table below.

**Table 8 - Performance objectives of prototype tracked air-cushion vehicle - USA**

Function	Required
1. Satisfactory operation in: (a) Temperature range (b) Rain (c) Winds (any direction)	-20°F tp 120°F 2"/hour steady 30 MPH steady 60 MPH gusts
2. Safe storage (non-operating) in: Winds (any direction)	70MPH steady 100MPHgusts
3. Speed on 3% grade and 30 MPH headwind (a) Forward (b) Reverse	150MPH 30MPH
4. Acceleration (a) Distance to go from start to 150 MPH up a 1.25% grade (b) Longitudinal - maximum	1.75 miles 0.15g
5. Deceleration a. Distance for maximum efforts top from 150 MPH(-1% grade and 30 MPH tailwind) b. Normal brake effort c. Emergency stop effort	0.5 miles 0.15g maximum 0.4g maximum
6. Ride Quality (a) Sustained acceleration:	

<ul style="list-style-type: none"> <li>• Longitudinal</li> <li>• Lateral</li> <li>• Vertical</li> </ul>	<p>0.15g maximum</p> <p>0.08g maximum</p> <p>0.10g maximum</p>
<p>(b)Rate of change of sustained acceleration</p> <ul style="list-style-type: none"> <li>• Longitudinal jerk(maximum)</li> <li>• Lateral jerk(maximum)</li> <li>• Vertical jerk(maximum)</li> </ul>	<p>0.03g/second</p> <p>0.03g/second</p> <p>0.04g/second</p>
<p>(c) Maximum acceleration standard deviations (30 second sample period, 0.1 to 15.0 Hz band)</p> <ul style="list-style-type: none"> <li>• 120 MPH velocity</li> <li>• Longitudinal sigma</li> <li>• Lateral sigma</li> <li>• Vertical sigma</li> <li>• 150 MPH velocity</li> <li>• Longitudinal sigma</li> <li>• Lateral sigma</li> <li>• Vertical sigma</li> </ul>	<p>0.025g</p> <p>0.025g</p> <p>0.030g</p> <p>0.039g</p> <p>0.039g</p> <p>0.047g</p>
<p>(d) Maximum acceleration standard deviations for total of 5% of item 8 sample period:</p> <ul style="list-style-type: none"> <li>• 120 MPH velocity <ul style="list-style-type: none"> <li>– Longitudinal acceleration</li> <li>– Lateral acceleration</li> <li>– Vertical acceleration</li> </ul> </li> <li>• 150 MPH velocity <ul style="list-style-type: none"> <li>– Longitudinal acceleration</li> <li>– Lateral acceleration</li> <li>– Vertical acceleration</li> </ul> </li> </ul>	<p>0.05g</p> <p>0.05g</p> <p>0.06g</p> <p>0.078g</p> <p>0.078g</p> <p>0.094g</p>
<p>7. Air conditioning cabin temperature (ambient 100°F, 50% R.H.)</p>	<p>72-77° D.B.</p>
<p>8. Passenger compartment noise level</p>	<p>65 dB (A)</p>
<p>9. Crew compartment noise level</p>	<p>75 dB (A)</p>
<p>10. External noise levels</p> <p>(a) 50' ahead of vehicle, stopped</p>	<p>63 dB (A)</p>

(b) 50' ahead of vehicle, cruise speed	73 dB (A)
11. Electromagnetic interference	Not to interfere with broadcasts or other communications
12. Emergency Egress Time (60 passengers plus crew)	90 seconds
13. Window impact protection	Baseball at 75 ft/sec
14. Positive vehicle grounding under all conditions	
15. Mean Time Between Failures (MTBF)	
(a) major (system stoppage)	2000 hours
(b) Minor (reduced performance)	1000 hours

### 7.3 Propulsion - Vehicle part

According to [2], the Propulsion – vehicle part refers to the system element that permits the MDS vehicle to travel longitudinally. It makes acceleration and deceleration possible. It could be friction-based (wheels), electromagnetic (LSM), electrodynamic (LIM), or a combination of these.

Synchronous or asynchronous linear motors are installed within the track to power the train. Propulsion force is produced on the train by the interaction of these motors with magnets. The propulsion system of MDS vehicles relies heavily on linear motors, which are transforming our conception of high-speed transportation. These motors eliminate the need for conventional wheels or rails by providing the thrust required to move MDS cars along their tracks.

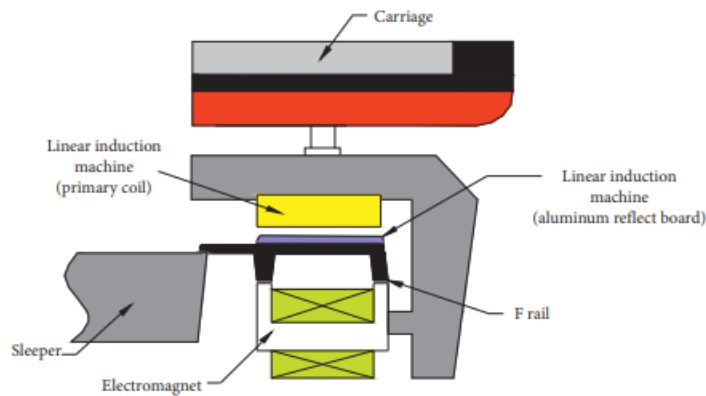
The following is a description of the design and development of the Propulsion – vehicle part of the various maglev systems which are currently in operation:

#### Beijing Line S1

Propulsion is based on Single Side Short Stator Linear Induction Motor (SLIM) technology. Motors are asynchronous. Power supply is 1500 V dc. [3]

#### Changsha Maglev

Propulsion is based on Single Side Short Stator Linear Induction Motor (SLIM) technology. Motors are asynchronous. Power supply is 1500 V dc. [4, 5]

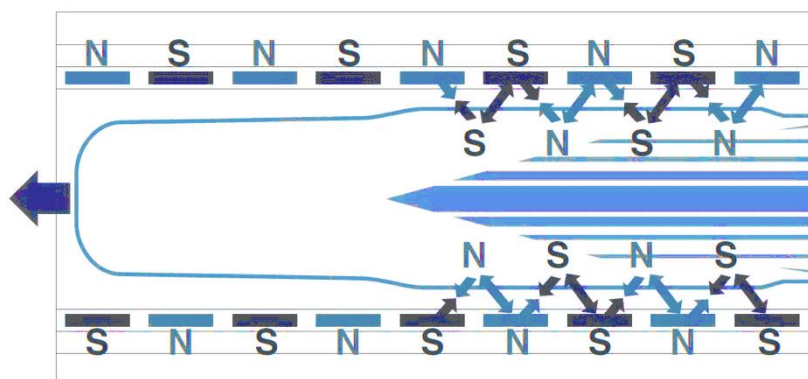


**Figure 19 – Half of the symmetrical EMS-SLIM system of the Changsha Maglev trains (same of Beijing Maglev trains)**

### Chuo Shinkansen

The propulsion method is the iron-cored long-stator LSM, wherein the superconducting magnets are also used as the field for LSM. [6 - 8]

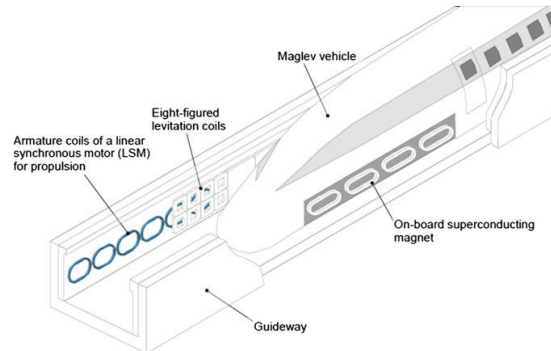
Passing current through the propulsion coils on the ground generates a magnetic field with north and south poles, propelling the vehicle forward by the attraction of opposite poles and the repulsion of same poles acting between the ground coils and the superconducting magnets (north and south poles arranged alternately) built into the vehicles (see figure below).



**Figure 20 – L0 propulsion system**

The propulsion, the levitation, and the transfer of energy to the vehicle are combined functions. The two magnetic fields from the superconducting magnets and the induced currents in the ground coils generate the magnetic pressure, which provides the vehicle both with levitation and guidance forces.

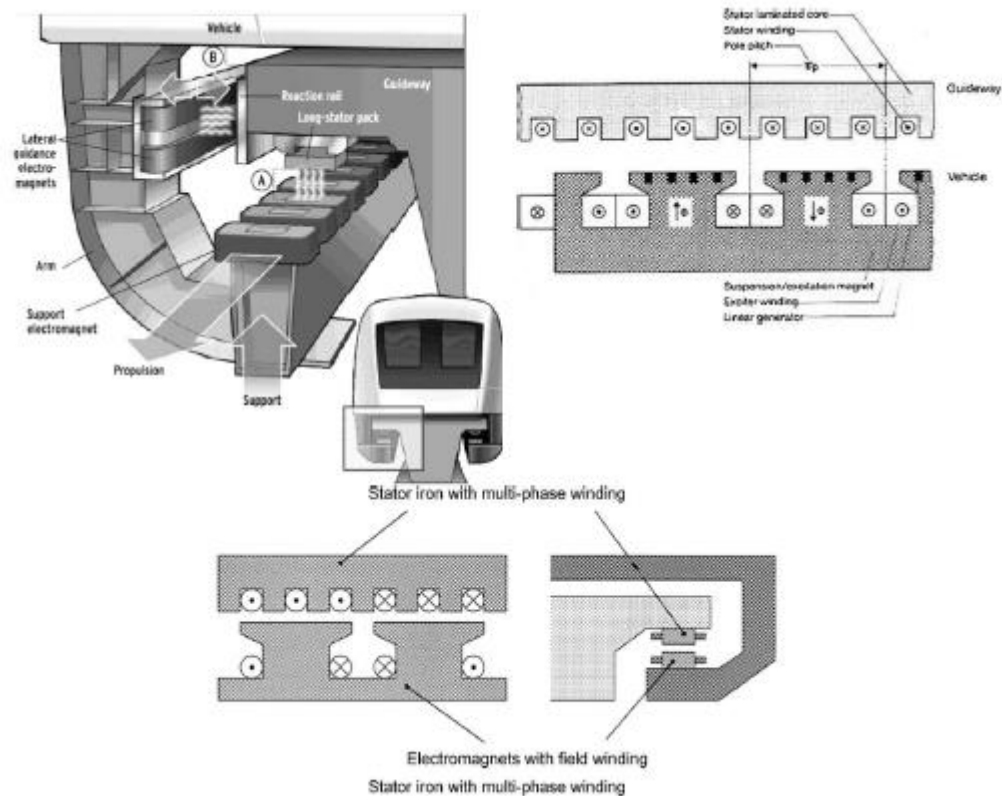
The propulsion method is the iron-cored long-stator LSM, wherein the superconducting magnets are also used as the field for LSM. This concept is a representative electrodynamic levitation system, with the prime advantage of having no active control requirement. The guideway has a U-shape made of concrete (see figure below). The three-phase primary windings of LSM are installed in between inner and outer layers of the side wall.



**Figure 21 -Japanese superconducting maglev system L0**

### Transrapid 09

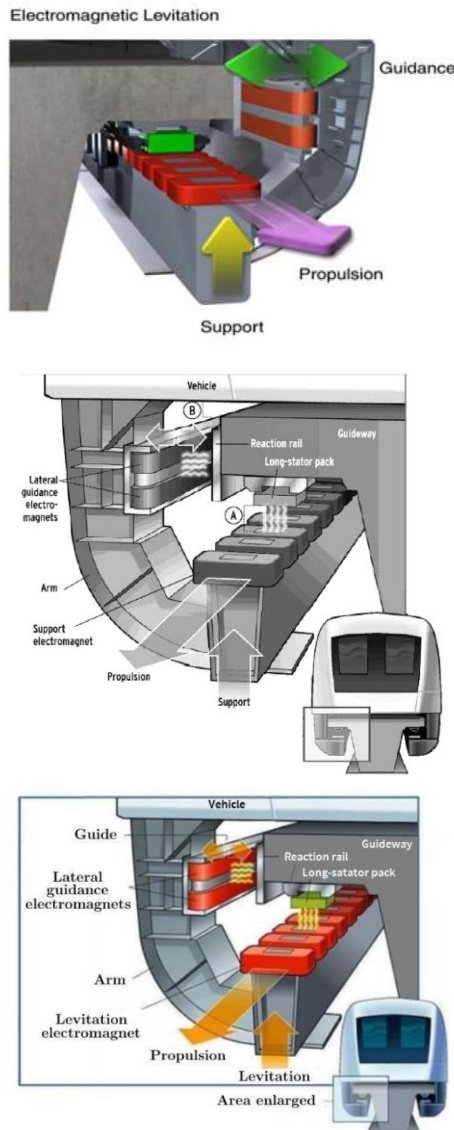
As shown in figure 12 Transrapid combines the propulsion the levitation and the transfer of energy to the vehicle in the same electromechanical system [10, 11]. The long stator is composed of lamination with teeth and yoke. The stator is energized by sectors up to 4 km length. On board of the vehicle, the poles of the motor are laminated. Each pole is surrounding by the DC coils of the excitation. The DC excitation assures the control (motor direct axis) of the levitation. Furthermore, each pole has four slots containing the wires of the linear generator. The choice of classical linear motors implies a short pole pitch of 258 mm, corresponding to more than 25 times the air gap (10 mm). This pole pitch dimension is necessary in order to decrease the motor end winding lengths. The maximum synchronous frequency is 300 Hz. such a limit frequency corresponds to a synchronous speed of about 500 to 550 km/h. Depending on the length of the vehicle, the mechanical power has a minimum of 8 MW.



**Figure 22-Transrapid – Propulsion - guidance - levitation – linear generator; Source: Thyssen-Krupp.**

### Shanghai Maglev

The synchronous long-stator linear motor of the Transrapid maglev system is used both for propulsion and braking [12, 13]. It functions like a rotating electric motor whose stator is cut open and stretched along under the guideway. Inside the motor windings, alternating current generates a magnetic traveling field which moves the vehicle without contact. The support magnets in the vehicle function as the excitation portion (rotor). The propulsion system in the guideway is activated only in the section where the vehicle runs. The speed can be continuously regulated by varying the frequency of the alternating current. If the direction of the traveling field is reversed, the motor becomes a generator which stops the vehicle without any contact. The braking energy can be re-used and fed back into the electrical network.



**Figure 23 - Shanghai Maglev: working principles of the bogie**

### **Incheon Airport Maglev (Ecobee)**

The thrust for acceleration and deceleration is achieved by the LIMs, with the on-board primary windings and the secondary reaction plate in the guideway [14].

ECOBEE system utilises short stator linear induction motor whereas the vehicle primary is equipped with the 3-phase winding and the infrastructure part is a propulsion rail.

The nominal air gap (mechanical clearance) between the primary unit core of the LIM and aluminium plate is 13 mm. The LIM is fed from a Variable Voltage Variable Frequency (VVF)



inverter. There are four LIMs per each side of the car, 8 LIMs per car. Each LIM and four suspension electromagnets create a suspension-propulsion unit.

Propulsion system can provide maximum acceleration of 1,1 m/s<sup>2</sup> and maximum deceleration of 1,25 m/s<sup>2</sup> in emergency.

### **Inductrack Urban Maglev**

The Urban MagLev system (low speed vehicles for inner-city service) relies on an attraction assisted EDS for levitation and a LSM for propulsion. The propulsion components are located on either side of the guideway [15].

### **Linimo**

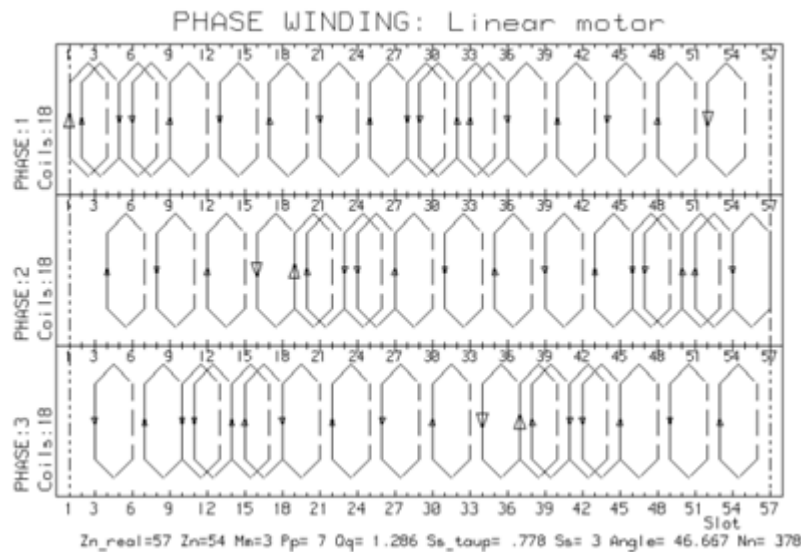
The thrust needed for propulsion is generated by 10 LIM per car. The rated thrust per car is 39.8 kW/car. One Variable Voltage Variable Frequency (VVVF) with IGBT and PWM is used per car. Although the current control is essentially achieved by the thrust command, the thrust command is compensated by the vehicle weight data, which is picked up by air suspension pressure transducers. In the range of high speed, the thrust is limited due to the limitations of the output voltage of the inverter. Non-contact speed detection devices are used as a source of speed data for the inverter system [16, 17].

### **Sengenthal**

The vehicles utilise electromagnetic levitation for propulsion while resting on skids when stationary [18 - 20].

### **Swissmetro**

The Swissmetro will be propelled by linear homopolar synchronous motors [24]. An air gap of 20 [mm] is considered for propulsion, magnetic levitation and guidance. The electromechanical components of Swissmetro are based on two proposed variants for the propulsion: a) the short stators of the linear homopolar motors are fixed with the tunnel tracks; b) the stators of the motors are on board of the vehicles. The choice of classical linear motors implies short pole pitch, such as 231 [mm], corresponding to more than 8 times the air gap. This value is necessary in order to decrease the motor end winding lengths. The maximum synchronous frequency is 300 Hz, which corresponds to today's technology limits of the power inverter. Such a limit frequency corresponds to a synchronous speed of about 500 to 550 km/h. The motor optimization leads to an appropriate number of slots, poles and a given coil opening. The winding configuration is based on a fractional number of slots per pole and per phase in order to decrease the reluctance forces and a coil opening which minimize the harmonic winding factors. The winding uses classical technology as seen in Figure permitting a high copper/aluminium filling factor (> 0.5), which is only possible for short stators.

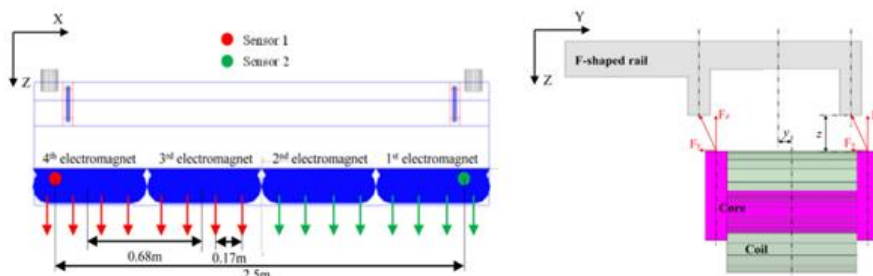


**Figure 24 - Swissmetro Winding Configuration**

### Fenghuang Maglev

Fenghuang Maglev uses a Linear Induction Motor [9].

As shown in Figure , the attractive magnetic force and the lateral restoring force between the U-shaped electromagnet and the F-shaped rail are parallel, continuously distributed forces along the longitudinal axis. However, the magnetic pole length corresponding to one coil winding is 0.68 m, which is much smaller than the length of a magnetic levitation vehicle and the 25 m span length of a girder. Therefore, the distributed magnetic force of an electromagnet can be equivalently conceptualised as multiple concentrated forces.



**Figure 25 - Fenghuang Maglev Configuration**

### Tongji University Maglev

Tongji University Maglev uses Linear Synchronous Motors (LSM) [29].

Electromagnetic levitation (EML) uses the LSM field excitation system, i.e., an electromagnet with a controlled air gap. The air gap between the levitation electromagnets and the stationary



ferromagnetic core of the three-phase winding is 10 mm. These field excitation and levitation electromagnets (36 kA) are fed by two quadrant transistor choppers with a maximum power of 48 kW and a sampling frequency of 100 kHz.

Single-sided LSM with rail-mounted three-phase armature winding provides propulsion and braking. Lateral stabilisation is provided by lateral guide electromagnets with controlled air gap.

The three-phase armature winding of an LSM is placed in slots of a laminated core fixed to both sides of the concrete track. There are single turn coils made of aluminium power cable. The pole spacing is 258 mm. The track (armature winding) is divided into sections. The average length of each section along the track is approximately 1.2 km. Only the section with the train is supplied by the power supply. The maximum current of the LSM is 1200 A at cruising speed.

In the train drive system, the long stator permanent magnet synchronous linear motor is adopted. The long stator of the motor is arranged alternately by three phase AC windings, fixed on the upper wall of the inner side of the suspension beam, and the corresponding electric motor mover is composed of permanent magnets and placed at the top of the suspension frame. The traveling wave magnetic field generated by the armature winding and the static magnetic field produced by the permanent magnet forms the electromagnetic traction force and drag the suspension frame and the carriage to move forward. In the actual driving control strategy, the conventional linear motor multi-modal control method is adopted.

### **USA tracked air-cushion vehicle**

Initially, the vehicle utilized "aero-propulsion," propelled forward by the exhaust from its three turbofan engines, which also provided lift. In 1973, using this propulsion method, the Test Center achieved a top speed of 91 mph, which was significantly below the envisioned 300 mph [25 - 28]. In December 1973, the vehicle's propulsion system was switched from aero-propulsion to electric propulsion to enhance its speed potential and to adapt to the limitations of the short track. A reaction rail was added at the bottom of the guideway to apply the Linear Induction Motor (LIM) propulsion. The LIM in the vehicle was installed and tested. This was prepared for high-speed testing, anticipating speeds of 240 mph.

## **7.4 Suspension**

According to [2], the Suspension refers to the component that allows the MDS vehicle to counteract vertical stress and/or retain its vertical position. It could be passive, pneumatic, mechanical (wheels), electromagnetic, electrodynamic, or mixed. The vehicle's suspension system provides comfort during the journey by reducing vibrations caused by ride elements. The system that attaches the support/guidance system to the vehicle chassis is typically known as the mechanical suspension. Depending on the support/guidance system being

used, the suspension system in the MDS domain may have a varied architecture. A completely active electromagnetic design is utilized for EMS systems, and the suspension system—which is integrated with the levitation control system—is the mechanism that stabilizes the suspension, which is intrinsically unstable. Generally speaking, the suspension stability and ride comfort requirements must be met by the system design.

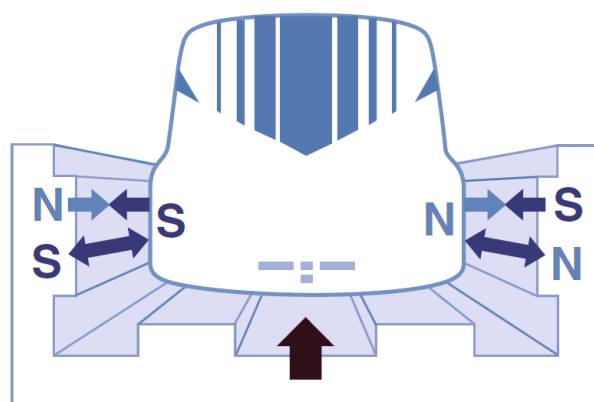
The following is a description of the design and development of the suspension of some of the maglev systems which are currently in operation:

### Beijing Line S1, Changsha Maglev and Daejeon Maglev

The suspension system of Beijing Line S1 [3], Changsha Maglev [4, 5] and Daejeon Maglev [21 - 23] is based on normal conducting EMS (electro-magnetic suspension) technology.

### Chuo Shinkansen

Levitation and guidance coils are installed on both sides of the guideway [6 - 8]. When the onboard superconducting magnets pass through these coils at high speed, an electric current is induced in the levitation and guidance coils, causing them to become electromagnets with forces that both push (repulsion) and pull up (attraction) the vehicle (superconducting magnets). The repulsive force for suspension is weak at low speed so the trains run on rubber tires up to the speed of 100 km/h before becoming magnetically levitated. This dual suspension makes the vehicles more complex, but the tests of high-speed running have proven the technical feasibility of the system.

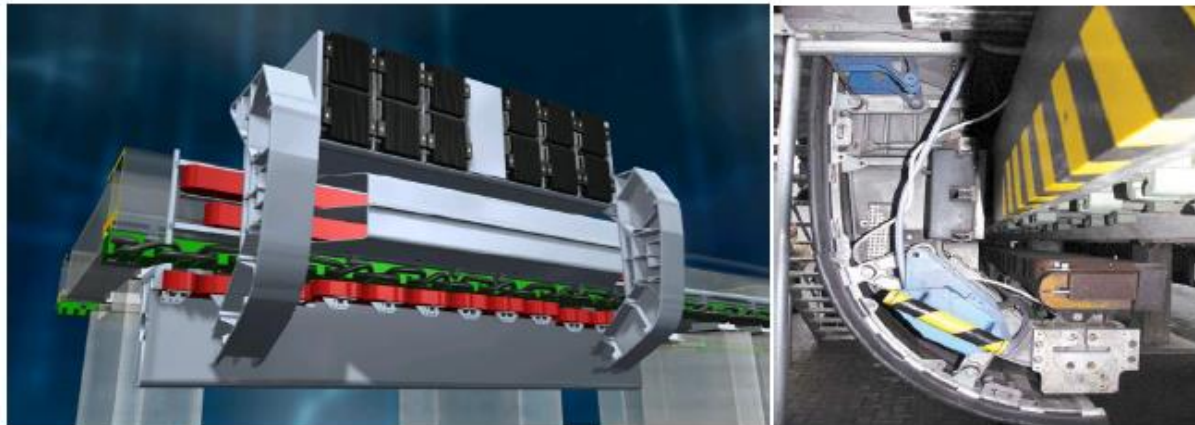


**Figure 26 – L0 levitation system.**

### Transrapid 09

For Transrapid, the attractive force between the single sided motor stator and the rotor poles creates the levitation forces (figure below) [10, 11]. These forces are distributed all along the

vehicle. The levitation control has to satisfy two values: the necessary levitation forces and a high motor power factor ( $>0.8$ ). The air gap is 10 mm. The no load vehicle linear mass is about 2.13 ton/m. For Transrapid, inductors, placed along each side of the vehicle, assure the lateral guidance per attraction. The corresponding air gap is 8-10 mm.



**Figure 27 - Transrapid 09: bogie details**

### **Shanghai Maglev**

Electronically controlled support magnets located on both sides along the entire length of the vehicle pull the vehicle up to the ferromagnetic stator packs mounted to the underside of the guideway [12, 13]. Guidance magnets located on both sides along the entire length of the vehicle keep the vehicle laterally on the track. Electronic systems guarantee that the clearance remains constant (nominally 10 mm). Incredibly, the Transrapid requires less power to levitate than is used by its air conditioning equipment. The levitation system is supplied from on-board power supply (batteries, inductive power supply or linear generators) and thus is independent of the propulsion system.

### **Incheon Airport Maglev (Ecobee)**

Levitation: the electromagnet for ECOBEE is composed of two poles, 4 yokes and 8 windings [14]. Long-pole design is employed to reduce the magnetic drag forces. The nominal current for empty load is measured to be about 30 A, while it is 35 A for full load, with nominal airgap of 8 mm. The levitation control is based on the 5 states feedback scheme. The measurement of airgap and acceleration is available through an external sensor module containing two gap sensors, and an accelerometer is placed in between two poles. Two inductive gap sensors are used to output a smoother signal from two measured signals by switching them, avoiding discontinuity in measured signals at rail joints.

### **Inductrack Urban Maglev (United States of America)**

Levitation system uses vehicle mounted permanent magnet double Halbach arrays [15]. The



orientation of the magnetization of the magnets in the Halbach array is arranged such as to concentrate the field lines below the array while nearly cancelling the field above the array. This results in a system which requires no active magnetic shielding of the passenger compartment. The levitation components are located on either side of the guideway.

### **Linimo**

The suspension and guidance forces are provided by a typical U-core electromagnet [16, 17]. The nominal and landed airgaps are 8 and 14 mm. The input voltage to the magnet driver is 275 V DC. The capacity of the levitation magnet is 10.2 kN/m. Influence of environmental change on levitation control is restrained.

The levitation and guidance system provide vehicles with non-contact support of the vehicle with high reliability and high stability. Magnets are of normal conductive and attractive type. The levitation control system consists of a MDU and sensors and provides a contactless stable support of the vehicle.

### **Sengenthal**

The vehicles utilise electromagnetic levitation for propulsion while resting on skids when stationary [18 - 20].

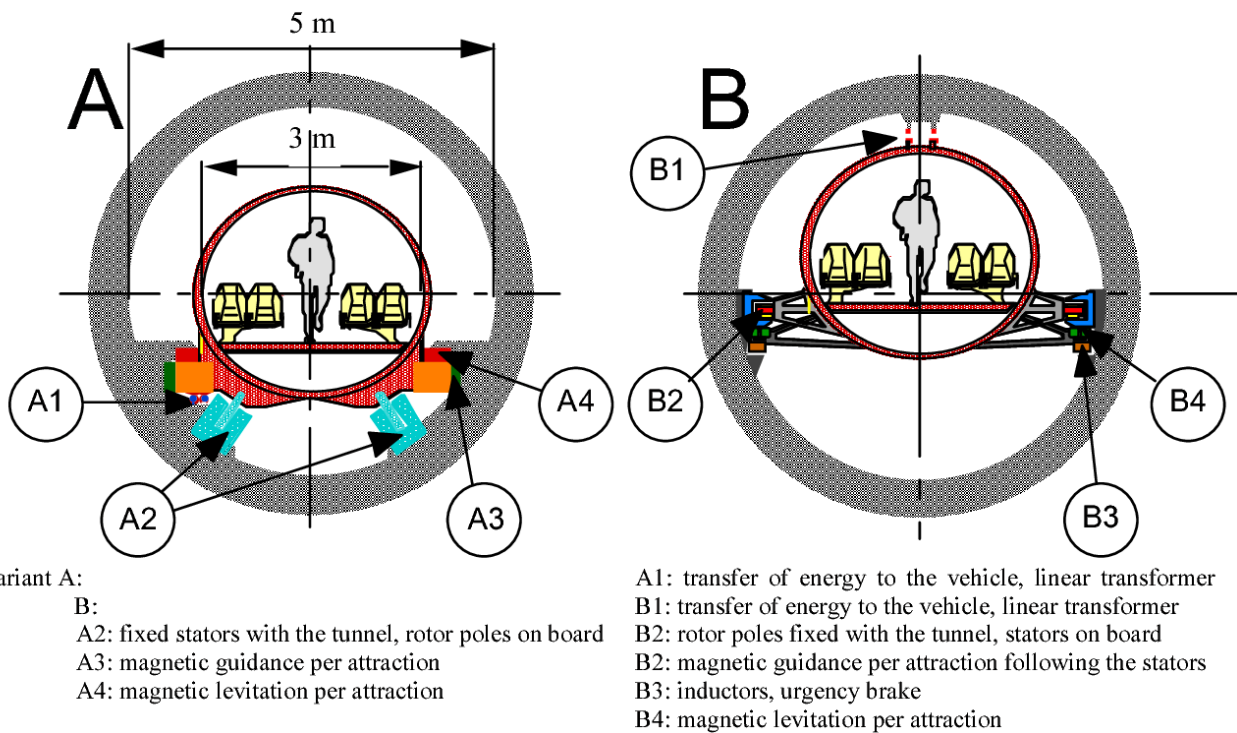
### **Swissmetro**

Magnetic inductors assure the levitation and the guidance of the vehicles [24]. The magnetic levitation is defined by individual inductors creating the levitation forces in specific points of the vehicle.

Each rigid section of the vehicle is equipped with 4 electromagnets. The force produced per electromagnet is 30 kN for a power loss mean value of 4.4 kW and a weight of 171kg.

For small air gaps, the chosen solutions are the magnetic levitation and guidance based on magnetic attraction, which produce a force at no speed. For Swissmetro, individual inductors creating the levitation forces in specific points of the vehicle define the magnetic levitation.

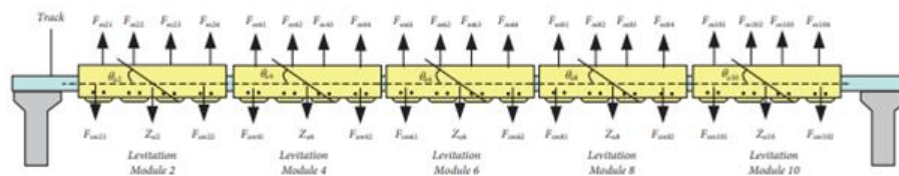
The air gap is 20 mm. Each rigid section of the vehicle is equipped with 4 electromagnets. For Swissmetro the magnetic guidance is assured by independent inductors. For all Maglev, the magnetic levitation and the guidance create a magnetic drag force, which is function of the speed. The magnetic drag forces request a laminated reactive rail.



**Figure 28 - Swissmetro levitation system**

### Fenghuang Maglev

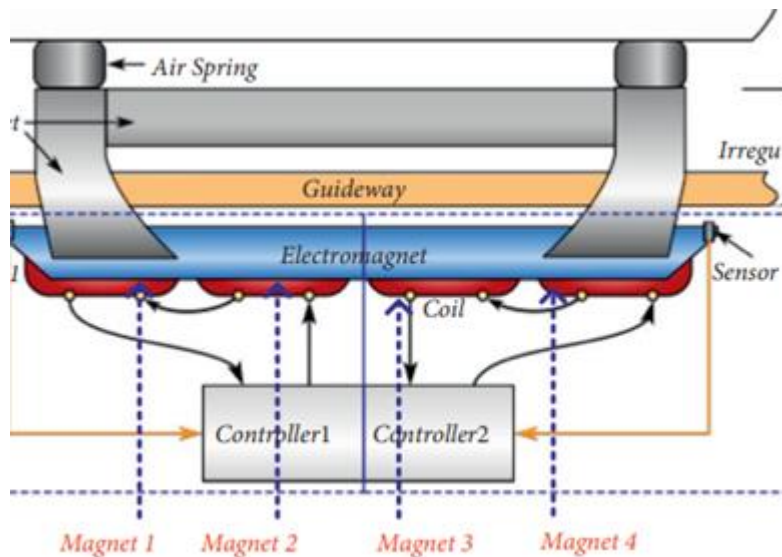
The system is based on normal conducting EMS (electro-magnetic suspension) technology [9]. The maglev train has 10 independent levitation modules. The levitation electromagnets are numbered from 1 to 10, and the electromagnets on the left track (as shown in Figure ) are defined as 2, 4, 6, 8, and 10. Regardless of the linear motor's traction on the suspension module, the forces received by the suspension module include gravity, electromagnetic force (including vertical suspension force and lateral guiding force), and the vertical effect of the car body on the suspension module through the air spring force. A single suspension module contains four electromagnet wire packages, which are generally divided into 2 suspension points for control.



**Figure 29 - Fenghuang Maglev levitation system**

A stable, reliable, and excellent levitation controller is the first requirement of the levitation system. Aiming at this system, a suspension control algorithm based on the serial cascade idea is obtained. Magnetic flux density feedback instead of traditional current feedback,

combined with mature PID control strategies as the outer loop, can simplify the block diagram structure of levitation control and improve system performance. As shown in Figure UPM10, the left and right ends of the levitation module are regarded as two levitation control units. Each levitation control unit consists of two series connected solenoid coils with same parameters, sensors (including gap, current, and acceleration sensors), controllers, and other components.



**Figure 30 – Schematic diagram of the suspension system for the Fenghuang Maglev**

### Tongji University Maglev

The system is based on normal conducting EMS (electro-magnetic suspension) technology [29].

The "Rainbow" suspension system adopts the ideal permanent magnet electromagnetic hybrid suspension control technology compared with the traditional electromagnetic hybrid levitation technology. Its obvious advantages are: the adaptive characteristics of the Halbach permanent magnet array are fully utilised to achieve vehicle suspension; the electromagnetic force acts as a suspension damper to adjust the unstable disturbance under the static magnetic field in real time to suppress vehicle oscillation.

At present, both Shanghai Maglev Train and Changsha Maglev Special Line, which are in commercial operation in China, still have major energy consumption problems, especially Shanghai Maglev Train. Meanwhile, Changsha Maglev Train has some improvement compared with the former in terms of suspension energy consumption. But its levitation energy consumption still accounts for about 40% of the total energy consumption of trains; in addition, the high energy consumption of trains often leads to high costs of train operation and maintenance, making it difficult to promote further commercialisation.

On the contrary, the "Rainbow" system uses a static magnetic field to realise the suspension control of the entire vehicle structure. The suspension energy consumption is generated only by the electromagnetic damper, and the suspension energy consumption of the integrated train is close to zero. In addition, electromagnetic dampers often only need to provide transient magnetic force adjustment, so there is no need to consider electromagnetic coil heating and other problems.

In the suspension guide structure, the system realizes the vertical suspension of the vehicle through Halbach permanent magnet array, and realizes the real-time dynamic suspension adjustment of train safety by combining with electromagnetic stability control. There are two sets of preset suspension limit wheels at the top of the suspension frame to prevent vertical suspension collision. In the horizontal direction, the electromagnetic steering structure completes the stable control on both left and right side, and the upper and lower end of the electromagnetic guide structure are respectively installed with mechanical limit pulley to form the two-stage guide protection structure of the guide system.

In addition, Secondary rubber wheels are installed on the outside of permanent magnetic levitation structure to prevent vehicle from colliding with permanent magnet array under unsteady conditions such as turning and tilting.

### **USA tracked air-cushion vehicle**

Air cushion - A low pressure air cushion suspension system levitates the vehicle from the guideway providing relatively friction-free motion [25 - 28]. The air supply system has air inlets with sound suppression, two compressors, air supply ducts, and cushion supply scoops. Two constant-speed, three-phase induction motors drive the compressor units. Eight peripheral jet-type air cushions guide and support the vehicle in the guideway. The 140 lb/sec (59 kg/sec) air supply at a pressure ratio of 1.28 from the PLF1A-2 turbofan is ample to maintain a 0.75 in. (19 mm) clearance at maximum vehicle weight, 44,820 lb (20, 330 kg).

## **7.5 Guidance**

According to [2], the Guidance refers to the subsystem that allows the MDS vehicle to be maintained in its lateral position. It could be pneumatic, mechanical (with wheels), electromagnetic, electrodynamic, or a combination of these. The train travels along a track structure that is embedded with electromagnets.

The following is a description of the design and development of the guidance of some of the maglev systems which are currently in operation:

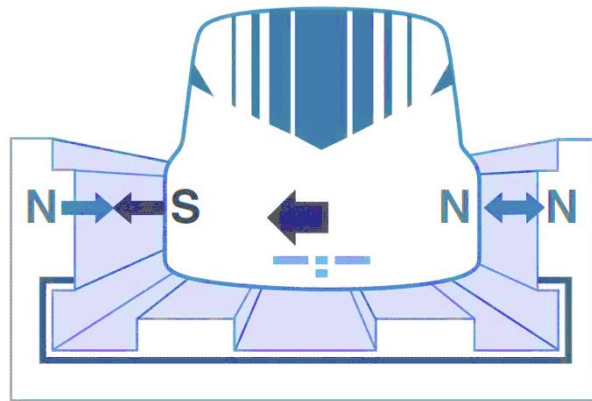
### **Beijing Line S1, Changsha Maglev and Daejeon Maglev**

The guidance system of Beijing Line S1 [3], Changsha Maglev [4, 5] and Daejeon Maglev [21 -

23] is based on normal conducting EMS guidance technology.

### Chuo Shinkansen

The levitation and guidance coils on both sides of the guideway always keep the vehicles in the centre of the guideway by exerting attraction on the far side of the vehicle and repulsion on the near side if the vehicle moves off centre to either side [6 -8].



**Figure 31 – L0 guidance system.**

### Transrapid 09 and Shanghai Maglev

Transrapid [10, 11] and Shanghai Maglev [12, 13] guidance system is based on EMS, Electromagnetic Guidance (attraction forces).

### Incheon Airport Maglev (Ecobee)

The guidance forces are provided by the lift magnets, which are proportional to lateral displacement [14].

### Sengenthal

The vehicles utilise electromagnetic levitation system with combined transport and driving functions [18 - 20].

### Swissmetro

Guidance, suspension, propulsion and braking are different functions of an integrated multifunctional component system [24].

For Swissmetro, the propulsion, the guidance, the braking, the levitation and the transfer of energy to the vehicle are independent functions.



### **Fenghuang Maglev**

Guidance system is integrated with suspension system [9].

### **Tongji University Maglev**

As well as “Fenghuang Maglev”, in this technology the guidance system is integrated with suspension system [29].

### **USA tracked air-cushion vehicle**

Air-cushion technology was implemented on the vehicle side, utilizing an airpad to create an air cushion between the vehicle and the track—a concrete U-shaped guideway [25 - 28].

## **7.6 Braking**

According to [2], the Braking refers to the combination of parts that either progressively reduces the speed of the moving vehicle or brings the vehicle to a halt and/or holds it stationary or fulfils both functions. It may be integrated with the propulsion system or mounted as a separate subsystem.

Most of the existing systems are using linear motors as traction, but also as service brake, e.g. Transrapid 09, Chuo Shinkansen, Sengenthal, SwissMetro, or Tongji University Maglev.

More specifically, the following is a description of the design and development of the braking system of some maglev systems which are currently in operation:

### **Beijing Line S1**

The Beijing Line S1 [3] mainly has three kinds of brake function such as service brake, quick brake and emergency brake. The emergency brake is implemented when the emergent situation and unforeseen circumstances occurs, to stop the train as soon as possible.

Emergency brake which results from the control switch or other reasons cause the disconnection of emergency circuit is raised from the process that the compressed air in air cylinder brake reservoir directly through the emergency valve of BCU and arrive the empty load brake valve, pre-control is controlled only load brake valve, the pre-control pressure from the empty and load brake valve arrives to the relay valve, opening the air storage cylinder and brake booster cylinder path of relay valve, and finally to boost pressure access to emergency brake cylinder. If there is any failure occurs in the emergency valve (judging from the signal of emergency switch on the BCU by BECU), the BECU will implement emergency brake according to the setting brake force by the pre-control pressure released by the aerating-exhausting solenoid valve.

## Chuo Shinkansen

In Chuo Shinkansen [6-8], regenerative braking is normally used for deceleration, but if it becomes unavailable, the Superconducting maglev also has wheel disc brakes and aerodynamic brakes. On the Yamanashi Maglev Line, the braking system has been repeatedly examined on tough scenarios, e.g., an unlikely scenario of having to switch from 311mph operation to wheeled operation, in order to ensure operational safety.

- Normal operation: regenerative braking. This system uses linear motors as generators to decelerate the train. The vehicle's kinetic energy is converted to electrical energy, and generated electricity is returned to power conversion equipment to be reused.
- In emergencies: wheel disc braking. This system uses disc braking equipment fitted to wheels to mechanically decelerate the train.
- In emergencies: aerodynamic braking. This system extends air drag panels from vehicle to use air resistance for deceleration. It gives a particularly significant deceleration effect when traveling at high speed.

## Transrapid 09 and Shanghai Maglev

Transrapid 09 [10, 11] and Shanghai Maglev [12, 13] use LSM propulsion (see propulsion details) being used also for service braking.

If the direction of the traveling field is reversed, the motor becomes a generator which stops the vehicle without any contact. The braking energy can be re-used and fed back into the electrical network.

## Linimo

Linimo [16, 17] is equipped with: Service Braking, Primary electrical braking, electrical and hydraulic co-operated braking with passenger load compensation; Emergency Braking namely Hydraulic braking by pressing on the rail surfaces, 6 Hydraulic Brakes per car; Hydraulic Brake System, each car has an independent hydraulic system. The hydraulic brake system consists of the section of hydraulic power brake pressure control and brake actuators.

## Swissmetro

Swissmetro [24] uses Linear Motor for braking. Braking is integrated with propulsion system. In the direction of displacement, the motor becomes a generator which stops the vehicle. It consists on efficient braking system without any contact and that allows regenerate the mechanical energy and become into electrical.

## Fenghuang Maglev

Fenghuang Maglev [9] is equipped with the DY-1 hydraulic brake system independently developed by CRRC Brake Technology Co., Ltd., meeting the needs of fast start and stop as



well as the operation on long, steep ramps.

### **Tongji University Maglev**

Tongji University Maglev [29] uses the linear motor also for braking. Single-sided LSM with track-mounted three-phase armature winding provides propulsion and braking. Lateral stabilization is provided with the aid of lateral guidance electromagnets with controlled air gap.

### **USA tracked air-cushion vehicle**

The USA tracked air-cushion vehicle [25 - 28] uses LIM to brake (see propulsion details). If the direction of the traveling field is reversed, the motor becomes a generator which stops the vehicle without any contact. The braking energy can be re-used and fed back into the electrical network.

## **7.7 Vehicle control system**

According to [2], the Vehicle Control System refers to the vehicle component that supervises electronically the vehicle movement, accelerations and deceleration curves, emergency responses and health checks, usually connected to the Command and Control subsystem. The following is a description of the design and development of the Vehicle Control System of some maglev systems which are currently in operation:

### **Chuo Shinkansen and Daejeon Maglev**

Chuo Shinkansen [6 - 8] and Daejeon Maglev [21 - 23] use an automatic train operation system (ATO).

### **Transrapid 09 and Shanghai Maglev**

Transrapid 09 [10, 11] and Shanghai Maglev [12, 13] use a vehicle control system category, as defined by the UIC, the GoA2 / STO semi-automatic train operation.

### **Inductrack Urban Maglev**

Inductrack Urban Maglev [15] uses a control system that operates with ATC driverless.

### **Linimo**

Linimo [16, 17] operates using ATC and ATO subsystems. This system consists of the following three interconnected subsystems: Control Console Control (panel, display); Train Integrated Management System (information of each equipment); Visual Display Terminal (diagnose data).



## **Sengenthal**

Sengenthal [18 - 20] is an automatic and driverless passenger transport system. The system is equipped with redundant Ethernet architecture. The trains incorporate a FRNT ring network, to which two Westermo wireless clients are connected. The wireless clients then connect to the redundant trackside networks. Should one of the trackside networks fail, both wireless clients automatically connect to the other network until the failed network is available again. This double redundancy leads to an even higher network availability. High priority CBTC, CCTV and value-added service data can share the same physical radio link. Multiple levels of security are implemented including wireless encryption, access authentication and end-to-end data encryption.

## **Fenghuang Maglev**

The signalling technology to be used by the Fenghuang maglev [9] is the Train Autonomous Circumambulate System (TACS), developed by Beijing National Railway Research & Design Institute of Signal and Communication (CRSCD).

TACS is an automated control system that allows train position, speed and route status to be broadcast between in-service trains, rather than directed via a central control centre.

The technology includes Automatic Train Protection (ATP), Automatic Train Operation (ATO) and Automatic Train Supervision (ATS), and Train Safety Control (STC). But a key feature of this product is that the Zone Controller (ZC) is removed, with the mobile authorisation calculated by the ATP.

## **Tongji University Maglev**

In the Tongji University Maglev [29], according to the vehicle state, different driving strategies is switched to adapt the situation, including slip frequency control, vector control, direct thrust control and so on.

In order to improve the safety degree of vehicle operation and the intelligence of train service, the "Rainbow" system has applied the technology of Internet of Things and artificial intelligence in the on-board system. The former collects and pre-processes all kinds of field data (including levitation height, magnetic field centre deviation, car body position, etc.) for the intelligent front-end system.

The wireless communication equipment connects the car to the cloud control terminal to realize the exchange of data information. The latter realizes the intelligent unmanned driverless and human-car friendly interactive system of running, organizing, managing and serving.

The mobile terminal can be implemented through APP, WeChat public platform and other

ways to implement the operation and personalized services, which mainly include: man and machine interface interaction, traffic data display, multimedia conversion and so on, to ensure that passengers have good and comfortable experience. In addition, the “Rainbow” system is equipped with the safety facilities of the conventional rail transit system, such as emergency brake button, escape ladder, smoke alarm and so on, to ensure the overall safety and reliability of the system.

### **Air levitation systems**

Air Levitation systems utilize a control system that operates driverless using ATC/ATO. The vehicle control system is integrated with braking components such as LIM braking, EDW braking and emergency brakes, enabling precise control over these mechanisms. Traction, braking, suspension, and guidance are managed by the CCS. For example, in the USA, the tracked air cushion vehicle tested at the Transportation Test Center (TTC) primarily uses manual control, but automatic operations like starts and stops have been demonstrated. Although the guideway at Pueblo was too short for a full demonstration, the same ATC system at Bendix Aerospace Corporation’s track in Ann Arbor, Michigan, successfully controls multiple vehicles for various maneuvers, including speed adjustments, route selection, and emergency procedures.

## **7.8 Electrical system**

According to [2], the Electrical System refers to the component essential to power all electrical and electronic devices in the vehicle which deals with the conversion, transmission, storage or switching of electric power with or without control of that power.

Most magnetic levitation systems operating at low and medium speed use current contact shoes and power rail, i.e. Beijing Line S1, Daejeon Maglev, Incheon Airport Maglev (Ecobee), Linimo, Yokohama Municipal Subway 10000 series, Osaka Municipal Subway 70 serie, Sendai, Subway Tozai Line, Sengenthal, Fenghuang maglev, or Hovertrain.

But there also others that use pantograph and overhead catenary such are Yokohama municipal subway 10000 series, SkyTrain rolling stock, Toei Ōedo Line (subway) or Sendai Subway Tozai Line.

Finally, Wireless Power Transfer (WPT) is used by MagRail, Shanghai Maglev, Transrapid 09 and Chuo Shinkansen.

The following is a description of the design and development of the Electrical System of some maglev systems which are currently in operation:

### **Beijing Line S1 and Incheon Airport Maglev**

In both systems, Beijing Line S1 (China) [3] and Incheon Airport Maglev (Ecobee) [14] the line is electrified at 1.500 VDC. The electric power is fed to the vehicle with the aid of two contact rails mounted at each side of the concrete elevation.

### **Changsha Maglev**

Electrical power in the Changsha Maglev [4, 5] is supplied from a local power grid, which is converted into the required format and voltage by power substations along the route. The system is equipped with high current batteries on board the vehicle.

### **Chuo Shinkansen**

Shinkansen [6 - 8] uses a 25 kV AC overhead power supply (20 kV AC on Mini-shinkansen lines), to overcome the limitations of the 1,500 V direct current used on the existing electrified narrow-gauge system. Power is distributed along the train's axles to reduce the heavy axle loads under single power cars.

### **Sengenthal**

In the Sengenthal [18 - 20], power systems are distributed along the wayside at intervals appropriate for block-switching, which keeps the LSM power demands to a minimum.

Grounded transformers have a voltage of 154 kV. On board there are battery packs plus liquid nitrogen and helium to maintain superconductivity state.

The vehicles run on 750 volts direct current. The energy required to lift the vehicle is between six and ten kilowatts. Up to 600 kilowatts are needed to move the vehicle.

### **Transrapid 09 and Shanghai Maglev**

Transrapid 09 and Shanghai Maglev [10 - 13] use the same technology. The power supply system of the Chinese Shanghai Maglev includes substations, feeder cable along with tracks, switch stations and other supply equipment. In this system, high-voltage alternating current (AC) supply is taken at 110 kV from the power grid which was stepped down to 20 kV and 1.5 kV using transformers. This stepped-down AC is converted into direct current (DC) using rectifiers, then into a variable-frequency AC supply of 0–300 Hz using inverters. After stepping up, this supply excites the long stator windings of linear motors on the guideway

### **Inductrack Urban Maglev**

In the Inductrack Urban Maglev [15], power systems are distributed along the wayside at intervals appropriate for block-switching, which keeps the LSM power demands to a minimum.

## Linimo

In the Linimo system [16 - 17], the electrical power system transforms the high voltage direct current (1500 V DC) supplied by rigid trolley lines at both sides of the girder into the following 3 types of electrical power: Main 275V DC Power for levitation and A/C; 100V AC 60Hz Power for general use; 100V DC Power for control and communication.

## Swissmetro

Swissmetro [24] is supplied by a 125kV, 50Hz system via the public grid, which is then stepped down to 6kV at the underground substation and is powered in the tunnels by the surface network - HV/MV transformer - rectifier - inverter and AC bus or DC bus and inverter - motor stator.

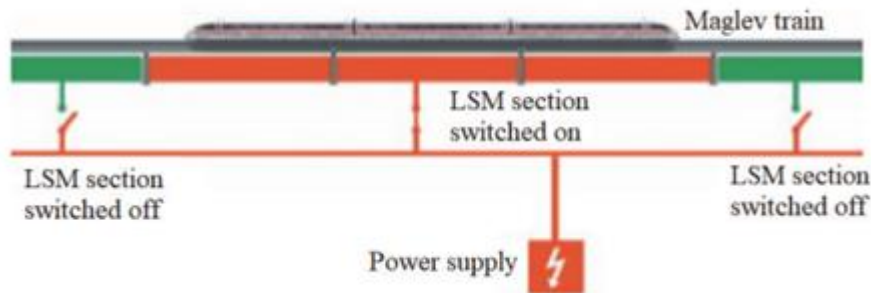
For variant A1, the chosen approach is based on using the three intermediate DC voltage levels between the rectifier and the inverter as a DC bus. The DC bus is defined along the track. Inverters supplying one to four motors ensure that the current and voltage systems are at the correct frequency. Long distances between the substations and the motor stators can be considered (>40 km). A significant number of inverters are required. For the B1 variant, the DC bus is used with mechanical contacts operating at speeds of up to 500 km/h and transmitting 7 MW. Apart from the fact that these contacts can operate in a partial vacuum atmosphere, this approach is the simplest as there are no electronic components in the tunnel. Long distances between two successive substations are considered (>40 km). For variant B2, a linear single-phase transformer is considered in parallel with the DC bus, the corresponding active power to be transmitted is approximately 7 MW. The secondary is on the vehicle. Such an approach leads to a high number of primary inverters and reactive power.

It uses a contactless energy transfer. Three energy transfer variants are considered: Variant A: propulsion, short stators fixed to the tunnel Variant A1: linear transformer, transmission of about 500 kW. Option B: propulsion, stators on the vehicle Option B1: mechanical contacts, transmission of 7 MW; Option B2: linear transformer, transmission of about 7 MW. Taking into account the propulsion variants for the Swissmetro system (discontinuous distribution of stators in the tunnel or stators on the vehicle), a transfer of energy along the entire length of the tunnel requires the use of a linear transformer or a mechanical contact.

## Tongji University Maglev

Finally, in the Tongji University Maglev [29], the power supply system consists of two 110 kV substations. Both 110 kV substations use one 110 kV/20 kV transformer and two 20 kV/1.2 kV rectifier transformers. Three different types of solid-state, water-cooled PWM converters (4 kA GTOs) are currently available to match the converter output to the vehicle acceleration and speed requirements: (a) high power 15.6 MVA converters; (b) medium power 7.5 MVA converters; (c) low power 1.2 MVA converters in the maintenance area. The three-phase inverter output voltage ranges from 0 to 2027 V and the frequency from 0 to 215 Hz. At higher frequencies, the output transformers (behind the inverters) can increase the voltage to a

maximum of 7800 V.



**Figure 32 - Tongji University Maglev Configuration**

### **Air levitation systems**

In the air levitation systems, electrical system control and interface all the components. For example, the primary power source for the tracked air cushion vehicle is three-phase electricity at 4160 volts, which is supplied to the vehicle through a multi-brush collector from power rails located alongside the track. The Linear Induction Motor (LIM) and the Power Conditioning Unit both operate using 4160-volt power. Similarly, the motors for the air compressors, which are essential for the air suspension and guidance systems, also utilize this power level. For the vehicle's secondary or 'hotel' power needs, an auxiliary transformer steps down the three-phase 4160-volt power to three-phase 208 volts and single-phase 120 volts. This transformed power is then regulated by circuit breakers in the power distribution unit before being distributed to various subsystems. Essential functions like vital control systems, lighting, and ventilation operate on battery power.

## **7.9 Monitoring & safety**

Finally, according to [2], Monitoring & Safety refers to the subsystem or set of subsystems that enables monitoring the vehicle state and condition, also preventing unwanted events (e.g., anti-collision system).

In the available literature, there is not much information on the safety systems used. The following are the main ones that are documented.

### **Chuo Shinkansen**

Chuo Shinkansen [6 - 8] is equipped with several monitoring and safety components.

Firstly, it has been equipped with power failure countermeasures. Even if the power goes out, levitation forces keep the train in the air while it is traveling at high speed. The vehicle comes safely to a stop rather than suddenly falling onto the track. Even if one substation suffers an outage, electricity can be fed from an adjacent substation, providing a high degree of



redundancy.

Secondly, the Superconducting Maglev is a quake-resilient system. Magnetic force from levitation and guidance coils keeps the vehicle centred in the guideway, both vertically and horizontally, preventing derailment at the time of an earthquake. The Earthquake Rapid Alarm System (TERRA-S), used successfully in the Tokaido Shinkansen, will also be adopted to decelerate and stop trains early in case of an earthquake.

Thirdly, the is constructed with non-flammable and flame-retardant materials that meet flammability specifications according to regulations. Fire extinguishers are deployed in cars for initial fire response. Partition doors are placed at both ends of the trainset, while gangway connections (automatic doors) are provided between individual cars. If a fire breaks out, the train continues to the next stop or outside of a tunnel before stopping, in principle, to ensure swift and safe passenger evacuation.

Finally, with respect to evacuation in case of emergency, approximately 86% of the Shinagawa - Nagoya section of the Chuo Shinkansen runs through tunnels. The emergency protocol is, similarly to the Tokaido Shinkansen, for the train to travel through to the next station or outside a tunnel. Even if it becomes inevitable to stop inside a tunnel and have passengers disembark for evacuation, JR Central will have a plan in place to guide and evacuate passengers safely and swiftly.

### **Incheon Airport Maglev**

The Incheon Airport Maglev (Ecobee) [14] is equipped with a system that prevents the effect of power failure. Stable levitation is maintained for at least 30 s after power failure with the aid of the backup battery system. The vehicle has landing skids for emergency landing and landing rollers for rescue operation by other vehicles.

### **Swissmetro**

Since Swissmetro [24] is a system that works exclusively in tunnels, its safety concept is based on four action levels: the vehicle continues, by itself, until the next stop; the vehicle is towed to the next station; the passengers are moved to an emergency vehicle; and the tunnel is re-pressurized.

The ambient pressure in the tunnel is the source of two hazards: the direct health effects due to an accidental exposure to low pressure and a prolonged exposure to a confined space (airtight vehicle). Then, a special monitoring system is used due to its particular characteristics.

### **Air levitation systems**

In air levitation systems, health check sensors are installed on the LM mover to monitor the

mover parameters, airgap, etc. There is an electrical/data interface to collect data about suspension state. There is an electrical/data interface to collect data about the electro-dynamic wheels' state. The monitoring and safety components receive data from braking ones to monitor the state and make sure that the brakes are engaged or disengaged. Vehicle and control and monitoring/safety components are connected electrically and also at the data exchange level

## 7.10 Compatibility with Technical Specifications for Interoperability (TSI)

The subsystems and components potentially compatible selected in WP2 were analysed with a view to carrying out a comparison for compatibility with the TSI in order to decline this compatibility (where existing) into a functional description of the required interfaces referred to the vehicle breakdown structure based on TSI. This analysis has been collected in Table 9:

**Table 9-The functional and technical specifications of the rolling stock subsystem**

LOC & PAS TSI: functional and technical specifications of the rolling stock subsystem	MDS common architecture – vehicle MDS System Name
General requirements (2.3. Rolling stock in the scope of this TSI)	<ul style="list-style-type: none"> <li>• TSI considers only speeds up to 350 km/h. For higher speed the procedure for innovative solutions shall be applied (2.3.3. Maximum speed)</li> </ul>
<ul style="list-style-type: none"> <li>• Structures and mechanical parts <ul style="list-style-type: none"> <li>○ General</li> <li>○ Mechanical interfaces</li> <li>○ Gangways</li> <li>○ Strength of vehicle structure</li> <li>○ Passive safety</li> <li>○ Lifting and jacking</li> <li>○ Fixing of devices to carbody structure</li> <li>○ Staff and freight Access doors</li> <li>○ Mechanical characteristics of glass (other than windscreens)</li> <li>○ Load conditions and weighed mass</li> </ul> </li> </ul>	<p>Structure</p> <ul style="list-style-type: none"> <li>• The structure of each vehicle shall be compliant to the specifications of Appendix J-1 of TSI.</li> </ul>
<ul style="list-style-type: none"> <li>• Track interaction and gauging <ul style="list-style-type: none"> <li>○ Gauging</li> <li>○ Axle load and wheel load</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• The loading gauge shall be adapted to be compliant with the one defined by the TSI.</li> </ul>

<ul style="list-style-type: none"> <li>○ Rolling Stock parameters which influence ground based systems</li> <li>○ Rolling stock dynamic behaviour</li> <li>○ Running gear</li> <li>○ Minimum curve radius</li> <li>○ Life guards</li> </ul>	<ul style="list-style-type: none"> <li>• The structure of the vehicle shall be compliant at least with one of the track gauges as defined by TSI (2.3.2. Track gauge).</li> </ul> <p>Propulsion – vehicle part</p> <ul style="list-style-type: none"> <li>• The vehicle shall be compatible with train detection system based on track circuits and other electronic track equipment for control command and signalling (4.2.3.3.1.1).</li> <li>• The requirements related to electromagnetic compatibility are specified in the specification referenced in Appendix J-2, index 1, clauses 3.2.1.and 3.2.2.</li> </ul> <p>Suspension</p> <ul style="list-style-type: none"> <li>• The suspension element load (equivalent to the axle load of a conventional rolling stock) shall be considered in combination with the axle spacing, with the train length and with the maximum allowed speed for the unit on the considered line (4.2.3.2.1. Axle load parameter). The axle load is a performance parameter of the infrastructure specified in clause 4.2.1 of the INF TSI and depends on the traffic code of the line.</li> <li>• The vehicle shall be compatible with train detection system based on track circuits and other electronic track equipment for control command and signalling (4.2.3.3.1.1).</li> <li>• The requirements related to electromagnetic compatibility are specified in the specification referenced in Appendix J-2, index 1, clauses 3.2.1.and 3.2.2.</li> </ul>
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	<p>Guidance</p> <ul style="list-style-type: none"> <li>The lateral guidance electromagnets shall apply a transversal load that, in combination with speed, is compatible with the performance parameters of the infrastructure.</li> </ul>
<ul style="list-style-type: none"> <li>Braking <ul style="list-style-type: none"> <li>General</li> <li>Main functional and safety requirements</li> <li>Type of brake system</li> <li>Brake command</li> <li>Braking performance</li> <li>Wheel rail adhesion profile — Wheel slide protection system</li> <li>Dynamic brake — Braking system linked to traction system</li> <li>Braking system independent of adhesion conditions</li> </ul> </li> </ul>	<p>Braking</p> <ul style="list-style-type: none"> <li>The unit braking control system shall have three control modes: <ul style="list-style-type: none"> <li>emergency braking: application of a predefined brake force in a predefined maximum response time in order to stop the train with a defined level of brake performance.</li> <li>service braking: application of an adjustable brake force in order to control the speed of the train, including stop and temporary immobilisation.</li> <li>parking braking: application of a brake force to maintain the train (or the vehicle) in permanent immobilisation in a stationary position, without any available energy on board.</li> </ul> </li> <li>(4.2.4.2.1. Functional requirements – (13))</li> </ul>
<ul style="list-style-type: none"> <li>Traction and electrical equipment <ul style="list-style-type: none"> <li>Traction performance</li> <li>Power supply</li> <li>Diesel and other thermal traction system</li> <li>Protection against electrical hazards</li> </ul> </li> </ul>	<p>Electrical system</p> <ul style="list-style-type: none"> <li>The electrical system of the vehicle shall be compatible with the power supply of the line.</li> <li>The TSI Energy specifies the following power systems: AC 25 kV 50 Hz system, AC 15 kV 16,7 Hz system, DC 3 kV system and 1,5 kV system. As a consequence, requirements defined below are related to these 4 systems only, and references to standards are valid for these 4 systems only.</li> </ul>

	<ul style="list-style-type: none"><li>• The electromagnetic interference limit levels rising from traction currents are specified in the specification referenced in Appendix J-2, index 1, clause 3.2.2. (4.2.3.3.1.1 Rolling stock characteristics for compatibility with train detection system based on track circuits - (10)).</li></ul> <p>Vehicle control system</p> <ul style="list-style-type: none"><li>• Information available to train staff or to vehicle control system shall allow the identification of degraded conditions concerning the vehicle (i.e., brake performance lower than the performance required), for which specific operating rules apply (4.2.4.9. Brake state and fault indication).</li></ul> <p>Monitoring and safety</p> <ul style="list-style-type: none"><li>• Vehicle shall be compatible with monitoring system and safety requirements applicable to conventional rolling stock.</li></ul>
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## 8 Description of the concept for vehicle subsystems – Hybrid MDS interoperable with the railway infrastructure

In this chapter, the vehicles' concepts (functional components and their properties), that have been briefly described in chapter 6.1.1 and 6.1.2, are comprehensively reported.

### 8.1 Structure

Vehicle structure of hybrid MDS can be divided in two categories:

- Structure derived from traditional railway wagons;
- New generation lightweight pods

The first category is based on a type of structure derived from traditional railway trains, in which the lower part is modified in order to accommodate MDS subsystems or components, like levitation/guidance and linear motors or permanent magnet for propulsion/braking.

Two major types of linear motor can be considered, synchronous (LSM) or asynchronous (LIM), and one new type of propulsion means derived from permanent magnet, electro-dynamic wheels can be considered as well. For the LIM family flat and U-shaped can also be considered.

The vehicle structure is a new structure designed to be compatible with TSI standards and it is connected to the bogies as well as holds in place and provides load transfer between MDS systems and the wagon/coach.

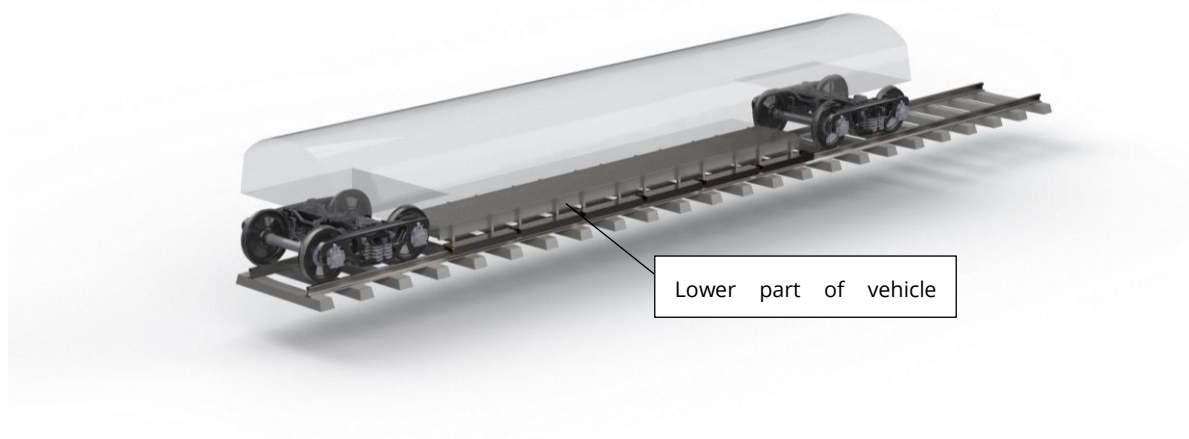
On a design perspective, the top part can be the same of standard vehicles and in some applications retrofitting could be viable.

The lower part is conceived in order to integrate additional or modified bogies and propulsion systems (further details will be addressed in D4.2). Since MDS and in particular levitation/guidance system require a distributed system architecture along the length of the wagon, a structural solution can be to adopt multiple bogies or a continuous frame that connects the MDS systems.

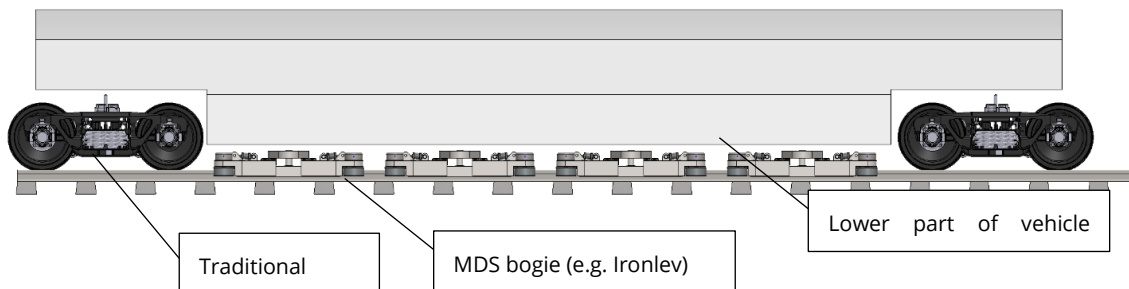
The structure of the vehicle and the loading gauge shall be designed to be compliant to the specifications of TSI.



**Figure 33 - Ironlev hybrid system with EMS lateral guidance – overview (Source: Ironbox)**

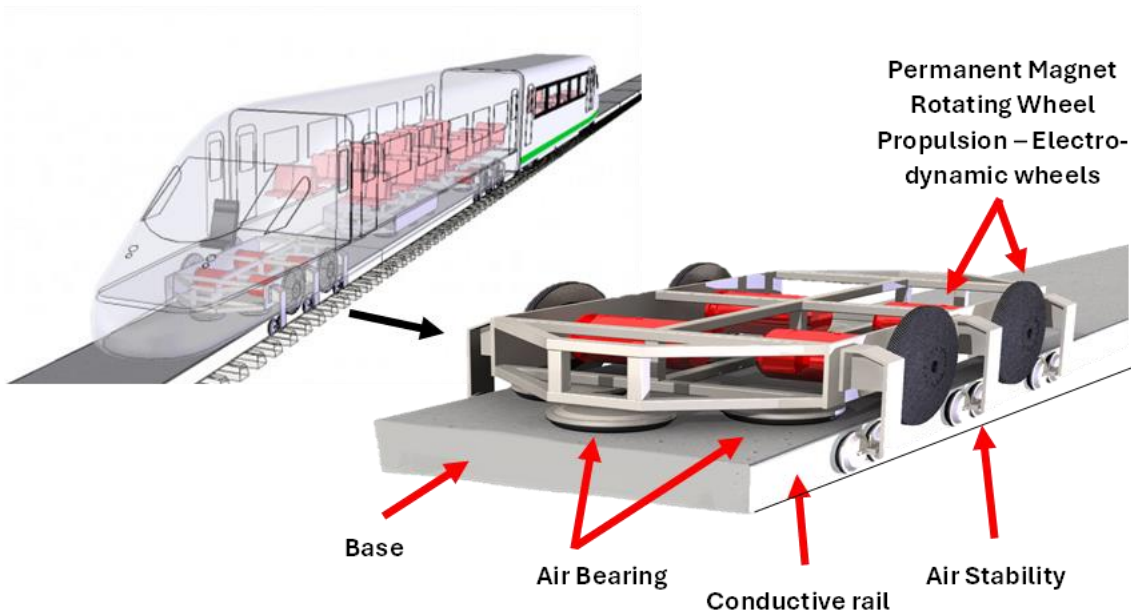


**Figure 34 - Ironlev sliders integrated in the vehicle structure (Source: Ironbox)**



**Figure 35 - Ironlev bogie coupled with standard bogie – lateral view. (Source: Ironbox, D2.1)**

For the air levitation, the vehicle is in size and dimensions the same as conventional trains only the bogie is replaced by a bogie which carry the load by air levitation and propelled by electro-dynamic wheels.



**Figure 36 - Airlev Train. Load carrying by air levitation and rotating permanent magnet wheel for propulsion/braking.**

The second category is based on a lightweight pod architecture conceived for mass transit or lightweight freight transport systems. The system might be thought for future expansion of the Current European Network, be linked through Interoperable Passengers' stations. The structure is made of new generation lightweight materials and new production processes and

takes advantage of functional performances of MDS systems, as the improvement of traction/braking performances of linear motors, that are not dependant on vehicle weight. Pod structural design couples wheel-based systems with MDS in order to provide hybrid full interoperability.

## 8.2 Propulsion - Vehicle part

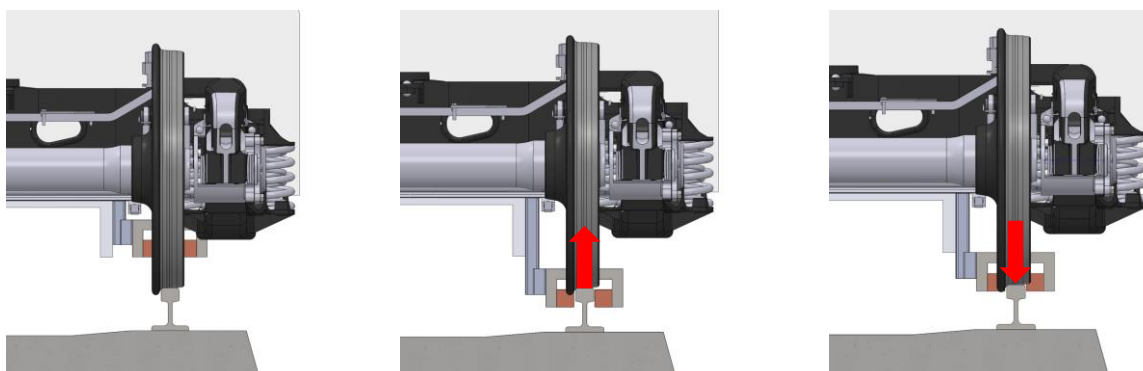
Hybrid MDS vehicles are based on the coupling of traditional wheel bogie or motor bogie with MDS propulsion subsystem, that can be based on:

- LIM
- LSM
- Electro-dynamic wheels
- Lateral traction wheels

The propulsion system is generally adopted for service braking operations. The type of MDS affects vehicle architecture and infrastructure.

In addition to the mentioned technologies, MDS subsystems can be adopted to improve traction/braking system performances of traditional wheels. As an example, ferromagnetic levitation can be used to increase contact force between vertical wheels and rail to increase friction and traction performances.

As an example, Ironlev sliders operations can be based on operative conditions: on wheels like switch crossing, Ironlev sliders are disengaged and retracted up inside the vehicle gauge (A); for cruise speed condition the Ironlev system is engaged and the levitation force is upwards to compensate vehicle load (B); for propulsion and braking phases the Ironlev sliders are engaged but the relative force is downwards. In this configuration the system can increase the loading on the rails and increase wheel traction/braking performances (C).

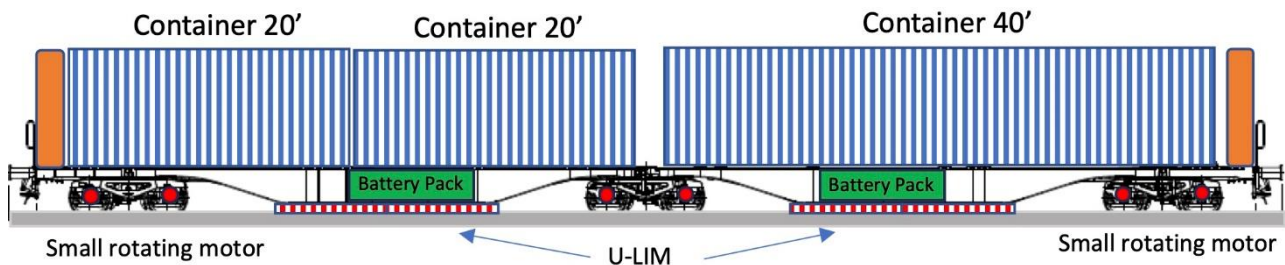


**Figure 37 - From left to right A) vehicle on wheels, B) Ironlev force upwards, C) Ironlev force downwards**

The vehicle shall be compatible with train detection system based on track circuits and other electronic track equipment for control command and signalling.

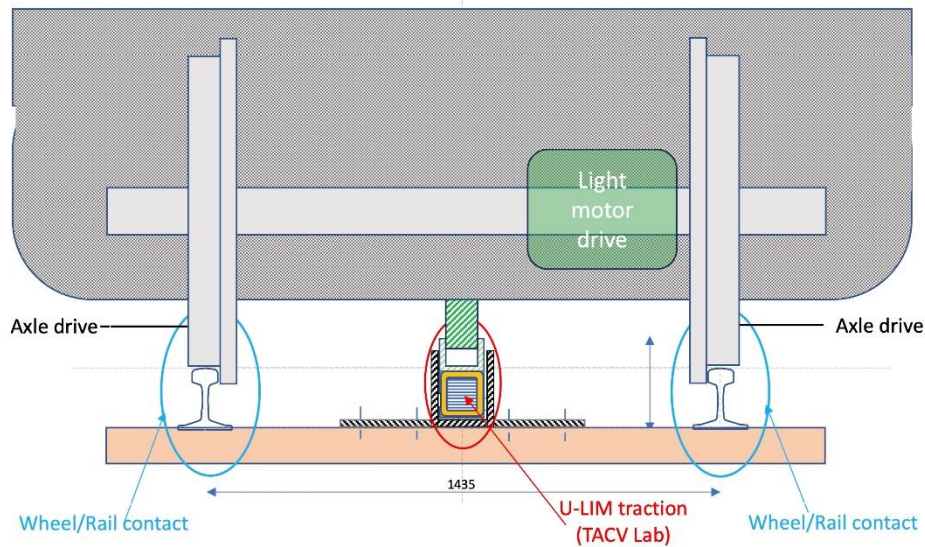
Second example is coupling the traditional wheel/rail contact sustentation with MDS propulsion subsystem based on LIM embedded on vehicle. In such case, an improved solution is to use the U-shaped LIM armature which offer the double function of traction and guidance by by means of lateral electromagnetic guidance resting on the vertical edges of the U-shaped armature of the LIM. Two possibles structures configuration:

- “U-CARS” structure (U-LIM Container Autonomous Rail Shuttle) for low-speed local containerized freight rail application, based on the standard design of an articulated freight wagon (Sggmrss90), with light axel electric drive (on one or up to six axels) for low-speed shunting.

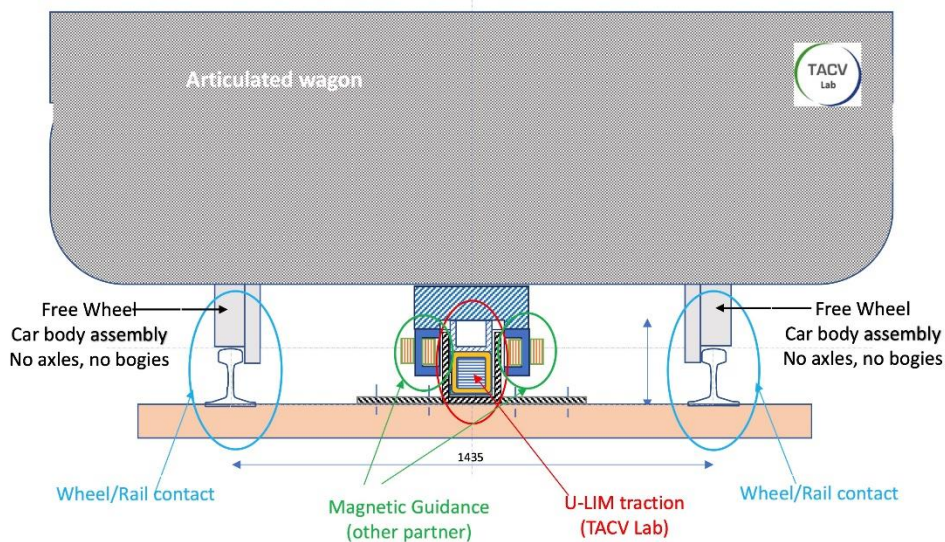


**Figure 38 - “U-CARS” (TACV Lab design based on standard articulated wagon, mix propulsion by U-LIM and light axel electric drive )**

- Light-weight wagon structure directly sustained by articulated independent wheels, (without bogies or axles). This very light structure requires a specific guidance system, that can be assumed by magnetic guidance system thanks to the vertical edges of the U-shaped frame.

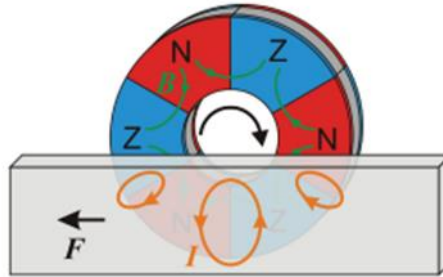


**Figure 39 - U-LIM integration and position in between the tracks (U-CARS TACV Lab design based on standard articulated wagon, mix propulsion by U-LIM and light axel electric drive)**



**Figure 40 - U-LIM integration with magnetic guidance system on light railcar body structure, directly sustained on articulated independent wheels.**

Another example is using the EDW for propulsion and braking. It is for magnetic propulsion and braking by using a wheel containing permanent magnets rotating contactless for instance along an aluminium conductor (stator). Due to this, Lorentz force is generated for propulsion (rotational velocity wheel larger than train velocity) and braking (rotational velocity lower than the train velocity), see figure below.



**Figure 41 - Propulsion and braking by rotating a wheel with permanent magnets along a stator**

### 8.3 Suspension

The suspension shall be obtained by using different technologies such as:

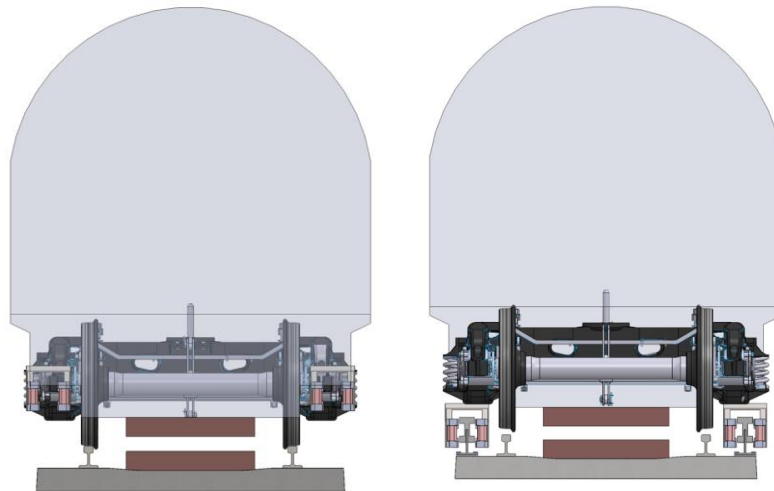
- EDS (inductrack)
- Ferromagnetic levitation (Ironlev)
- Air levitation

An MDS system can be adopted in combination with traditional wheeled systems to obtain a hybrid system architecture where traditional wheels are used at low speed and over track switches, while there are dedicated maglev corridors in between for high speed and high efficiency ride. This architecture is designed in order to increase the overall efficiency of the system by eliminating the contact friction.

On the infrastructure side, the hybrid configuration is obtained by adding auxiliary guideways to the traditional railway track that interact with the MDS suspension subsystem. As an example, it can be made of conductive rails or coils for EDS, iron rails for ferromagnetic levitation or dedicated track for air levitation. In case of iron rails, MDS suspension can be directly applied to traditional guideways without adding additional rails (ref. Ironlev).

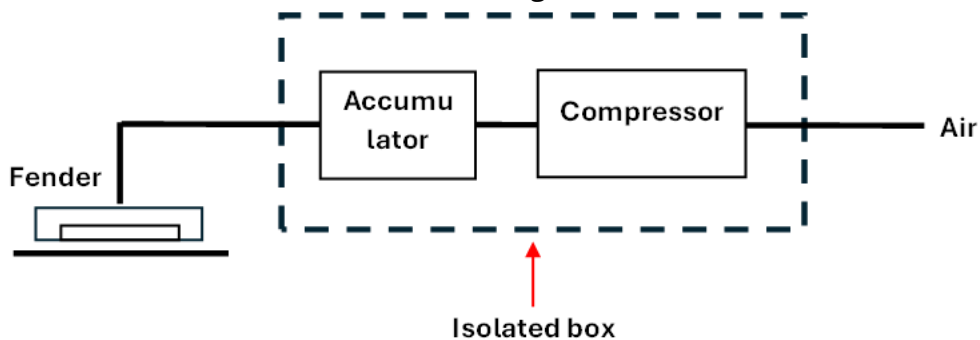
In order to provide interoperability, gauge dimensions and interferences issues must be addressed with a dedicated structural design as well as additional or auxiliary subsystems. The auxiliary systems can be made of electromechanical systems that engage or disengage suspension systems for the rails based on the operating phase of the vehicle: during low speed switch crossing and/or stopping at stations, MDS is magnetically removed from the dedicated rail and the vehicle operates on wheels; instead during speed cruise phase MDS is engages and bears the load of the wagon.

As an example, below is represented on the left an image of a system operating on traditional bogie wheels while MDS systems are retracted onboard the vehicle for low speed and switch crossing; instead on the right the system operates on MDS suspension along maglev corridors by ensuring high efficiency and increased performances (ref. Ironlev).



**Figure 42 - From left to right A) vehicle operating on wheels B) Ironlev system engaged on Ironlev guideways, on dedicated maglev corridors (source: Ironbox)**

Another example is the air levitation. To carry the load by air using air fenders are used. This technology has proven to be effective for several air levitation transportation systems, see summary of air levitation air cushion in Deliverable D2.1. Instead of using for instance a fan, an air compressor in combination with an accumulator (for a stabilized air pressure) will be used placed in a sound isolation chamber, see figure below.



**Figure 43 - Air fender - air compressor system**

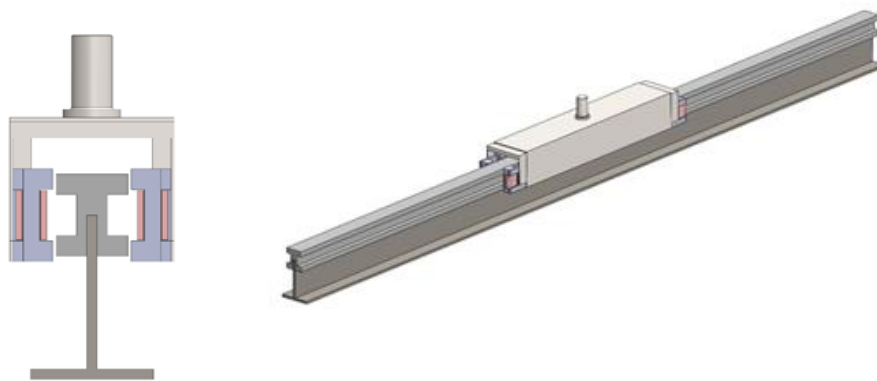
## 8.4 Guidance

The guidance shall be obtained by using different technologies such as:

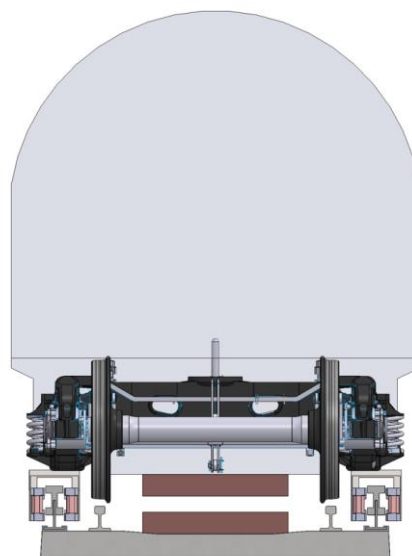
- EDS (inductrack)
- EMS
- Air cushion
- Lateral wheels

The hybrid systems combine wheel-based subsystems with MDS suspension. When the system operates on wheels, the guidance is provided by vertical wheels like traditional trains, instead when the system operates on MDS suspension, lateral guidance is required according to the suspension system itself.

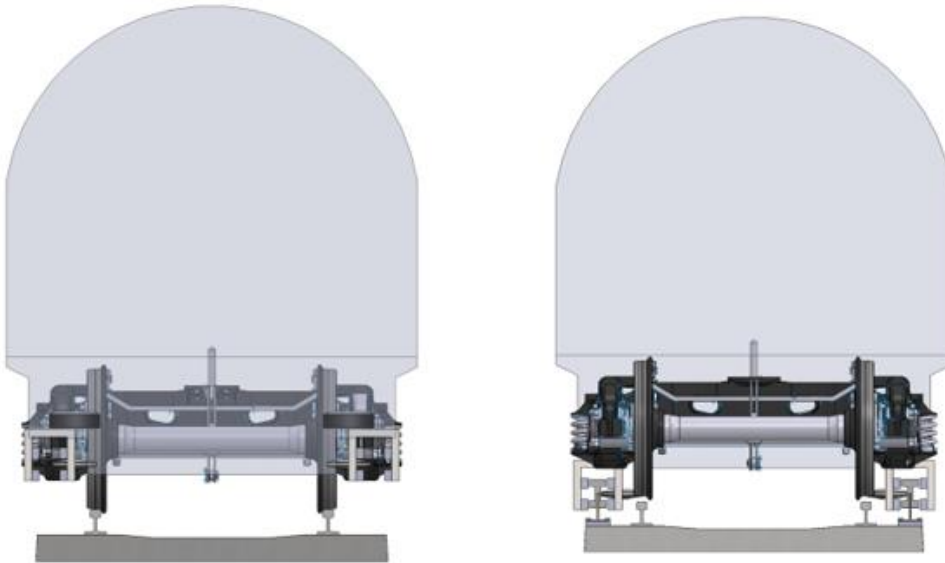
Generally, guidance subsystem is based on the same technology of the suspension system and integrated in the MDS suspension subsystem (e.g., EDS, EMS or air levitation), so it requires auxiliary guideways for lateral guidance that are generally integrated in the same auxiliary rail used for the suspension. For Ironlev technology, instead, guidance and suspension can be separated and based on EMS or lateral wheels.



**Figure 44 - Example of EMS lateral guidance applied to Ironlev system. From left to right A) section view B) overview (source: D2.1)**



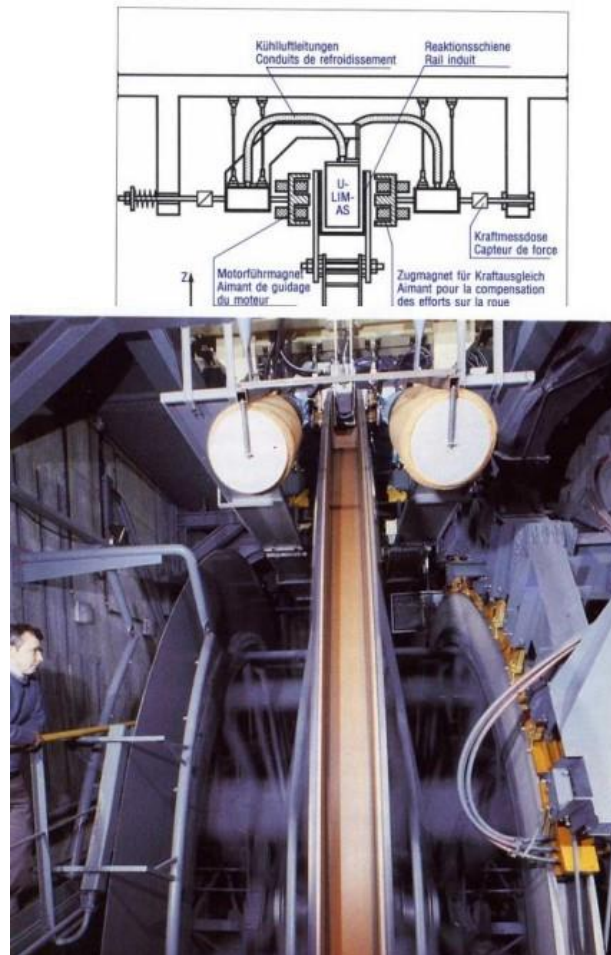
**Figure 45 - Ironlev hybrid system with EMS lateral guidance - section view (Source: Ironbox)**



**Figure 46 - Ironlev hybrid system with lateral wheels lateral guidance – section view  
(Source: Ironbox)**

An innovative guidance system could be achieved thanks to the vertical edges of the U-shape armature of the U-LIM which can be used for centralized magnetic guidance.

This magnetic guidance system has already been tested up to 300km/h on Grenoble Wheel test bench.



**Figure 47 - illustration picture of the magnetic guidance using the lateral edges of the U-shaped armature (source: picture of the magnetic guidance on the Grenoble Wheel test bench, “Deufrako” French-German research program).**

The guidance of the airlev train will be realized by air fenders as well, as shown in Figure 54. Each side of the airlev bogie has six small air fenders for guidance.

## 8.5 Braking

Generally, braking functionality is provided by the same system adopted for propulsion. In hybrid vehicles, service braking is provided by MDS subsystems, while emergency braking and parking braking can be based on traditional systems, according to the class of vehicle and the specifications.

Linear induction motors (flat and U shaped) and electro-dynamic wheels can also brake the vehicle using three modes:

- by regenerating energy in hyper-synchrone mode, it is possible to stop the vehicle, this mode uses the traction converter system.

- by DC current injection, which can be the emergency mode, then it should be assisted by a mechanical braking system. This mode uses a fully independent electrical circuit with a specific highly reliable energy storage system.
- by rotating in the opposite direction, it can generate Lorenz forces that act on the vehicle, effectively slowing it down and bringing it to a stop.

## 8.6 Vehicle control system

In the following caption, some general considerations about vehicle control system have been described. It is important to note that to elaborate on it in more details, an MDS along with system applications and operating environment must be defined. For vehicles utilizing a linear synchronous motor, typically seen in infrastructure-controlled linear motors, the control subsystem is predominantly located in the trackside elements, such as the control centre. Conversely, vehicles employing a linear induction motor system have their control mechanisms directly within the vehicle.

Key to the operation of these systems is the integration of multiple sensors on the vehicle. These sensors are critical for accurately determining the vehicle's position, speed, and other essential control variables. Additionally, at a higher operational level, each control subsystem is designed to interface seamlessly with the Traffic Management System (TMS), ensuring cohesive and efficient operations.

Concerning the LIM (flat or U-shaped) and electro-dynamic wheels, an innovative solution consists in using an autonomous driving system adapted from the road autonomous cars (day/night camera obstacle detection, lidar-sonar, GPS location), traffic control, 4G/5G communication, which allows real-time remote control (teledriving) by a deported operator. Such system is not yet authorized on the railway network but can be used on dedicated rail lines (ports or factories infrastructures, dedicated short lines).

## 8.7 Electrical system

In the following caption, some general considerations about electrical system for hybrid MDS have been described. It is important to note that to elaborate on it in more details, an MDS along with system applications and operating environment must be defined.

The electrical system in vehicles with a hybrid MDS configuration encompasses several key components. Primarily, it includes an onboard power supply, essential for powering the vehicle's onboard electronics. This is a crucial part of the system, ensuring that all electronic devices and systems in the vehicle receive the necessary power to function correctly. Additionally, the system features an intricate network of wiring. This wiring is responsible for the efficient and safe transfer of power throughout the vehicle, connecting various



components and systems to the power supply. Furthermore, the system may also incorporate a power collector, e.g., wireless power transfer or pantograph, which plays a vital role in certain configurations. However, such change may require railway infrastructure redesign and approve e.g., third rail in an open railway network. For closed infrastructure, the process of approval may be easier. This component is designed to harness and distribute power efficiently, ensuring that the vehicle's electrical demands are met consistently. Overall, these elements work together seamlessly to support the vehicle's functionality and enhance its performance.

Considering the LIM traction, the current contact shoes and power rail are a very relevant compact system for low-speed freight rail shuttle, using the standard DC voltage (750V DC or 1500V DC) electrical rail supply. It can be coupled with an embedded energy storage capacity, which can avoid energy transfer in the event of an absence of an energy transfer system over a certain length of the track on non-electrified railway lines and container transshipment area using gantries lifting.

For the airlev system, the traditional catenary-pantograph electrical setup is compatible due to the replacement of the standard bogie with the airlev bogie. This allows the existing power for conventional motors to drive electro-dynamic wheels. Additionally, power for air compression can be sourced through same methods.

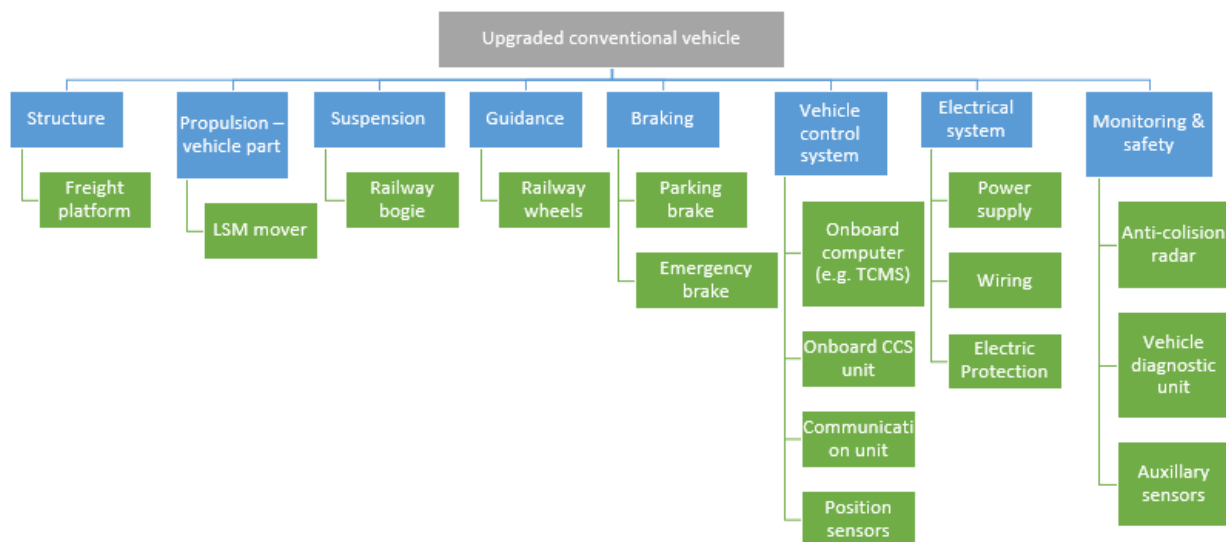
## 8.8 Monitoring & safety

In the following caption, some general considerations about monitoring and safety units for hybrid MDS have been described. It is important to note that to elaborate on it in more details, an MDS along with system applications and operating environment must be defined. The vehicle safety and monitoring system integrates key features to protect the vehicle and its environment. It includes an Anti-collision System, using a front-mounted radar to detect obstacles within 100 meters. This system serves two purposes: it enables safe braking at low speeds, and at high speeds, it helps to reduce collision damage. This radar is essential for preventing and reducing accidents. Additionally, the system has a Self-diagnostic System with an onboard CPU and sensors. These sensors monitor the vehicle's condition, tracking vibration, current, voltage, pressure, and temperature. If it detects any issue, it quickly alerts the central control, ensuring prompt action and enhancing the system's safety and reliability.

## 9 Description of the concept for vehicle subsystems – Conventional railway vehicle upgraded with MDS subsystems or technologies

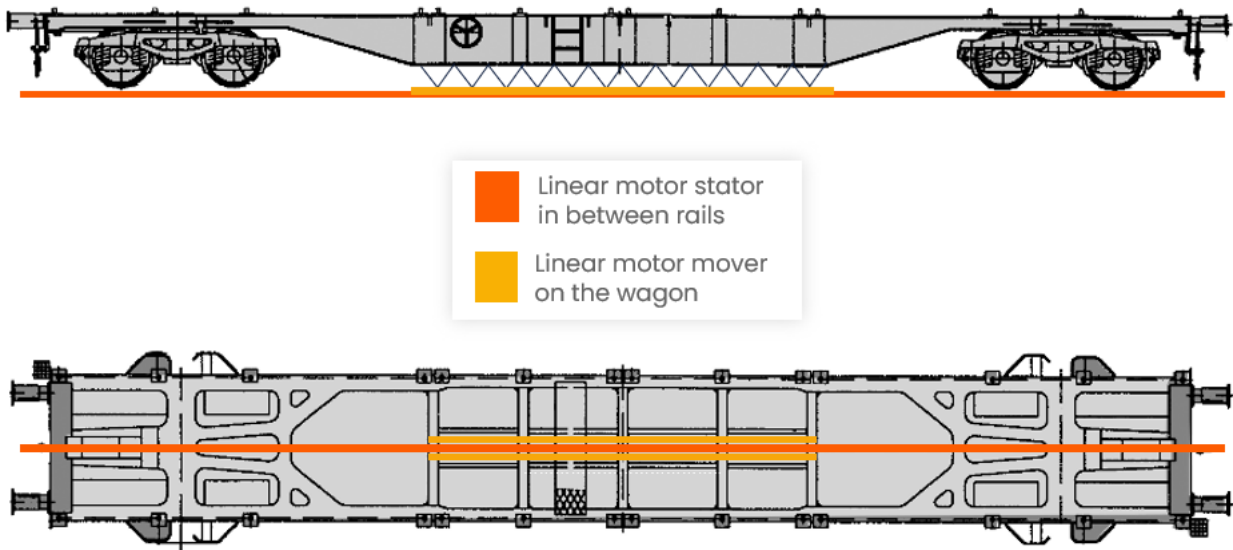
An example of a maglev derived system is the linear motor-powered retrofitted wagon. It is a rail system used to transport goods using existing rail infrastructure e.g. in freight yards, sidings, but also, if applicable, in the open railway network. It uses modified freight wagons. These wagons are equipped with a linear motor rotor (with permanent magnets), as well as the necessary vehicle electronics. The conventional rail infrastructure is supplemented with a linear motor stator and linear motor power and control systems, as well as communication systems. The linear motor-powered retrofitted wagon system allows goods to be moved conveniently and quickly within industrial units (closed railway network) or between facilities through European common network without the need for use of heavy shunting locomotive.

The SBS of the retrofitted wagon concept is shown in Figure 48 - System Breakdown Structure - retrofitted freight vehicle. A detailed description of each component is provided in the following captions. It must be noted that the SBS is not exhaustive and shows a general concept. Some components are not included since specific solutions remain confidential. Moreover, current concept is at TRL6, therefore many of the components configurations is still to be selected.



**Figure 48 - System Breakdown Structure - retrofitted freight vehicle**

Such a concept has been selected since such configuration has been investigated in WP7 use cases and analyses.



**Figure 49 - Linear motor-powered retrofitted freight platform**

## 9.1 Structure

The mechanical structure of a retrofitted vehicle combines a classic freight wagon with a linear motor mover. At its core, the vehicle features a standard freight wagon chassis, capable of carrying a variety of heavy cargo. Under the wagon, a set of permanent magnets is mounted in a housing that provides protection from adverse weather conditions and other harmful phenomena. In order to install the mover on the structure, either a frame upgrade must be performed which may lead to re-homologation, or a specific type of freight wagon should be selected that allows for mover installation without structure change.

## 9.2 Propulsion - Vehicle part

The permanent magnets installed beneath the wagon serve as the essential components of the linear motor rotor and are essential for creating the propulsion force for the vehicle. The permanent magnets are securely enclosed within a robust and sealed housing, effectively safeguarding them from e.g., adverse environmental conditions or electrocution. This protective housing shields the magnets from moisture, dust, and other potentially harmful external factors that could compromise their performance. By maintaining the integrity of the magnets, this design ensures the long-term reliability and efficiency of the linear motor system. This combination of powerful permanent magnets and protective housing underscores the system's durability and its ability to deliver consistent and dependable linear motion for the wagon in various operational scenarios.

## 9.3 Suspension

Stability during the operation is achieved using conventional railway wheels. These wheels, which are a fundamental part of the freight platform design, provide crucial stability and

guidance along the track. The interaction of the wheels with the traditional rail tracks that ensures steady and controlled movement. The railway wheels distribute the weight of the vehicle evenly and engage with the rails, preventing lateral swaying and maintaining the wagon's alignment. This synergy between the linear motor technology and the time-tested reliability of classic railway wheels strikes a balance between innovation and proven engineering, resulting in a transportation system that combines the benefits of magnetic propulsion with the stability and safety associated with traditional rail travel.

## 9.4 Guidance

Guidance system in relies on wheels. Train wheels are designed to run smoothly on rails, ensuring stability and preventing derailment, even, potentially, at high speeds or sharp turns. Moreover, the linear motor propulsion, due the self-alignment feature, additionally stabilizes the vehicle during the movement.

## 9.5 Braking

Braking mechanisms play a pivotal role in ensuring safety and control during operations. The primary braking method employed is electromagnetic braking, utilizing the characteristics of the linear motor. This form of braking allows for precise speed control and vehicle stopping by manipulating the magnetic field within the magnetic track. Additionally, the system is complemented by frictional braking, achieved through traditional brakes that act directly on the railway wheels. This comprehensive approach to braking provides redundancy and operational safety, enabling immediate and effective vehicle stopping in case of electromagnetic braking system failures. With this braking system in place, operations are both precise and reliable, serving as a crucial element in ensuring the safe and efficient operation of the entire transportation system. The last braking component in the vehicle is parking brake that enables maintaining the position while stopped and prevent from e.g. moving down the incline.

## 9.6 Vehicle control system

The vehicle control system in this setup operates in a unique manner, as vehicle movement is primarily controlled from the infrastructure side. Consequently, the vehicle itself is equipped with a minimal set of sensors and devices, specifically tailored for infrastructure safety, control, and guidance systems. These sensors encompass a wide range of functions, including the measurement of position through GPS, IMU, and odometry, as well as monitoring parameters like pressure, voltage, currents, and vibrations. Additionally, the vehicle is equipped with communication units that facilitate the exchange of crucial information with the infrastructure control systems. This collaborative approach between the vehicle and infrastructure ensures precise control, optimal safety, and efficient guidance throughout the entire transportation process.

## 9.7 Electrical system

The electrical system in this configuration is designed to support the operation of the vehicle's electronic devices and communication systems. It consists of two key components:

Firstly, there is an onboard battery with a voltage rating of 72V. This dedicated battery serves as the primary power source for the vehicle, ensuring the continuous operation of essential electronic devices and communication systems throughout the journey. It plays a pivotal role in providing the necessary electrical energy to sustain the functionalities of these critical components.

Secondly, the electrical system includes a comprehensive cable wiring network that efficiently distributes electrical power to the various devices and sensors installed within the vehicle. This structured wiring system acts as the backbone of the electrical infrastructure, facilitating the seamless flow of power to all relevant components. It ensures their proper functioning and enables effective communication between the vehicle's systems, ultimately contributing to the safe and efficient operation of the entire transportation system.

## 9.8 Monitoring & safety

In the domain of monitoring and safety measures, this system incorporates several critical elements to ensure the well-being of both the vehicle and its surroundings.

Firstly, an Anti-collision System is integrated into the setup. This system utilizes a radar mounted on the vehicle's front to detect obstacles up to 100 meters. Its functionality serves a dual purpose: at lower speeds, it facilitates safe braking before reaching an obstacle, while at higher speeds, it works to minimize damage in the event of a collision. This radar-based system is pivotal in accident prevention and mitigation.

Secondly, a Self-diagnostic System is deployed within the vehicle. This system consists of an onboard CPU and an array of sensors responsible for monitoring the vehicle's overall health. It tracks various parameters, including vibration, current, voltage, pressure, and temperature. In cases of emergencies or the detection of anomalies, the self-diagnostic system rapidly relays this critical information to the central control system and engages the emergency braking. This proactive monitoring and real-time reporting capability enhance safety measures and enable swift responses to potential issues, thereby bolstering the overall safety and reliability of the entire transportation system.

## 10 Vehicle interfaces Identification

In this chapter the interfaces related to Hybrid MDS and Conventional vehicle upgraded with MDS subsystems or technologies are considered. This methodology has been defined following the use cases defined in WP6, which exclude the Full MDS.

### 10.1 Command, Control and Signalling (CCS) Systems

The railway signalling system that has become the European standard quite over all the UE railways network before 2040 This is an ambitious program to have a Single ETCS Railway Area in Europe, and probably is the State-of-the-Art standard CCS for conventional train worldwide (applications with Global Navigation Satellite System (GNSS) technology are still considered premature) is the ERTMS/ETCS, so it is obvious to assume it as the reference CCS standard to analyse compatibility for those vehicles MDS which are expected to circulate on railway lines with ETCS signalling. For this system (see also §10.3.2 below) there are well-defined specifications that regulate its operation. ERTMS/ETCS signalling requires there to be wayside and onboard systems. The cooperation between these systems makes it possible to achieve the correct distribution of vehicles on the line without there being accidents, while respecting the timetable.

This document deals with the correct coexistence of the ETCS On Board system inside the MDS vehicle and the compatibility with the CCS trackside systems.

Any type of MDS vehicle that will have to travel on a railway line managed with an ERTMS/ETCS signalling system must be compatible with the rules contained in the TSI Baseline 4. Moreover, the description of the interface characteristic and the test that must be performed are also described in TSI Baseline 4.

#### 10.1.1 CCS On Board interfaces

The ETCS on-board system whose core is called EVC (European Vital Computer) has the task of carrying out Automatic Train Protection functions.

The ETCS interacts with on-board modules with the driver and via radio with the wayside systems. The on-board ETCS system is based on odometry to evaluate the distance travelled with respect to defined points along the line (EUROBALISE) and to calculate braking curves to ensure spacing between trains.

To carry out odometry it uses sensors that can be installed on the wheel axles or other sensors that use high frequency radio signals (radar) or accelerometers or other potential systems such as the GNSS receiver. In ERJU R2DATO project, studies are underway to develop multi-sensors-based solutions to obtain train odometry.

Radio communication between the ETCS EVC system and the Radio Block Centre (RBC) system



installed wayside also follows well-defined rules and communication in the GSM-R band is currently used. In the future the FRMCS system will include this band but will also include 5G/6G solutions and other bands.

Another fundamental component is the reading of the Eurobalises installed along the line. The Eurobalises are activated by a 27MHz signal produced by the on-board system that powers them and a magnetic field is created which produces two frequencies that shall be used for frequency shift keying (FSK) of the Uplink data. The two frequencies shall nominally be 3.951 MHz for a logical 0 and nominally be 4.516 MHz for a logical 1. In a shift between the two frequencies the carrier shall have a continuous phase (i.e., with continuous phase frequency shift keying modulation shall apply). The centre frequency shall be 4.234 MHz  $\pm$  175 kHz and the frequency deviation shall be = 282.24 kHz  $\pm$  7 %.

The information encoded in this way produces telegrams that contain various information. Furthermore, the position of the Eurobalise is used as a reference point to calculate the relative distance to a point to be protected or to any event to be transmitted on board the train.

In general, the on-board system must comply with the European standard EN 50155. This describes all the operating conditions to which the on-board system must be compliant. This obviously has an impact on the vehicle that must host it as these rules must be respected. Therefore, on the MDS vehicle the ETCS on-board system must be hosted in an environment that respects the mechanical, electrical and electromagnetic limits present in EN 50155.

In the past, during the construction phase of the locomotive, depending on the type of vehicle, well-defined compartments were created where all the electronic equipment was located.

Furthermore, for the odometric sensors, that are installed on the wheels, and the BTM Antenna that interacts with the Eurobalises they are in an open field below the train, the rules seen previously must be apply to these too.

For the Eurobalises it is necessary to add the Subset 034 which reports the specifications and the Subset 085 which describes the type of test to be performed.

All the interfaces/interactions of a generic ERTMS/ETCS on-board system are:

- Inside the vehicle:
  - Odometric Sensors
  - Vehicle (including TCMS)
  - Driver
- With the trackside:

- Eurobalises
- Radio

### 10.1.1.1 Odometric Sensors

These sensors can be of different families:

- Sensors installed on the wheel axle produce a square wave where each pulse indicates that a portion has been travelled in the observed time interval. The circumference of the wheel is divided into parts and each part corresponds to an impulse produced by the sensor.
- Radar Sensor. These sensors use the radar doppler effect for measuring the speed and distance. the radar beams are aimed towards the ground and measures every variation in it to determine the movements. these sensors at a set frequency, usually every 50 ms, report the speed and distance travelled.
- accelerometers and/or gyroscopes, these usually consistently installed on the vehicle typically report the acceleration and direction of movement of the train every 100ms - 300ms.

For each type of sensor, it is necessary to verify that the vehicle MDS is non-intrusive, and that the quality of the signal complies with the performance expected from the on-board system. Odometry is a vital aspect for a rail vehicle, if it were to fail, it would immediately block the train.

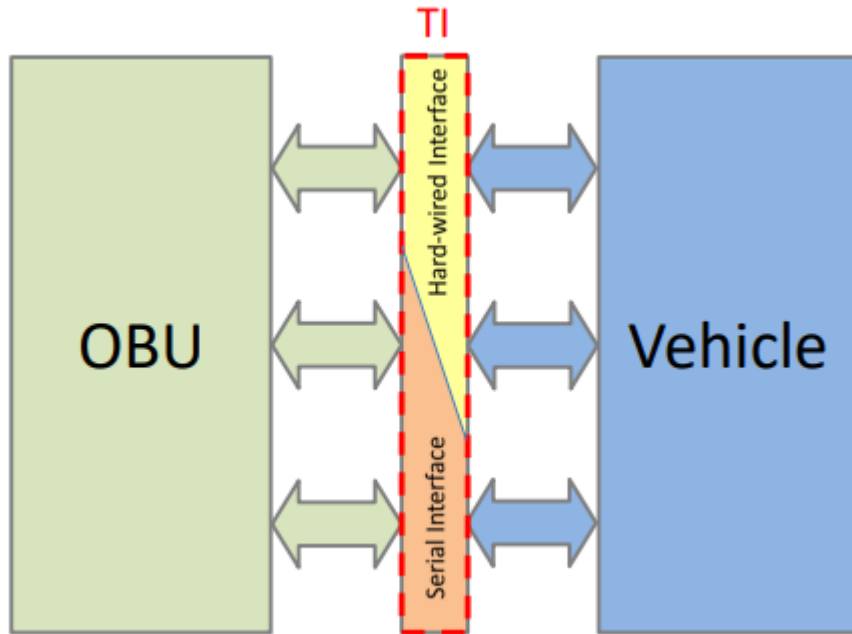
### 10.1.1.2 Vehicle Interface (including TCMS)

All the interfaces of the ETCS On Board system with the vehicle are specified in the Subset 034 and Subset 119, these include the interfaces with TCMS and with the control unit that manages the brake.

The Train Interface specified consists of serial interface and hard-wired interface. Some signals are only supported over serial interface due to the type of data. ETCS on-board equipment shall support four signals on the hard-wired interface:

- Emergency Brake Command 1
- Emergency Brake Command 2
- Traction Cut-Off
- Isolation (of ETCS).

Figure shows the OBU (green colour) interfaced to the vehicle (blue colour) via hard-wired and serial Interface. The interface itself is drawn in red colour.



**Figure 50 - Hard-wired and serial links between vehicle and ERTMS/ETCS on-board**

The following table reports all the interface managed by the ETCS On Board Unit. It is indicated the Source (OBU On Board Unit or TR Train). M stand for Mandatory and O for Optional. All the Mandatory must be implemented in the vehicle.

**Table 10 – ETCS OBU Functional I/O**

No	Functional I/O	Source	Wired interface	Serial interface
1.	Sleeping	TR	O	M
2.	Passive Shunting	TR	O	M
3.	Non-Leading	TR	O	M
4.	Isolation (of ETCS)	OBU	M	-
5.	Automatic Driving	OBU	O	M
6.	Remote Shunting	OBU	O	M
7.	Service Brake Command	OBU	O	M

8.	Brake pressure	TR	-	M
9.	Emergency brake Command	OBU	M	M
10.	Regenerative Brake Inhibit	OBU	-	M
11.	Magnetic Shoe Brake Inhibit	OBU	-	M
12.	Eddy Current Brakes for Service Brake Inhibit	OBU	-	M
13.	Eddy Current Brakes for Emergency Brake Inhibit	OBU	-	M
14.	Special Brake Inhibition area – STM Orders	OBU	O	M
15.	Special Brake Status	TR	O	M
16.	Additional Brake Status	TR	O	M
17.	Change of Traction System	OBU	-	M
18.	Powerless Section with Pantograph to be Lowered – Trackside Orders	OBU	-	M
19.	Pantograph – STM orders	OBU	O	M
20.	Air Tightness – Trackside orders	OBU	-	M
21.	Air Tightness – STM orders	OBU	O	M
22.	Station Platform	OBU	-	M
23.	Powerless Section with Main Power Switch to be Switched Off – Trackside Orders	OBU	-	M
24.	Main Power Switch – STM orders	OBU	O	M
25.	Change of allowed Current Consumption	OBU	O	M
26.	Engine Orientation in Supervised Manoeuvre	OBU	O	M
27.	Traction Cut-Off	OBU	M	M
28.	Cab Status	TR	O	M

29.	Direction Controller	TR	O	M
30.	Train Integrity	TR	O	M
31.	Traction Status (only for STM)	TR	O	M
32.	Set Speed (for DMI indication)	TR	-	M
33.	Type of Train Data Entry	TR	O	M
34.	Overall Consist Length Information	TR	-	M
35.	Train Data Information	TR	O	0
36.	Train Running Number	TR	-	M
37.	National System Isolation	TR	O	M

### 10.1.1.3 Driver

The interface with the driver involves interacting with the DMI (Driver Module Interface) and listening to the sound signals produced by the system.

The DMI is a graphic interface defined by the standards for which the vehicle must be designed to accommodate it on the driving desk in an easy-to-access ergonomic position. The DMI complies with the same environmental standards as other on-board systems.

### 10.1.1.4 Eurobalises

This is a CCS Functional Interface and needs wayside compatibility.

For the specific project of the MDS vehicle it is necessary to verify the electrical, electromagnetic and mechanical compatibility.

Since failure to read one or more Eurobalises has intrusive effects on the regular operation of the system, it is necessary to ensure that the MDS vehicle does not introduce side effects to operation, for example, it must not produce an electromagnetic signal that could disturb the Up Link or energization phase. The TSIs report the noise masks for which the Eurobalises can be influenced in their operation. This must be strictly avoided. In addition to the verification of the disturbance masks produced by the vehicle which must be compatible with the operation of the Eurobalise in subset 085 and subset 076, the functional and not functional

tests that must be performed to verify correct functioning are also reported.

From a mechanical point of view, it is necessary to verify that the position of the antenna for reading the Eurobalises is rightly aligned with respect also to the centre line where the Eurobalises are usually installed. All these mechanical aspects are reported in the technical interoperable specifications TSI.

### 10.1.1.5 Radio

This is CCS Functional Interface and needs wayside compatibility.

The interface with the radio is essential especially for the ETCS Level 2 and Level 3. If there were disturbances that compromised its functioning, these would be extremely intrusive in the movement of the train on railway lines, causing the emergency braking activation.

For this reason, it is necessary to carry out tests that certify the Quality of Service of radio communication in different operating conditions.

### 10.1.2 CCS Wayside interface

Other CCS wayside elements, that aren't functionally linked to the ETCS On Board, can be affected by the MDS vehicle are:

- Interface with TDS (Train Detection System) The track circuits that are used to verify the presence of the train in the section are of different designs and often also depend on the power supply of the line. Depending on the country there are direct current systems and others that work in audio frequency. For each of these systems, the disturbance mask must be applied according to the catenary power supply. Then there are the systems called axle counter which instead work on the interaction (without contact) of the wheel towards a sensor. For these too, it is necessary to verify that the MDS vehicle is not intrusive. The measurement of the effect of the interaction between the MDS vehicle and the axle counter must be performed with the wheel approaching and with the wheel superimposed on the sensor for the different types of sensors. Then there are similar systems that are used to warn level crossings of the train's arrival. The same types of tests must be conducted.
- Interface with HBD (Hot Box Detector). These systems analyse the state of the wheels and bushings (Box) to verify that their temperature does not go beyond a certain threshold. These systems then inform the CCS of the detected problem, temperature above threshold, and the trackside system brings the train that presented the problem to a safe state. This could be due to brake problems which may have stuck during braking. Also, in this case the frequencies used are different, some systems use the

infrared band. In any case, the MDS vehicle must produce a noise emission mask compatible with the operation of the HBDs. On the new MDS vehicles the HBD could be integrate on board. In this case the problem is mitigate.

### 10.1.3 ATO in CCS

The ATO (Automatic Train Operation) that implements the automation functions for the railway lines within the ERJU is taken care of by R2DATO project.

Within R2DATO, the definition of requirements and the creation of demonstrators up to the GoA4 automation level are envisaged (The GoA4 allows to have a completely autonomous vehicle for the railway system without the presence of the driver). In this context, the new systems that will carry out the automation functions will have to be installed on board the vehicles.

In addition to the impact of finding the space in which to install them, there are the needs of having systems that are compatible with the new elements that will be installed. Specifically, there will be:

- i) a dedicated module for radio communication between ATO and the corresponding trackside system. Radio communication, depending on the degree of GoA automation, becomes increasingly important and increasingly requires greater bandwidth.
- ii) an interface between ATO and TCMS for automation purpose that manages acceleration and deceleration, as well as braking.
- iii) sensors for the Perception functions, which will be at least cameras, radars, lidars that implement some of the functions that in the conventional non autonomous vehicles are performed by the driver.
- iv) APM module that, thanks the information coming from the other modules, implements the decisions that typically are taken by the driver.
- v) GNSS receivers.

All these new devices must comply with EN 50155 but it is also necessary that the vehicle does not influence their operation, especially those that impact safety.

Furthermore, the new interfaces will have to be evaluated to have adequate computational resources to dedicate to the required functions.

Therefore, these parts must also be considered when defining the architecture of the new MDS vehicle.

On-board ATO has similar characteristics to the on-board ETCS system. It should be

considered that ATO will have to interact in a more integrated way with the train's traction and the other functions that are currently carried out by the driver.

## 10.2 Hybrid MDS based on maglev vehicle

### 10.2.1 Vehicle-vehicle interfaces

In hybrid MDS vehicles, the main interfaces between vehicle subsystems are as follows:

- Structure
  - Traditional wheel-based systems
  - MDS suspension
  - MDS propulsion/braking
- Propulsion/braking
  - Structure
  - Electrical system
  - Vehicle control system
- Suspension
  - Structure
  - Traditional wheel-based systems
  - Guidance
  - Propulsion
  - Electrical system
  - Vehicle control system
- Guidance
  - Structure
  - Traditional wheel-based systems
  - Suspension
  - Propulsion
  - Vehicle control system
- Vehicle control system
- Electrical system
- Monitoring & safety

### 10.2.2 Vehicle-infrastructure interfaces

To ensure that both a MDS and a conventional rolling stock can continue to circulate on the same railway infrastructure, any MDS shall leave unchanged the existing conventional

interface rail standards between infrastructure and rolling stocks. ( <sup>1</sup> )

Specifically, this implies that a MDS shall leave unchanged the interface conditions between trackside systems and any other systems, as envisaged by the TSIs (in particular the CCS, INFRASTRUCTURE and ENERGY ones, available on the [ERA - European Railway Agency website](https://www.era.europa.eu/era)).

By way of example only, below are some essential points to be respected of the three aforementioned TSIs by a generic MDS to travel on a conventional railway infrastructure.

### 10.2.2.1 Command, Control and Signalling (CCS) Systems

According to this TSI, a Command, Control and Signalling system consists of (§2.2 of the Annex I of the Regulation UE 2023/1695):

- a train protection system;
- a train detection system;
- a voice & data radio communication.

On each of these, a generic MDS shall not introduce more binding conditions than those provided by the TSI CCS and in particular by its Technical Document ERA/ERTMS/033281 "*Interfaces between Control-Command and Signalling trackside and other subsystems*" (v5 et seq. modifications and supplements).

Please note that this Technical Document ERA/ERTMS/033281 is the same referenced by TSI Rolling Stock - Locomotives and Passengers and by TSI Rolling Stock – Freight Wagons to be respected by "on-board" point of view.

For illustrative and non-exhaustive purposes, the following essential points from that, shall be verified:

- EMC between MDS and Eurobalises (Eurobalises are fundamental elements of the European standard Train Protection System): the emissions from the MDS (both stator and rotor) shall guarantee the correct functioning of the Eurobalises.

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( <sup>1</sup> ) As already observed in the previous chapters, a mixed MDS/conventional traffic presents many critical issues (e.g. not optimized maintenance costs of the infrastructure, risk management, vocation too heterotatic): therefore if the existing infrastructure is updated for an exclusively MDS use (or even if a totally new dedicated MDS infrastructure is created, interfaced with the conventional one through appropriate interchange stations) makes the statements of this paragraph obsolete, because in this case for the MDS infrastructure is possible to hypothesize brand new (and simpler to be applied) *ad hoc* norms.

- Mechanical compatibility between MDS and Eurobalises (the positioning of any stator shall not imply a modification of the standard position and installation of either Eurobalises or rolling stock antennas).
- EMC between MDS and the Train Detection Systems, such Axle-Counter, Track Circuits, Loops (in particular, the emission limits established for rolling stocks by the Technical Document ERA/ERTMS/033281 shall be respected).
- Mechanical compatibility between MDS and generic trackside devices (e.g. Track Circuits cables).
- EMC between MDS and generic Wheel Detectors or Track Circuits, used not for train detection (e.g. for Level Crossing applications, or for Hot Box Detectors), as per Technical Document ERA/ERTMS/033281 criteria.
- Geometric dimensions and Metal Free Spaces on the lower part of MDS are to be compliant with the Technical Document ERA/ERTMS/033281 criteria.
- Compatibility between stator and Linear Motor, and standard quality and quantity of sand used for braking by rolling stokes as per Technical Document ERA/ERTMS/033281 criteria.

### 10.2.2.2 Energy

A MDS shall not impose on trackside devices more restrictive mechanical and electrical conditions than the ones individuated by TSI ENE.

Where the MDS should use the conventional traction power supply system, the reference standard to be fulfilled for the interface are the following (declared mandatories by TSI ENERGY itself):

- EN 50388-1 - Railway Applications - Fixed installations and rolling stock - Technical criteria for the coordination between electric traction power supply systems and rolling stock to achieve interoperability - Part 1: General;
- EN 50367 - Railway applications - Fixed installations and rolling stock - Criteria to achieve technical compatibility between pantographs and overhead contact line;
- EN 50163 - Railway applications - Supply voltages of traction systems.

For example, both linear motor and stator shall be mechanically and electrically compatible with the Return Circuit of the Traction Power system and the power demand should be compatible with the capability of the existing power supply system.

### 10.2.2.3 Infrastructure

From the point of view of this TSI, it is assumed that a generic MDS shall verify all the applicable points from the standard (mandatory by TSI itself) for rolling stock's acceptance:

- EN 14363 - Railway Applications – Testing and Simulations for the acceptance of running characteristics of railway vehicles – Running behaviour and stationary tests.

In case of introducing tilting technology on MDS, a further check has to be done in order to:

- understand which level of tilt can reasonably be implemented on MDS on an existing infrastructure, or how to reasonably modify the track's cant and/or transition curves in order to pursue higher levels of speed with the MDS;
- avoid "seasickness" on MDS' passengers.

For this purpose, it is recommended to start by a comparison with what is stated by the technical documents used for this topic for conventional rolling stocks, such:

- EN 13803 – Railway Applications – Track – Track alignment design parameters – Track gauges 1435 mm and wider;
- EN 15273 (series) - Railway applications – Gauges;
- UIC IRS 70705 Infrastructure for tilting trains.

#### 10.2.2.4 Summary of interfaces

All above stated, the interfaces between vehicle and infrastructure for hybrid MDS vehicle to be designed, are as listed below:

- Guideways/rails
  - Traditional wheel-based systems
  - Suspension/guidance
  - Propulsion/braking
- Linear motor stator
  - Propulsion/braking
  - Electrical system
  - Vehicle control system
  - Suspension

### 10.3 Hybrid MDS based on airlev vehicle

The interfaces discussed in the following chapter pertain to conventional railway vehicles and the airlev train subsystems described in Chapter 8. The structure of these interfaces is generalized, enabling them to be redefined for any MDS vehicle based on the MDS system breakdown structure. It is important to note that the presented interfaces offer a high-level overview. Consequently, more detailed considerations should be made during the MDS vehicle design phase in future works.

Generally, two types of interfaces can be distinguished. The first type is the internal vehicle interfaces, which define interactions between vehicle components. The second type is the

external interfaces, which focus on the interactions between vehicle components and external elements such as infrastructure, energy systems, or CCS.

In this chapter, the focus on external interfaces has been limited to vehicle-infrastructure interactions. However, as MDS development progresses, a detailed definition of interfaces for all MDS subsystems should be prepared.

This section discusses the air levitation train system, focusing on components like the fender, bogie, and electro-dynamic wheels, as well as track and system interfaces, as depicted in Figure 54. **Errore. L'origine riferimento non è stata trovata.** Key details are derived from the US (US10293803B2) and EU (EP2701960) patents concerning a levitation system for trains.

### 10.3.1 Internal vehicle Interface

A table has been created to outline the possible interactions between various vehicle components as follows. These components were selected based on the MDS vehicle breakdown structure.

**Table 11 - Internal airlev vehicle interfaces**

	Structure	Propulsion - vehicle	Suspension	Guidance	Braking	Vehicle Control	Electrical system
Propulsion vehicle	I.1						
Suspension	I.2	I.8					
Guidance	I.3	I.9	I.14				
Braking	I.4	I.10	I.15	I.19			
Vehicle Control	I.5	I.11	I.16	I.20	I.23		
Electrical System	I.6	I.12	I.17	I.21	I.24	I.26	
Monitoring and safety	I.7	I.13	I.18	I.22	I.25	I.27	I.28

The interfaces between selected vehicle components have been enumerated from I.1 to I.21. While not all interfaces exist for the specific vehicle concept described in Section 9, they may be relevant for other configurations. Table below provides a description and definition for each interface.

**Table 12 - Description of the internal airlev vehicle interfaces**

<b>Interface number</b>	<b>Description</b>
I.1	Electro-dynamic wheels are mounted mechanically to the airlev bogie, then to replace the normal bogie using adjustable mountings.
I.2	Suspension component – air fenders – are mounted mechanically to the airlev bogie using adjustable mountings.
I.3	Guidance component – air fenders – are mounted mechanically to the airlev bogie using adjustable mountings.
I.4	EDW and braking component are mounted mechanically to the airlev bogie. Since there may be more than one such component, they can be fixed in different places to the vehicle structure.
I.5	Vehicle control hardware devices, such as the onboard computer, sensors, and communication devices, are mechanically attached to the vehicle structure.
I.6	Electrical hardware, including both electrical boxes and electrical wiring, is secured to the structure.
I.7	The monitoring and safety devices, such as anti-collision radar, are mechanically coupled to the vehicle structure.
I.8	EDW and the air fenders need to be spatially aligned to function properly. This interface is crucial for maintaining the air gap between the air fenders and the track slab.
I.9	EDW and the air fenders for guidance should be aligned spatially to function properly. This interface is crucial for maintaining the air gap between the air fenders and the track slab.
I.10	EDW operates for both propulsion and braking. Since it is the same component, no separate interface is defined.
I.11	No interface for the concept described. The EDW is passive, so no control is required.
I.12	No interface is defined.
I.13	Structure health monitoring sensors are installed on the EDW and air fender to monitor their parameters, such as, air flow, rolling speed, airgap, etc.
I.14	Suspension and guidance are mechanically coupled (railway bogie), particularly since both components are served by an air compressor. In other configurations, they may be decoupled and not share any mechanical interface, requiring only a spatial alignment interface.
I.15	The braking components, such as EDW braking and emergency mechanical braking, exert some dynamic influences on the suspension

	system, which can be managed by the control system.
I.16	If the suspension is active, a sensor is used to monitor the gap between the air fender and the track slab. This gap value is a key parameter for vehicle dynamic control.
I.17	The wiring for the suspension sensors is mechanically mounted to the air fender.
I.18	There is an electrical/data interface to collect data about suspension state.
I.19	No interface is defined.
I.20	If the guidance system is active, there is a sensor monitoring the interface between the air fender and the track slab.
I.21	No interface is defined.
I.22	If the guidance system is active, there is a sensor monitoring the interface between the air fender and the track slab.
I.23	Vehicle control is connected to the braking components, including EDW braking and emergency brakes. This connection enables the vehicle control system to engage the braking mechanisms.
I.24	The electrical system is mechanically mounted to the braking components, and there is an electrical interface to transmit power to the EDW motor.
I.25	The monitoring and safety components receive data from the braking systems to monitor their status and ensure that the brakes are engaged or disengaged.
I.26	Vehicle control and electrical components are interfaced at multiple levels: mechanically, electrically, and at the data exchange level.
I.27	Vehicle control and monitoring/safety components are connected both electrically and at the data exchange level.
I.28	Monitoring and safety components supervise electrical components by checking parameters such as voltage levels, flowing and induced currents, battery state, and other critical metrics.

### 10.3.2 Vehicle-infrastructure Interface

Using the same methodology as in the last section, the table below shows the interfaces between the infrastructure and the airlev vehicle. This approach is generalized since the concept in Section 9 is defined at a very high level.

**Table 13 Airlev vehicle-infrastructure interfaces**

	<b>Rails</b>	<b>Substructure</b>	<b>Infrastructure</b>
Propulsion - vehicle	E.1	E.8	E.15
Suspension	E.2	E.9	E.16
Guidance	E.3	E.10	E.17
Braking	E.4	E.11	E.18
Vehicle Control	E.5	E.12	E.19
Electrical System	E.6	E.13	E.20
Monitoring and safety	E.7	E.14	E.21

To differentiate the internal and external interfaces, the external ones related to infrastructure have been enumerated from E.1 to E.21. As with the internal interfaces, some of these external interfaces may not be relevant to the concept in Section 9 but may be applicable in other configurations. Table below provides descriptions of the external vehicle-infrastructure interfaces.

**Table 14 - Description of the internal airlev vehicle interfaces**

<b>Interface number</b>	<b>Description</b>
E.1	No interface for the concept described in Section 9.
E.2	No interface for the concept described in Section 9.
E.3	No interface for the concept described in Section 9.
E.4	No interface for the concept described in Section 9.
E.5	No interface for the concept described in Section 9.
E.6	No interface for the concept described in Section 9.
E.7	No interface for the concept described in Section 9.
E.8	Track slab with aluminum strip for propulsion is attached upon ballast.
E.9	Track slab for air fenders to provide suspension is attached upon ballast.
E.10	Track slab for air fenders to provide guidance is attached upon ballast.
E.11	Track slab with aluminum strip for braking is attached upon ballast.
E.12	No interface for the concept described in Section 9.

E.13	No interface for the concept described in Section 9.
E.14	No interface for the concept described in Section 9.
E.15	The interface between the airlev vehicle and the infrastructural part of the EDW, with aluminum strips as the stator, is key to generating propulsion and braking forces. This involves a spatial alignment interface, maintaining the air gap and enabling contactless force transmission through Lorentz forces.
E.16	Air fenders create a slim air gap between vehicle and track slab – as one component of infrastructure.
E.17	Air fenders for guidance create a slim air gap between vehicle and track slab – as one component of infrastructure to keep vehicle along to the track.
E.18	The primary braking system of the vehicle relies on the electromagnetic interaction between the EDW and the aluminum strip in the infrastructure.
E.19	No interface for the concept described in Section 9.
E.20	No interface for the concept described in Section 9.
E.21	No interface for the concept described in Section 9.

## 10.4 Conventional railway vehicle upgraded with MDS subsystems

The interfaces in the following chapter are identified for conventional railway vehicle with MDS subsystems described in Paragraph 9.3. However, the structure of the interfaces is generalized so that they can be redefined for every MDS vehicle since it is based on the MDS system breakdown structure. Moreover, it must be noted that the presented interfaces depict a high-level approach. Therefore, in the MDS vehicle design phase in future works, more detailed considerations should be performed.

In general, two types of interfaces could be distinguished. First are the internal vehicle interfaces that define the interaction between vehicle components. Second type is the external interfaces, specifically the interactions between the vehicle components and the external ones included in infrastructure, energy or CCS.

In this chapter the considerations about external interfaces have been narrowed to vehicle-infrastructure interactions but during the further steps of MDS development, detailed interfaces definition considering all MDS subsystems should be prepared.

## 10.4.1 Internal MDS vehicle interfaces

A matrix has been created to outline the possible interactions between various vehicle components. These components were selected based on the MDS Vehicle breakdown structure. The matrix is shown in the Table 15.

**Table 15 - Internal MDS vehicle interfaces matrix**

	Structure	Propulsion - vehicle	Suspension	Guidance	Braking	Vehicle Control	Electrical system
Propulsion - vehicle	I.1						
Suspension	I.2	I.8					
Guidance	I.3	I.9	I.14				
Braking	I.4	I.10	I.15	I.19			
Vehicle Control	I.5	I.11	I.16	I.20	I.23		
Electrical System	I.6	I.12	I.17	I.21	I.24	I.26	
Monitoring and safety	I.7	I.13	I.18	I.22	I.25	I.27	I.28

The interfaces between selected vehicle components have been enumerated from I.1 to I.21. Not all interfaces exist for the specific vehicle concept from 9.3, however for other configurations they may be relevant. In Table 16, each interface has been described and defined.

**Table 16 - Description of the internal MDS vehicle interfaces**

Interface number	Description
I.1	Linear synchronous motor mover is mounted mechanically to the structure using adjustable mountings.
I.2	Suspension component – railway bogie - is mounted mechanically to the structure using adjustable mountings.
I.3	Guidance component – railway bogie - is mounted mechanically to the structure using adjustable mountings.
I.4	Braking component is mounted mechanically to the structure. Since there may be more than one such component, they can be fixed in different places to the vehicle structure.
I.5	Vehicle control hardware devices such as onboard computer, sensors, communication devices are attached mechanically to the vehicle structure.

I.6	Electrical hardware - both electrical boxes and electrical wiring is fixed to the structure.
I.7	The monitoring and safety devices e.g. anti-collision radar, are mechanically coupled to the vehicle structure.
I.8	Linear motor mover and the suspension should be aligned spatially to function properly. This interface is relevant to maintain the air gap in the linear motor.
I.9	Linear motor mover and the guidance should be aligned spatially to function properly. This interface is relevant to maintain the air gap in the linear motor.
I.10	No interface for the concept described in 9.3. LM operating as braking is utilized but as it is the same component, no interface is defined.
I.11	No interface for the concept described in 9.3. The LM mover is passive, so no control is required.
I.12	No interface for the concept described in 9.3.
I.13	Health check sensors are installed on the LM mover to monitor the mover parameters, airgap, etc.
I.14	Suspension and guidance are mechanically coupled (railway bogie), especially since both components are served by wheels. For other configurations, they may be decoupled and does not share any mechanical interface. Instead, they should only meet the spatial alignment interface.
I.15	Braking component e.g. friction brake is the part of the suspension, so they have a mechanical interface between each other.
I.16	If the suspension is active, there is an electrical interface between them. For the concept in 9.3, there is no interface identified.
I.17	The wiring is mounted to the suspension component mechanically (suspension sensors).
I.18	There is an electrical/data interface to collect data about suspension state.
I.19	No interface for the concept described in 9.3.
I.20	If the guidance is active, there is an electrical interface between them. For the concept in 9.3, there is no interface identified.
I.21	No interface for the concept described in 9.3.
I.22	There is an electrical/data interface to collect data about the wheels' state.
I.23	Vehicle control is connected via databus with the braking components - linear motor braking, friction and parking brakes. It enables the vehicle control to engage braking.
I.24	Electrical system is mounted to the braking components mechanically and there is an electric interface to transmit the power to the actuators and valves.

I.25	The monitoring and safety components receive data from braking ones to monitor the state and make sure that the brakes are engaged or disengaged.
I.26	Vehicle control and electrical components are interfaced at w few levels: mechanically, electrically and also at the data exchange level.
I.27	Vehicle and control and monitoring/safety components are connected electrically and also at the data exchange level.
I.28	Monitor and safety components supervise electrical components, e.g., the voltage levels, flowing and induced currents, battery state, etc.

## 10.4.2 Vehicle-infrastructure interfaces

Using the same methodology as in 10.3.1 there is a matrix in the Table 17 showing the interfaces between the infrastructure and the MDS vehicle. And also, the approach is generalized since the concept in 9.3. is defined at a very high-level.

**Table 17 - Vehicle-infrastructure interfaces matrix**

	<b>Rails</b>	<b>Substructure</b>	<b>Propulsion - infrastructure</b>
Propulsion - vehicle	E.1	E.8	E.15
Suspension	E.2	E.9	E.16
Guidance	E.3	E.10	E.17
Braking	E.4	E.11	E.18
Vehicle Control	E.5	E.12	E.19
Electrical System	E.6	E.13	E.20
Monitoring and safety	E.7	E.14	E.21

To differentiate the internal and external interfaces, these external ones related to infrastructure have been enumerated from E.1 to E.21. And also in this case, some of the interfaces are not relevant to the concept in 9.3 but may be applicable somewhere else. In Table 18, the external vehicle-infrastructure interfaces are described.

**Table 18 - Description of the external interfaces**

<b>Interface number</b>	<b>Description</b>
E.1	No interface for the concept described in 9.3.

E.2	Mechanical interface that allows for vertical stabilization of the vehicle. Wheel-rail contact but no propulsion force transmission.
E.3	Mechanical interface that allows for lateral stabilization of the vehicle. Wheel-rail contact.
E.4	No interface for the concept described in 9.3. The interaction between the friction brake and rail is through the suspension.
E.5	No interface for the concept described in 9.3.
E.6	No interface for the concept described in 9.3.
E.7	Cameras supervise the state of the rails. The collision avoidance system monitors the infrastructure in front of the vehicle.
E.8	No interface for the concept described in 9.3.
E.9	No interface for the concept described in 9.3.
E.10	No interface for the concept described in 9.3.
E.11	No interface for the concept described in 9.3.
E.12	No interface for the concept described in 9.3.
E.13	No interface for the concept described in 9.3.
E.14	No interface for the concept described in 9.3.
E.15	The interface between the vehicle and infrastructural part of the linear motor is a key to generate propulsion force. There is spatial alignment interface - airgap and the contactless force transmission.
E.16	No interface for the concept described in 9.3.
E.17	No interface for the concept described in 9.3.
E.18	The primary braking system of the vehicle is based on the electromagnetic interaction between the mover and the stator in the infrastructure.
E.19	No interface for the concept described in 9.3. Vehicle control sends the information to the CCS subsystem that is not part of the infrastructure subsystem.
E.20	No interface for the concept described in 9.3.
E.21	Cameras supervise the state of the linear motor stator. The collision avoidance system monitors the infrastructure in front of the vehicle. And the onboard healthcheck sensors monitor the magnetic field in the airgap.

## 11 Technical enablers for MDS vehicle

Technical enablers refer to technologies, tools, or resources that enable or facilitate the accomplishment of technical tasks or objectives. These enablers could include specialized equipment, software, infrastructure, or methodologies that help streamline and support technical processes or advancements. In various contexts, technical enablers can play a crucial role in enhancing efficiency, effectiveness, and innovation within a specific field or industry.

One of the technical enablers is the implementation of Automatic Train Operation (ATO) systems adapted to both Maglev-derived systems and traditional railways. These ATO systems are designed primarily for use in closed network environments, such as urban transit systems and dedicated routes. They provide autonomous control and precise monitoring of train operations, optimizing safety, energy efficiency, and scheduling. The adaptability of ATO technology to MDS and railways enhances the potential for seamless integration, allowing for the efficient use of existing railway infrastructure. This advancement not only streamlines operations but also positions the system for future expansion onto open network lines. This technical enabler promises improved transportation efficiency and safety while paving the way for integrating Maglev-derived systems into broader railway networks.

Another technical enabler is the utilization of advanced magnetic materials, notably permanent magnets, and high-permeability materials, represents a significant technological advancement with a focus on sustainability, economic viability, and self-reliance within the European Union (EU). These materials, which play a pivotal role in various applications, including electric vehicles, renewable energy generation, and advanced manufacturing, are undergoing enhancements to reduce reliance on external suppliers and ensure a more self-sustaining supply chain within the EU. Pursuing sustainable practices encompasses the development of materials with reduced environmental impact, energy-efficient production processes, and responsible sourcing of raw materials. Achieving economic viability involves optimizing production costs, fostering innovation, and promoting competitiveness in global markets while adhering to stringent EU regulations. By prioritizing the advancement of these magnetic materials, the EU aims to bolster its technological independence, reduce supply chain vulnerabilities, and foster a more sustainable and resilient economy while promoting breakthroughs in key industries. This strategic approach underscores the EU's commitment to technological innovation and a greener, self-reliant future.

The next technical enabler is the implementation of sustainable and long-duration energy storage systems. These systems significantly enhance line capacity management and energy efficiency during the acceleration and deceleration of MDS vehicles, keeping, for passengers' vehicles, the comfort levels within the expected threshold by efficiently storing and managing energy, they contribute to smoother operations, reduced energy consumption, and overall improved sustainability in MDS. This advancement aligns with the growing demand for eco-



friendly and energy-efficient transportation solutions, making it a pivotal component of the MDS's technical capabilities.

This technical enabler revolves around the adoption of sustainable practices in the manufacturing of steel and aluminium components. It encompasses eco-friendly methods that significantly reduce the environmental footprint of producing these essential materials. Such methods prioritize resource efficiency, minimal waste generation, and reduced energy consumption throughout the manufacturing process. Additionally, sustainable manufacturing techniques often involve the use of recycled materials, promoting circular economy principles. These approaches align with global efforts to combat climate change and enhance environmental stewardship by minimizing greenhouse gas emissions associated with steel and aluminium production. By implementing sustainable methods, manufacturers contribute to a more environmentally responsible and economically viable supply chain. They also play a crucial role in addressing sustainability challenges and fostering a greener and more resilient future for industries reliant on these materials.

The implementation of advanced cybersecurity measures stands as a crucial technical enabler within the system. These cybersecurity methods are specifically designed to guarantee the safety and security of operations within the Maglev-derived system. In an era marked by increasing digitalization and interconnectedness, safeguarding against cyber threats is paramount to protect passengers, infrastructure, and data. These advanced cybersecurity methods encompass cutting-edge technologies, protocols, and practices. They include robust encryption techniques, intrusion detection systems, real-time threat monitoring, and secure network architecture. The objective is to fortify the system against potential cyberattacks, unauthorized access, and data breaches. By prioritizing cybersecurity, the system not only ensures the safety of cargo and operational integrity but also safeguards against disruptions and potential vulnerabilities. This technical enabler plays a critical role in bolstering confidence in the system's reliability and resilience in the face of evolving cybersecurity challenges, making it an indispensable component of the Maglev-derived transportation system.

Secure communication systems equipped with enhanced throughput capabilities constitute a pivotal technical enabler within the system. These communication systems are designed to facilitate the exchange of text and media in a highly secure manner, ensuring the confidentiality and integrity of transmitted information. The foundation of these secure communication systems lies in advanced encryption techniques, secure protocols, and dedicated channels for data transmission. They enable the seamless and rapid exchange of text messages, images, videos, and other media formats while safeguarding against potential eavesdropping, interception, or data tampering. The higher throughput these systems offer translates into faster and more efficient communication, improving operational responsiveness and decision-making. Whether for operator information, system monitoring, or emergency response, secure communication systems with enhanced throughput play a



vital role in enhancing the overall efficiency, security, and reliability of the Maglev-derived transportation system. By prioritizing secure and high-throughput communication, the system ensures the protection of sensitive information, supports real-time data sharing, and strengthens its resilience against emerging cyber threats, making it an indispensable component of the Maglev-derived system's technical capabilities.

Virtual coupling represents a transformative technical enabler within the system, aimed at optimizing capacity and mitigating bottlenecks. This innovative concept involves the integration of cutting-edge technologies and methodologies to enhance the efficiency and throughput of the Maglev-derived transportation system. Virtual coupling fundamentally involves the coordination and synchronization of multiple vehicles operating within the system. Through precise control algorithms and communication systems, vehicles are virtually coupled together, allowing them to move in a closely coordinated manner without the need for physical connections. This breakthrough approach optimizes available track space, reducing the risk of congestion and bottlenecks. By virtually coupling vehicles, the system achieves several critical benefits. It significantly increases the overall system capacity by allowing for tighter vehicle spacing, which, in turn, leads to higher throughput and reduced waiting times for passengers. Additionally, virtual coupling enhances safety by ensuring vehicles maintain safe distances and move synchronously. This technical enabler holds the potential to revolutionize the efficiency and performance of the Maglev-derived system, addressing capacity challenges and enhancing the passenger experience. Through virtual coupling, the system can adapt to evolving demands, optimize resources, and position itself as a sustainable and responsive mode of transportation for the future.

Smart moving blocks divide the track into intelligent segments equipped with sensors and V2V (vehicle-to-vehicle) communication. These blocks continuously monitor vehicle positions and conditions, facilitating real-time coordination. They optimize route planning and manage vehicle spacing dynamically, reducing congestion and increasing line capacity. This innovative approach not only improves transportation efficiency but also enhances passenger experience and system sustainability. Smart moving blocks with V2V communication represent a transformative technical enabler that leverages real-time data and intelligent routing to boost line capacity and streamline operations within the Maglev-derived transportation system.

The establishment of a comprehensive regulatory framework stands as a critical technical enabler within the system. This framework is designed to provide clear guidelines, standards, and oversight for the operation and integration of Maglev-derived systems into existing transportation networks. The regulatory framework encompasses a range of essential aspects, including safety standards, operational protocols, interoperability requirements, and environmental regulations. It ensures that the Maglev-derived system adheres to the highest safety and performance standards, fostering passenger and system safety. Moreover, this technical enabler promotes seamless integration with other modes of transportation, such as



traditional railways, urban transit systems, and road networks. By providing a structured and well-defined regulatory environment, it encourages the expansion and interconnectivity of the Maglev-derived system, enhancing its versatility and utility. The regulatory framework is a foundational element, underpinning the safe, efficient, and sustainable operation of the Maglev-derived transportation system. It ensures compliance with established standards while fostering growth and integration within broader transportation networks.

## 12 Conclusions

The Deliverable 4.1: Document on the MDS vehicle subsystem including subsystem definition, system-level interface identification, and methods of integration into the overall common-architecture MDS is a result of Work Package 4, which is included in the Grant Agreement.

The objectives of this deliverable are:

- Defining the concept and the breakdown structure for the vehicle subsystem of Maglev-Derived Systems (MDS);
- Giving an overview of the vehicle concept of the 3 configurations of MDS – Full MDS, Hybrid MDS vehicle interoperable with railway infrastructure, conventional rail vehicle upgraded with MDS subsystems or technologies;
- Describing the technology concepts, considering the main components of the vehicle subsystem like propulsion, guidance, suspension and braking;
- Describing and identifying the main interfaces for the vehicle subsystem.

The main output from WP2 has been taken into account, especially for the technologies which have been considered as potentially implementable and compatible with the conventional railway system. The lack of specific knowledge at industrial level for many of the identified technologies makes it difficult to define the concepts related to the vehicle subsystem and their potential implementation in the existing infrastructure.

More in-depth research and analysis have been performed for the vehicle subsystems of MDS with more available information. The methods of integration of such vehicles with other subsystems have been partially described through the identification of the interfaces and further analysis will be necessary to understand the associated risks and their related mitigation and resolution actions. Inputs from the risk analysis of WP3 are necessary to properly develop these tasks.

Therefore, this deliverable has to be considered only as a starting point and an input for the analysis of the MDS implementation in the Common European Network, especially for what concerns the vehicle subsystem and all its relevant interfaces, which need an in-depth study for each system configuration and application.

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