MaDe4Rail FA7

Deliverable D 6.1

Technology Readiness Assessment of Maglev-derived Systems

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1 Executive Summary

The objective of this deliverable is to provide set of possible use cases to be analysed, based on a comprehensive technology readiness assessment on the technical maturity of the technologies involved in maglev-derived systems (MDS).

To this end, this document first provides a comprehensive technology readiness assessment of the technical maturity of the technologies involved in MDS. A Technology Readiness Assessment (TRA) is a formal, metrics-based process and accompanying report that assesses the maturity of the technologies that are to be used in the systems. Then, this first task has provided the TRA of each technology constituent and has served to propose which of them fits best to the different MDS, as well as evaluating the overall TRL for each MDS.

The TRA concludes with the findings and comparison of the different systems, considering the four main subsystems of an MDS: vehicle, infrastructure, energy system and TMS. As a result, this task has completed a technology analysis by comparing the different systems and identifying and exploring significant development gaps.

Based on the results of the TRA, an analysis of the state of development of each MDS and the pipeline of future work has been carried out to outline the possible expected evolution for the sector.

The second step, also based on the TRA results, has been to analyse different use cases for the different technologies and to identify and propose a set of uses to be evaluated in further work packages.

To this end, a multi-criteria analysis (MCA) was carried out to select the various MDS use cases that would be most suitable for consideration in further work packages for use on existing railway lines. Several criteria were used. From a technological point of view, aspects such as TRA, scalability, adaptability, impact on existing infrastructure and the possibility of installation on existing railways were considered. The type of vehicle and system configuration were also considered. Finally, the criterion of the type of service has been used to select the appropriate services for each MDS. The results of the MCA have shown that the most useful configurations are the hybrid MDS, which is based on both the magnetic levitation and the air levitation systems, and the upgraded rail vehicles.

After the selection of the three MDS configurations through the MCA and the analysis of the possible use cases where they could be applied, an early selection of the most interesting use cases was made in terms of applicability of the MDS technology to the specific use case, considering the actual existing needs for transport infrastructures or services across Europe.

Finally, a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis was carried out for each of the use cases. The results of the SWOT analysis carried out for the selected use cases will facilitate the selection of the MDS to be analysed in further WPs.

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
5G	5th Generation of wireless cellular technology
ATO	Automatic Train Operation
CAN	Controller Area Network
CBTC	Communication Based Train Control
COTS	Commercial off-the-shell
CT	Critical Technology
EDS	Electrodynamic systems
EDW	Electrodynamic Wheel
EMC	Electro Magnetic Compatibility
EMS	Electromagnetic systems
ERTMS	European Railway Traffic Management System
ETCS	European Train Control System
FRMCS	Future Railway Mobile Communication Systems
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GSM-R	Global System for Mobile Communications-Railway
HSGT	High-speed ground transportation systems
HSR	High-speed rail
ITS-G5	European Standard for vehicular communications
LIM	Linear Induction Motor
LSM	Linear Synchronous Motor
LTE	Long Term Evolution, sometimes referred as 4G LTE
MCA	Multi-Criteria Analysis
MDS	Maglev Derived System
MVB	Multifunctional Vehicle Bus

OCC	Operations Control Center
PIS	Passenger Information System
TCMS	Train Control Module System
TCS	Train Control System
TMS	Traffic Management System
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level
U-LIM	Linear Induction Motor U shaped armature
VC	Virtual Coupling
VVVF	Variable voltage variable frequency
WBS	Work Breakdown Structure
WPT	Wireless Power Transfer

3 Background

The present document constitutes the Deliverable D6.1 “Technology Readiness Assessment of maglev-derived systems” in the framework of the Flagship Project HORIZON-ER-JU-2022-FA7-02 – Maglev-Derived Systems for Rail (MaDe4Rail) as described in the EU-RAIL MAWP.

4 Objective/Aim

This document has been prepared to provide a technological readiness assessment on the technical maturity of the technologies involved and the overall system and propose the most appropriate technologies for the different subsystems that best fit the MDS identified, with the objective to provide a key input for task 7.1, in particular in the identification of the technology to be evaluated in the use case section.

A Technology Readiness Assessment (TRA) is a formal, metrics-based process and accompanying report that assesses the maturity of the technologies to be used in systems. TRA are used to evaluate the maturity of technologies and whether they are developed enough to be incorporated into a system without too much risk.

This deliverable includes a comprehensive technology readiness assessment of maglev-derived systems at both system and subsystem levels. It also identifies and discusses the significant development gaps and proposes the technical characteristics of the MDS that best suit each of the selected types of services/applications.

Deliverable D6.1 is a result of Tasks: 6.1 and 6.2 and produces a cross-matrix of technologies and systems against use cases.

Task 6.1 “Technological readiness assessment of the different maglev-derived systems identified in WP2” considers the different MDS and the technologies involved in MDS related to the type of guidance (levitation, suspension), propulsion, Command, Control and Signalling (CCS) Systems, energy, communications, etc.

The primary outcome of this task is to provide the TRA of each technology constituent and propose which of them fits best to the different MDS identified in the previous WP, as well as evaluating the overall TRL (Enspire Science, 2023) for each MDS system. Then, in this task, a technology analysis has been completed by comparing the different systems. This analysis is included in section 5.4 of this document.

This task also provides data about each maglev-derived system's development status and pipeline of future works, outlining the possible expected evolution for the sector. This analysis is included in section 5.5 of this document.

This technological readiness assessment would be used as an input in Task 6.2. Then, Task 6.2 “Definition of the different use cases for the different technologies and identification of the MDS to be evaluated in the technical-economic feasibility study” defines the MDS to be studied in WP7.

For this purpose, the study is segmented according to the application of MDS to passengers or freight sector and the type of traffic (considering urban, interurban, high-speed traffic, and others) or local applications (e.g., ports, intermodal hubs, etc.). Then, taking into consideration the TRA and scalability of each system, a SWOT analysis has been completed, and a set of criteria and a selection process has been identified to facilitate the selection of the maglev-derived systems to be analyzed in WP7.

For each type of MDS chosen, the most appropriate technologies and operating conditions (e.g., operating speed, gradient, traction force, etc.) have been identified based on technological maturity (resulting from Task 6.1) and the cost of implementing this technology/characteristic in the chosen type of service/application.

This task has produced a cross matrix, including technologies and systems, against use cases, providing the technical characteristics of the MDS that best fit each of the selected types of services/application and will serve as a basis for selecting the use cases to be developed in WP7 and WP8.

All these analyses are included in section 6.2 of this document.

The workflow of the studies performed in this document is shown in **Figure 1**.

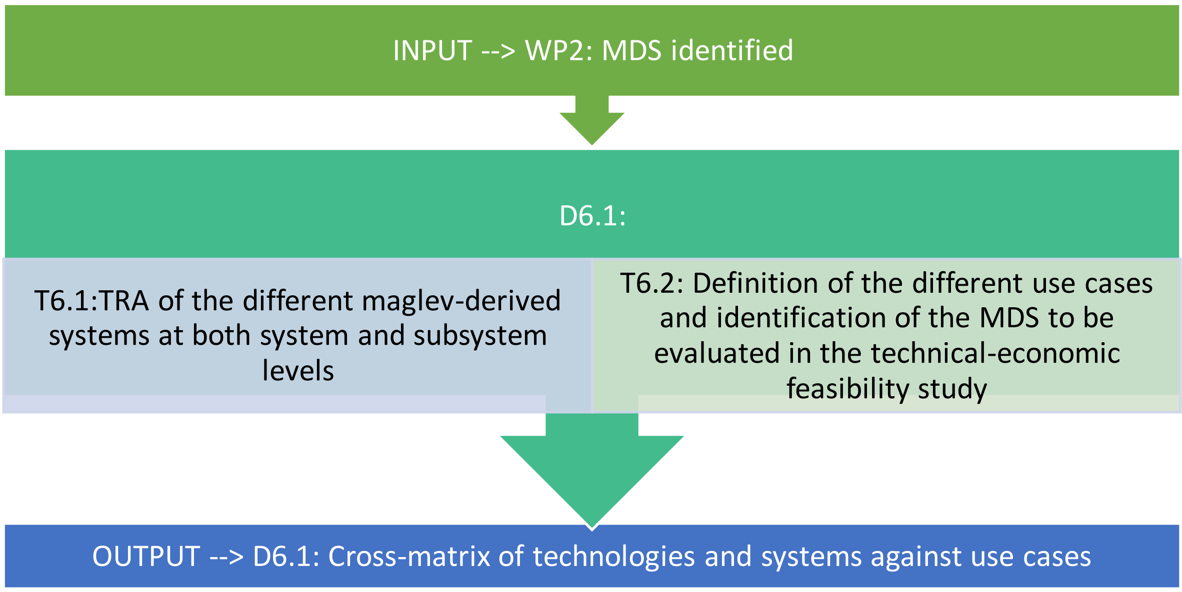


Figure 1. D6.1 workflow.

5 Technology Readiness Assessment of Maglev-derived Systems

A Technology Readiness Assessment (TRA) is a systematic, evidence-based process that evaluates the maturity of the Critical Technologies (CTs) that are vital to the performance of a larger system. It is a normal outgrowth of the system engineering process and relies on data generated during the course of technology or system development. The TRA uses a maturity scale—technology readiness levels (TRLs)—that is ordered according to the characteristics of the demonstration or testing environment under which a given technology was tested at defined points in time. The scale consists of nine levels, each one requiring the technology to be demonstrated in incrementally higher levels of fidelity in terms of its form, the level of integration with other parts of the system, and its operating environment than the previous, until the final level where the actual operation of the technology is in its final form and proven through successful mission operations. The TRA evaluates CTs at specific points in time for integration into a larger system.

Technology readiness assessments (TRA)—evaluations that determine technology's maturity—have been used widely at the U.S. Department of Defense (DOD) and National Aeronautics and Space Administration (NASA) since the 1990s. This approach has also been embraced by other government agencies, as well as industry in aerospace, maritime, oil and gas, electronics, and heavy equipment that use TRAs to help manage their acquisitions. Relatively few agencies have guides for assessing a technology's maturity.

There are a few guides that suggest the process to follow in developing a TRA. The Guide (US Government Accountability Office - GAO-20-48G, 2020) provides a methodology for evaluating technology maturity based on best practice. It has two objectives: (1) to describe generally accepted best practices for conducting high-quality TRAs of technology developed for systems or acquisition programs, and (2) to provide technology developers, program managers, and governance bodies with useful information to more effectively mature critical technologies, determine a technology's readiness, and manage and address risk.

Based on the comparative and benchmarking analysis performed in WP2, the analysis conducted in this section considers the different MDS and the technologies involved in MDS and provides a technological readiness assessment (TRA) of each technology constituent, proposing which of them best fits the different MDS identified, as well as assessing the overall TRL for each MDS system.

Then, a technology analysis will be completed by comparing the different systems, providing data about each maglev-derived system's development status and pipeline of future works, outlining the possible expected evolution for the sector.

5.1 State of the art about TRA and previous studies

There are several references of previous TRA studies applied to Maglev systems. The most important ones are listed below:

The paper (Miller and Wackers, 1993) included a brief description of the Transrapid maglev system, the state of development as well as the operational performance and safety standards achieved. It summarized the results of the comprehensive studies "Technical Readiness for Application of Transport Maglev System" and "Possible Application of the New High Speed Rail Systems (High Speed Maglev and Railroad Technology)" published by the German Federal Railway and MVP (Test and Planning Organization for Maglev Systems).

In (Geerlings, 1998) the development of high-speed rail systems in Europe, Japan and the United States was presented (in 1998). The study included an assessment and synthesis of the factors of success and failure, with explicit emphasis to the interdisciplinary aspects of and the implications for technology policy. One of the conclusions was that the best strategy to successfully implement this project was not to relate it to terms such as "competition" and "substitution", but to present it in terms of "complementation".

In the reference (Federal Transit Administration Team, 2002) was analysed the possibility of introducing magnetically levitated slow speed vehicles (under 160 kph) for urban mass transportation in the United States. The FTA evaluated a few candidate technologies for application in its Urban Maglev Program. One of the technologies considered was the Chubu High Speed Surface Transport (CHSST) developed in Japan and proposed by the Maglev Urban System Associates (MUSA). The FTA formed a team of consultants that visited the CHSST facility and held technical meetings with CHSST and funding agencies for Japanese urban applications. Based on the information gathered during this visit and technical reports submitted by MUSA, the FTA team evaluated the CHSST as presented in his report. Emphasis was placed on how well the CHSST system satisfied the FTA system level performance, safety and cost requirements, and the U.S. mandatory requirements for public transportation systems. They analysed Guideway System, Vehicle Design and System Capacity, Levitation and Guidance, Propulsion System and Power, Braking System, Automatic Train Operation, Environmental Impact, Performance and Safety Tests and Performance and Safety Tests. This reference is a good example of how to elaborate a FTA.

The paper (Janic, 2003) presents a multicriteria evaluation of High-Speed Rail, Transrapid Maglev and Air Passenger Transport in Europe. Operational, socio-economic, and environmental performance indicators of the specific high-speed transport systems were adopted as the evaluation criteria. By using the entropy method, weights were assigned to particular criteria in order to indicate their relative importance in decision-making. The TOPSIS method was applied to carry out the multicriteria evaluation and selection of the preferable alternative (high-speed system) under given circumstances.

Related to HSGT, (Liu and Deng, 2004) compares high-speed rail (HSR) and magnetic levitation (Maglev) with focus on the engineering comparison of HSR and Maglev systems. The emphasis was on the overview of technology, comparison of operating characteristics of HSR and Maglev, and the implications of their potential application in a 1,300-km-long corridor from Beijing to Shanghai—the top economic, population, and culture engine in China. They conducted a performance comparison of HSR and Maglev including aspects as: speed, acceleration, and deceleration, capacity, safety and reliability, energy consumption, and noise. They also developed a case study focused on the operating characteristics of Maglev and HSR in the Beijing–Shanghai corridor, including travel time, capacity, environmental impact and operating experience and safety records.

Reference (Gmünder et al., 2004) described methods and models to quantify risk caused by external and internal hazards of the Transrapid transportation system. The presented methodology allowed to manage risks and supported the safety certification process for a specific link.

In (Rojas G, 2007) a study was presented to examine the reasons for choosing a maglev system, regulatory barriers to implementing such a system, and the costs associated with a Maglev system built in the Texas Triangle.

From aspects of scientific value, technical feasibility and economic efficiency, the paper (MAO et al., 2008) reviewed practical demonstrations of transport projects related to the application of different types of maglev technologies in different countries. Based on the experienced progress, it summarized the advantages and disadvantages of the world's maglev technologies in the possible development of China and presented their technological and economic feasibility of different types of maglev systems and their current technical maturity from the viewpoint of engineering construction. Authors studied the demonstration process of several maglev projects carried on in the countries such as Germany, Japan, America, Netherlands and U.K., and analysed the major technical parameters adopted, the relevant conclusions in engineering and economy and the reasons why these projects had not been started so far. The paper gave a preliminary analysis of the feasibility to apply maglev technologies in some regions of Yangtse Rive Delta, Zhujiang Delta and Beijing-Tianjin Region, and some intercity transport corridors between several important city pairs such as Shenyang-Dalian, Chongqing-Chengdu et al. Authors further estimated the economic efficiency for the application of maglev technologies.

The paper (Stephan and Pereira, 2020) showed that Magnetic Levitation can fulfil the demand and fits with smart grid concepts. Moreover, the levitation method based on the diamagnetic property of high-temperature superconductors in the proximity of rare-earth permanent magnets presents advantages in comparison with other levitation methods. This technological solution was tested with the operation of a real scale prototype inside the campus of the Federal University of Rio de Janeiro (UFRJ), operating since 2014. The paper presents a historical and technological overview of the steps necessary to turn this prototype into a commercial product. The development is framed within Technological Readiness Levels (TRL). Based on the experimental data of the MagLev2-Cobra project, the perspectives of operation in an environment of intermittent energy are unveiled. The paper concludes with the steps to turn MagLev2-Cobra into a Commercial Product.

The report (U.S. Department of Transportation, 2015) summarises an initial stage investigation into current research and development of alternative modal concepts. The research project was a multimodal effort, organized by the Federal Highway Administration's (FHWA's) Exploratory Advanced Research (EAR) Program, with the participation of the Federal Transit Administration, Federal Railroad Administration, and Office of the Assistant Secretary for

Research and Technology. Staff from the John A. Volpe National Transportation Systems Center (Volpe Center) conducted this project on behalf of the EAR Program. The authors of this report discuss the current state of novel surface transportation modal concepts, identify opportunities and challenges for these concepts, and present a set of potential future research needs. The authors have summarised the information from both research on novel modes and the viewpoints shared at the novel modes workshop. Some references to Maglev systems are included.

The reference (Wenk et al., 2018) conducted a practical investigation of future perspectives and limitations of maglev technologies. With the aim of tracking current trends in the market perspectives of magnetic levitation, or maglev technologies, the non-profit International Maglev Board conducted a primary study in the spring of 2018 among maglev specialists and transportation professionals based on an Internet-based online survey. More than 1.000 professionals took part in the survey. Main topics of the study are questions comparing the suitability of conventional wheel-on-rail and maglev technologies according to application areas. Predicted opportunities and developments in maglev technology, acceptance issues and research needs were analysed. The study covers aspects such are future relevance of Maglev, probability of Maglev Implementation, key factors and possible weak points, and Maglev research needs and research tasks.

The conclusions of this study show that the ratings vary greatly according to the expertise and origin of the respondents. In certain fields of application, wheel-rail systems remain the preferred transport technology. But in certain other fields of application, maglev technologies have become preferred over conventional steel-wheel-rail by most transport professionals. This is particularly the case for high-speed maglev transport and for the new application of maglev elevators in buildings. At the same time, many respondents see a continuing need for research.

5.2 TRA methodology

The primary outcome of this deliverable is to provide the TRA of each technology constituent and propose which of them fits best to the different MDS identified, as well as evaluating the overall TRL for each MDS system.

There are several guides to developing a TRA, but one of the most widely used is the Technology Readiness Assessment Guide (US Government Accountability Office - GAO-20-48G, 2020). This guide presents a five-step process that provides the framework for planning, assessing, and reporting a TRA. The process represents a consistent methodology based on government and industry best practices that can be used across organizations to assess the maturity of CTs. **Figure 2.** shows the five steps for conducting a TRA.

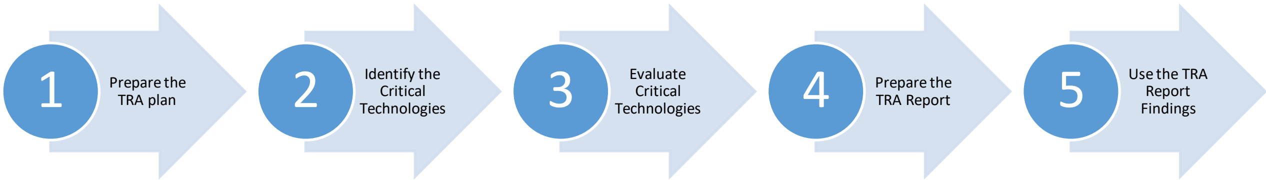


Figure 2. Five Steps for Conducting a Technology Readiness Assessment

5.3 Technological readiness assessment of each technology

Following the methodology and guidelines indicated in this guide, the TRA has been developed in the following the five steps, which are discussed in the next sections.

5.3.1 Preparation of the TRA

Based on deliverable D2.1 (MaDe4Rail D2.1, 2023), the initial key TRA information has been collected and reviewed by the TRA team to ensure the development of the TRA. The initial key TRA information comes from the report included in (MaDe4Rail D2.1, 2023).

The TRA for the MDS under consideration is based on the Technology Readiness Assessment Guide (US Government Accountability Office - GAO-20-48G, 2020). This systematic and evidence-based process will assess the maturity of Critical Technologies. For each identified CT, the TRL obtained from the demonstration or test environment will be shown.

A TRA report will then be conducted for each CT to provide useful information on the maturity of the technology, its state of development and potential areas of concern and risk. The information will help to identify maturity gaps and formulate plans to mature the technologies.

5.3.2 Critical Technologies Identification

In this step, CTs have been identified and selected by a systematic process. Selecting CTs during early technology development before product development is a best practice.

Technologies are considered critical if they are new or novel, or used in a new or novel way, and needed for a system to meet its operational performance requirements within defined cost and schedule parameters.

The most common approach used is the work breakdown structure (WBS)—a deconstruction of a product or system into smaller specific elements that are suitable for management control. It is the cornerstone of every program because it defines in detail the work necessary to accomplish a program's objectives.

A technical WBS helps to enforce a rigorous, systematic, and repeatable TRA process when reconciling the identification of CTs. It can be used to identify CTs as well as low-risk heritage technologies.

While selecting CTs is fundamental to the TRA, some technologies may not be characterised as a CT but are nevertheless important and could pose concern if certain conditions changed. For example, the TRA team can identify additional "watch elements" that represent significant areas of risk once the system operation is finalised. Highlighting these watch elements adds an additional level of visibility throughout the project.

The WBS considered for the TRA is as defined in (MaDe4Rail D2.1, 2023) as shown in **Figure 3**:

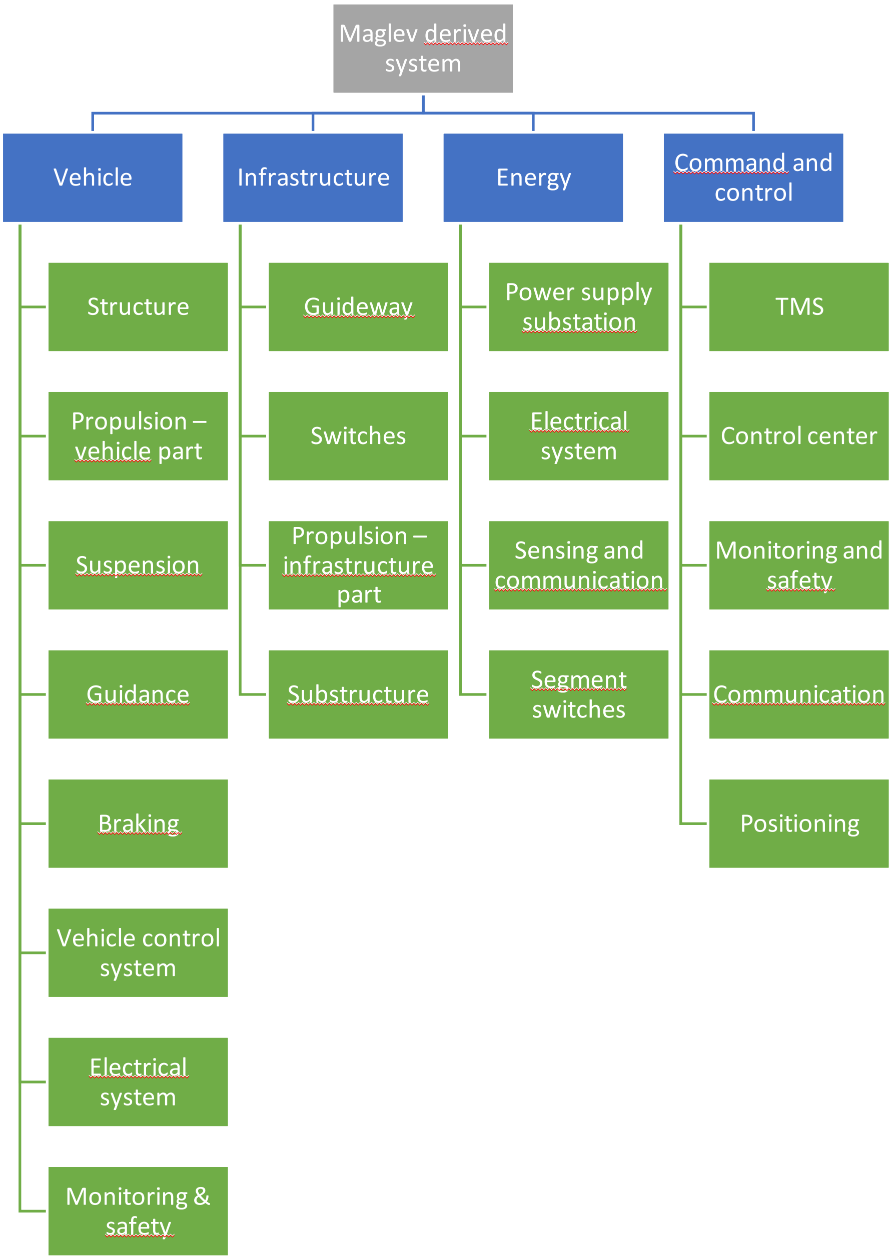


Figure 3. WBS considered at system, subsystem and component level

To identify the different critical technologies involved in each system, a systematic methodology called morphological analysis will be used.

Morphological analysis is the process of examining possible resolutions to unquantifiable, complex problems involving many factors (TechTarget, 2023). One of the most widely used tools for these analyses are morphological charts (Annemiek van Boeijen and Jaap Daalhuizen, 2010; Smith, 2007).

Morphological charts are tools for representing large qualitative design spaces. These charts contain the functions identified for a design problem and the means (solutions) that can perform each function. A potential integrated conceptual design solution is created by combining a means for each function.

They provide a structured approach to concept generation to widen the scope of the search for solutions to a defined design problem. These can help the team to generate a full range of alternative design solutions for a product through a systematic analysis of the form/configuration that a system could take.

For each of the different main subsystems identified in the WBS: Vehicle, Infrastructure, Energy, Command and Control, the following morphological tables have been developed, showing their main components and critical technologies involved:

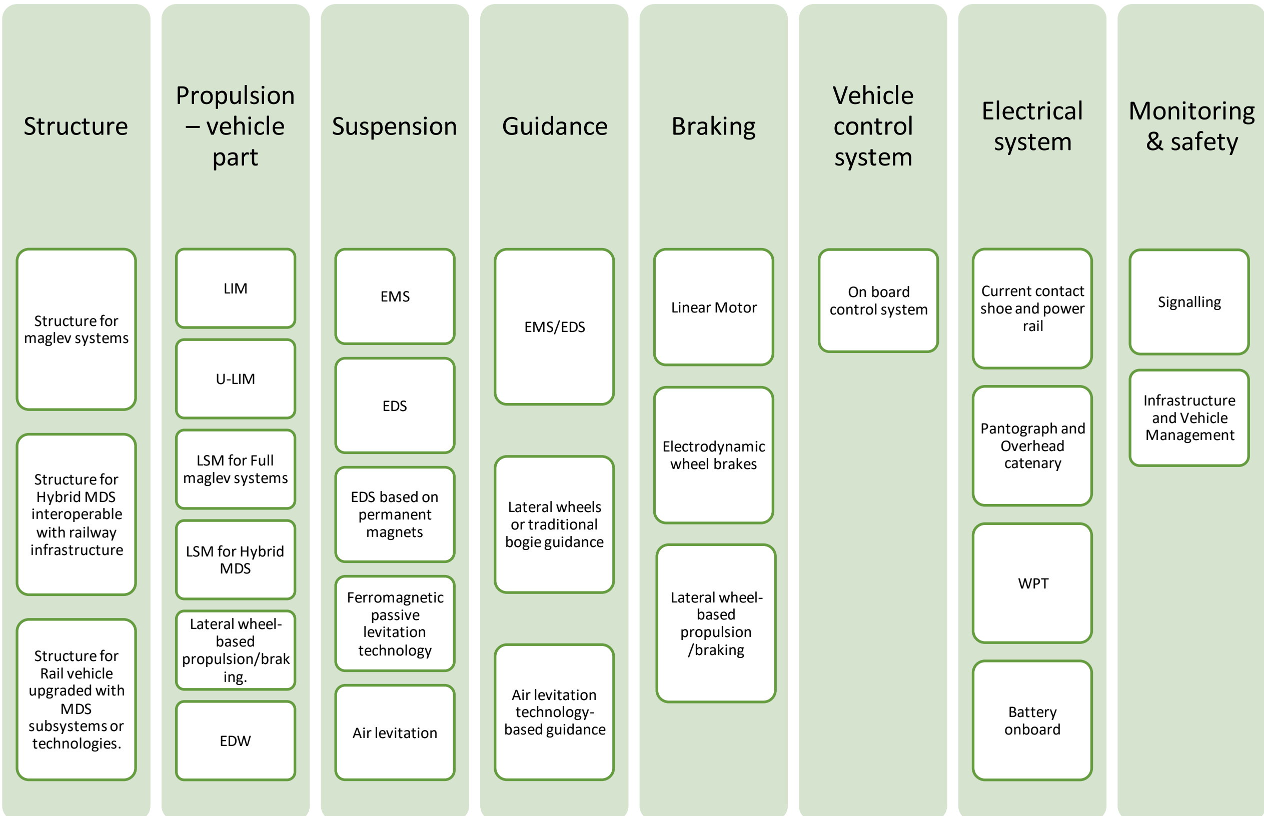


Figure 4. Critical technologies identified for the Vehicle subsystem and components.

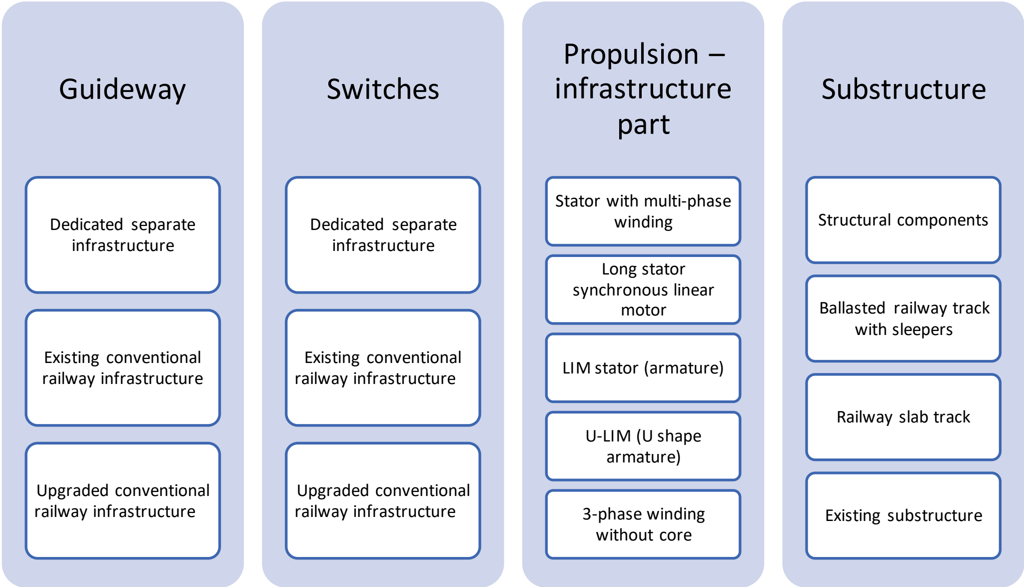


Figure 5. Critical technologies identified for the infrastructure subsystem and components.

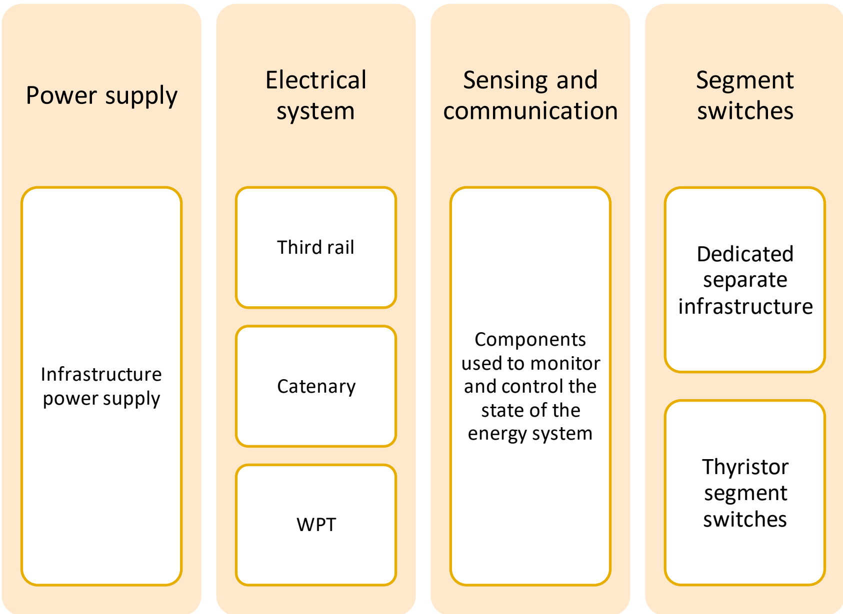


Figure 6. Critical technologies identified for the Energy subsystem and components.

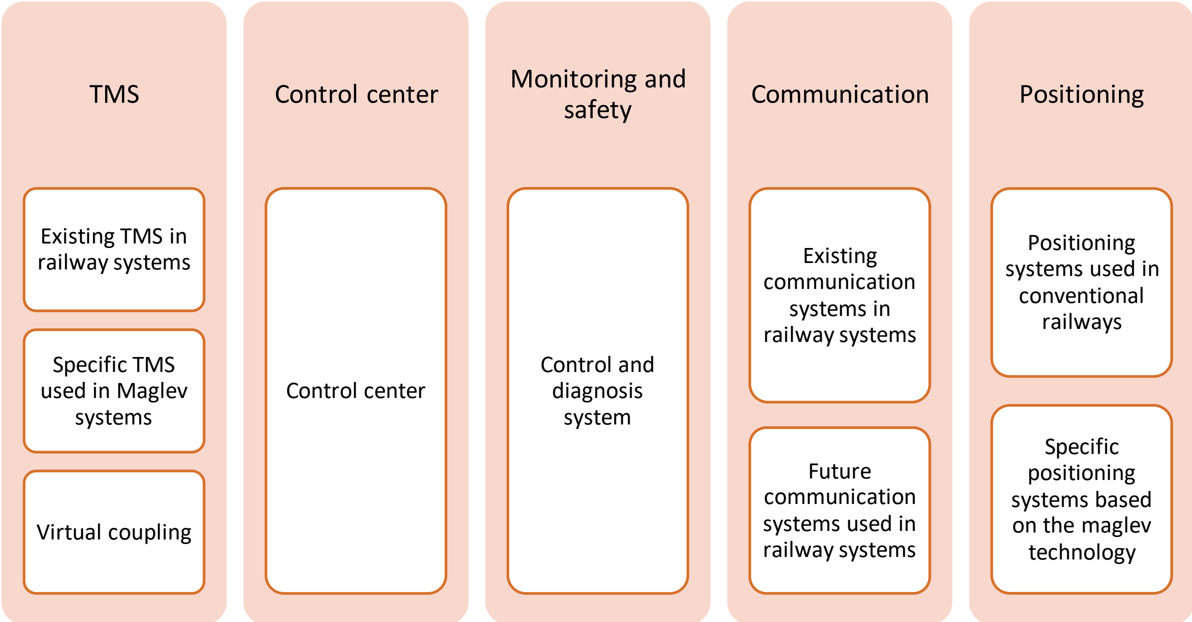


Figure 7. Critical technologies identified for the command and control subsystem and components.

5.3.3 Critical Technologies Assessment

To determine the maturity of CTs involved in each Considered MDS, the TRA team assesses them and assigns a TRL for each one. The TRLs are determined through an objective evaluation of information against general criteria. These criteria are defined in the TRL descriptions and are confirmed by the TRA team.

The report summarizes the TRL rating of each CT, including supporting documentation, to justify the assigned TRL.

The following tables, based on the previous morphological charts, includes the CTs assessment performed for each constituent technology involved in an MDS. The first two columns include the different systems and subsystems. The third column shows the different technologies used for each subsystem. The fourth column includes the TRL or range of TRLs achieved, and the last column includes the evidences (real implementations, projects or references) demonstrating the TRL reached.

Definitions of what each subsystem and component means can be found in (MaDe4Rail D2.1, 2023).

Table 1. CTs assessment for the Vehicle subsystem

Subsystem	Component	Technology used	TRL	Evidences
Vehicle	Structure	Structure for maglev systems	9	Beijing Line S1, Birmingham maglev, Daejeon Expo Maglev, Fenghuang Maglev, Incheon Airport Maglev (Ecobee), Linimo, Chuo Shinkansen
		Structure for Hybrid MDS vehicle interoperable with railway infrastructure	4-5	Prototype of Ironlev bogie applied on existing 50E5 rail is under testing phase.
			5	Prototype of Nevomo the full-scale bogie (MagRail system)
		Structure for Rail vehicle upgraded with MDS subsystems or technologies.	2	Ironlev concept design of structural integration with rail vehicle structure.
			5-6	Nevomo: Proven the platform equipped with the linear motor using a retrofitted freight platform. However, the TMS systems are not included.
	Propulsion – vehicle part	Linear Induction Motor (LIM)	9	Beijing Line S1, Birmingham maglev, Daejeon Expo Maglev, Fenghuang Maglev, Incheon Airport Maglev (Ecobee), Linimo
		Linear Induction Motor U shaped armature (U-LIM)	9	Full scale tests at Grenoble wheel test bench (Ø13m) 300km/h (U-LIM 6m length supplied by a PWM inverter 1MW-2kV corresponding to the traction/braking of a 20 tons vehicle. Few industrial U-LIMs are in operation from 5m/s to 360km/h (STECH'03, 2003).

Subsystem	Component	Technology used	TRL	Evidences
		Linear Synchronous Motor (LSM) for Full MDS	9	High-speed Maglev systems worldwide including Chinese Shanghai Maglev, Japanese SCMaglev, German Transrapid
		Linear Synchronous Motor (LSM) for Hybrid MDS	6	Nevomo uses Linear Synchronous motor with permanent NdFeB magnets on the vehicle side in MagRail and MagRail Booster systems Zeleros test track Inductrack test track
		Lateral wheel-based propulsion / braking.	5 - 6	Traction/braking is under testing phase with the Ironlev bogie prototype applied on 50E5 rail 2 km railway operating line.
		Electrodynamic wheels (EDW)	6-7	(Hijlkema, 2019), (Shi et al., 2023), (Bird and Lipo, 2006), (Noland, 2021), (LEVX, 2017)
	Suspension	Electromagnetic systems (EMS)	9	Beijing Line S1, Changsha Maglev, Daejeon Expo Maglev, Fenghuang Maglev, Incheon Airport Maglev (Ecobee), Linimo, Shanghai Maglev
		Electrodynamic systems (EDS)	5 - 8	Chuo Shinkansen, HTS Maglev–ETT,
		Electrodynamic systems (EDS) based on permanent magnets	6	MagRail, Inductrack
		Ferromagnetic passive levitation technology	6-7	Ironlev technology was tested in a full scale UNI60 track and is currently testing a bogie prototype applied on 50E5 rail 2 km railway operating line.

Subsystem	Component	Technology used	TRL	Evidences
		Air levitation	5-8	Aérotrain, Aerotreno, Hovertrain, TALAV, Transrapid 03, Otis Hovair, Airport MiniMetro
	Guidance	EMS/EDS	9	Beijing Line S1, Changsha Maglev, Daejeon Expo Maglev, Fenghuang Maglev, Incheon Airport Maglev (Ecobee), Linimo, Shanghai Maglev
		EMS /U-LIM	6	Full tests at Grenoble Wheel laboratory on the U-LIM up to the speed of 300km/h in the frame of the French-German Deufrako project. EMS guidance was set up by Thyssen.
		Lateral wheels or traditional bogie guidance	5 6	At low speeds, Nevomo uses modified railway wheels for guidance Ironlev proved lateral wheels guidance in static conditions with TRL 6; dynamic condition under testing phase.
		Air levitation technology-based guidance	8	(Bailey, 1993; Ferreira and Stephan, 2019)
	Braking	Linear Motor	7-9	Transrapid 09, MLX01, Sengenthal, SwissMetro, Tongji University Maglev, XP-01, XP-02
		U-LIM	9	Full tests at Grenoble Wheel Laboratory up to 300km/h. Also, other U-LIM are in operation.
		Electrodynamic wheel brakes	6-7	(Hijlkema, 2019), (Shi et al., 2023), (Bird and Lipo, 2006), (Noland, 2021), (LEVX, 2017)

Subsystem	Component	Technology used	TRL	Evidences
		Lateral wheel-based propulsion / braking	5 - 6	Ironlev is currently testing a bogie prototype with lateral wheels applied on 50E5 rail 2 km railway operating line.
			2 - 5	Aérotrain, TALAV
	Vehicle control system	TCMS Train Control Module System (also called On-board control system)	9	Daejeon Expo Maglev, Incheon Airport Maglev (Ecobee). Depending on the versions, it is applied in all traction systems.
	Electrical system	Current contact shoe and power rail	9	Most maglev system running at low and medium speed: Beijing Line S1, Beijing Line S1, Daejeon Expo Maglev, Incheon Airport Maglev (Ecobee), Linimo, Yokohama Municipal Subway 10000 series, Osaka Municipal Subway 70 serie, Sendai, Subway Tozai Line, Sengenthal, Fenghuang maglev, Hovertrain
		Pantograph and Overhead catenary	9	Yokohama municipal subway 10000 series, Ironlev hybrid system, SkyTrain rolling stock, Toei Ōedo Line (subway), Sendai Subway Tozai Line
		Wireless power transfer (WPT)	9	MagRail, Shanghai Maglev, Transrapid 09, European hyperloop centre, test track in Limoges, Chuo Shinkansen
		Battery onboard (charged with third rail during stop)	9	M-Bahn, XP-01, XP-02, Test track in Toulouse

Subsystem	Component	Technology used	TRL	Evidences
	Monitoring & safety	Two types of applications: signalling, and Infrastructure and Vehicle Management	9	There is a very wide application for these systems. All railway lines have infrastructure diagnostic systems and signalling systems to prevent accidents

Table 2. CTs assessment for the infrastructure subsystem

Subsystem	Component	Technology used	TRL	Evidences
Infrastructure	Guideway	Dedicated separate infrastructure	9	The vast majority of existing and described maglev systems. All Maglev guideways are elevated or tunnel infrastructure. Maglev systems are running as shuttle without "railroad crossing". Switches are installed at terminal station.
		Existing conventional railway infrastructure	6	Ironlev is currently testing a bogie prototype applied on 50E5 rail 2 km railway operating line.
		Upgraded conventional railway infrastructure	6	Nevomo testtrack MagRail and MagRail Booster in Nova Sarzyna
			3	Ironlev custom rail for upgrading conventional track, proof of concept demonstrator built

Subsystem	Component	Technology used	TRL	Evidences
	Switches	Dedicated separate infrastructure	9	Maglev track switches, for trains with regular rails plus linear motors with aluminium plate stator, or third rail. Full high speed Maglev systems (Transrapid and Lo Maglev) use switches only for the stop or terminal station.
		Existing conventional railway infrastructure	9	Railway application on wheels
		Upgraded conventional railway infrastructure (long stator LM)	2	Conceptual designs of the switches in R&D process in Nevomo.
	Propulsion – infrastructure part	Stator with multi-phase winding	8	Chuo Shinkansen
		Long stator synchronous linear motor	9	Transrapid high-speed Maglev system
		LIM stator (armature)	9	Yokohama subway, Osaka subway, Sendai subway, Skytrain, Toei Oedo subway, Vancouver Skytrain, Incheon Maglev
		U-LIM (U shape armature)	6	Wheel test bench at Grenoble, and industrial applications (Steel/copper, Steel/alu.)
		3-phase winding without core	6	Nevomo testtrack in Nova Sarzyna

Subsystem	Component	Technology used	TRL	Evidences
	Substructure	Structural components	9	All maglev systems use elevated track or tunnel track, then the track is installed on pillar using concrete foundation designed according to civil works standards (Eurocode or similar)
		Railway slab track	9	SkyTrain Vancouver, japanese LIM-powered metro systems
		Ballasted railway track with sleepers	6	MagRail Booster systems
		Existing substructure	9	Railway applications

Table 3. CTs assessment for the Energy subsystem

Subsystem	Component	Technology used	TRL	Evidences
Energy	Power supply	Infrastructure power supply	9	Shanghai Maglev, Transrapid 09 Beijing Line S1, Daejeon Expo Maglev, Incheon Airport Maglev (Ecobee), Linimo, Yokohama Municipal Subway 10000 series, Osaka Municipal Subway 70 serie, Sendai, Subway Tozai Line, Toei Ōedo Line (subway)
	Electrical system	Third rail	9	Some references ca be found in (Han and Kim, 2016; Liu Z et al., 2022) Vancouver Skytrain
		Catenary	9	Some references ca be found in (Han and Kim, 2016; Liu Z et al., 2022)

Subsystem	Component	Technology used	TRL	Evidences
		WPT	9	MagRail, Shanghai Maglev, Transrapid 09, European hyperloop centre, test track in Limoges, Chuo Shinkansen, (Prasad and Jain, 2023; Ying et al., 2019)
	Sensing and communication	Components used to monitor and control the state of the energy system	9	Shanghai Maglev, Transrapid 09, most maglev systems
	Segment switches	Dedicated separate infrastructure	9	Shanghai Maglev, Transrapid 09
		Thyristor segment switches	6	Nevomo

Table 4. CTs assessment for the Command and Control subsystem

Subsystem	Component	Technology used	TRL	Evidences
Command and control	TMS	Existing TMS in railway systems: ATO, CBTC, ETCS L2 – L3	7-9	CBTC applied mainly on subway solution. ETCS applied in Europe and around the world for railway lines. ATO is transversal and is present in both CBTC and ETCS applications
		Specific TMS used in Maglev systems	9	Existing systems use specific ATO
		Virtual coupling	4	(Felez and Vaquero-Serrano, 2023)
	Control centre	ERTMS, CBTC and also national solutions	9	Train Management System (TMS) with different development stage is present in all the modern lines (railway and metro)

Subsystem	Component	Technology used	TRL	Evidences
	Monitoring and safety	Control and diagnosis system. Usually are Interlocking, ATP, diagnosis systems	9	Usually are included in CBTC or ERTMS/ETCS application. Also National solutions adopt these systems. Also in existing maglev systems like Transrapid or Shinkansen. They are "ad hoc" ATO developed for the maglev line.
	Communication systems	GSM-R and GPRS	9	GSM-R is the radio system considered for the ETCS/ERTMS It is deployed on more than 150 000 km of lines in Europe. Among them 23 000 km are high speed lines. Lo maglev system will use the same communication system ATC installed for the Shinkansen rolling stocks.
		Wi-Fi, IEEE 802.11p, ITS-G5	9	Wi-Fi standard is widely considered in several CBTC in the world. The American version IEEE 802.11p and the European one ITS-G5 have been designed specifically for automotive applications and offer a good basis for railway applications.
		Future systems used in railway systems: LTE, 5G, FRMCS, satellites	6	There exist demonstrators of all these technologies

Subsystem	Component	Technology used	TRL	Evidences
	Positioning systems	Positioning systems used in conventional railways	6 - 9	TRL 9 for Eurobalise, KVB, track circuits TRL 6 for some demonstrated solution based on GNSS and multi sensors.
		Specific positioning systems based on the maglev technology	9	German Transrapid Maglev test line and Shanghai line. Ecobee system

5.3.4 TRA Report

TRA reports provide useful information about the maturity of technology, its state of development, and the potential areas of concern and risk. The information can help to identify maturity gaps, formulate plans for maturing technologies, address potential concerns, and determine whether programs that will integrate CTs have achieved TRLs at a certain decision point and are ready to move to the next acquisition phase.

The content in a TRA report can vary based on its purpose. In this case, we will develop a knowledge-building TRA report that is prepared with a focus on maturing technologies, not as a pass/fail assessment.

Table 5 shows a schematic of a TRA with the different items to be considered and the expected content of each of them.

Table 5. TRA general description and contents

Concept	Description
Technology Reviewed:	Provide a detailed description of the technology that was assessed. The level of detail can vary depending on the phase of development, design characteristics, and scope of review. Organizations should strive to provide a sufficient amount of information to facilitate an understanding of the technology assessed
Function:	Describe the functions of the critical technologies.
Relationship to Other Components	Describe how the critical technologies interface with other systems.

Concept	Description
Development History and Status	Summarize pertinent development activities that have occurred to date on the critical technology.
Relevant Environment	Describe relevant parameters inherent to the critical technology or the function it performs as it relates to the intended operational environment.
Comparison of the Relevant Environment and the Demonstrated Environment	Describe differences and similarities between the environment in which the critical technology has been tested and the intended environment when fully operational. The demonstrated environment must correspond to the identified relevant environment for the TRL to be justified.
Technology Readiness Level Determination	State the TRL determined for the critical technology and provide the basis justification for the TRL.
Operational Requirement	Describe the required/traceable system functional performance and enabling features for the critical technology elements.
Test Results	Describe the analytical reports, test reports, or other information that was used to test the readiness, and functionality of the critical technology.

5.3.4.1 TRA Report for Vehicle System

5.3.4.1.0 Structure

Structure	Structure for maglev systems
Technologies Reviewed:	The structure of the vehicle is dedicated to operations as a full maglev system.
Function:	The component that enables transferring internal (e.g., from payload) and external (e.g., track dynamic responses, wind, etc.) forces and distributes them safely to maintain the vehicle's integrity. The structure affects both trainset and pod-type vehicles.
Relationship to Other Components	As the structure is the central component of the vehicle, a variety of other components can be attached to the structure. The main ones include linear motor mover, suspension, onboard electronics, safety systems, payload, etc..
Development History and Status	The structure itself as a frame has been known for centuries and has been used in railway systems and other transportation modes for a very long time.

Structure	Structure for maglev systems
Relevant Environment	The relevant environment is a dedicated maglev track that are not interoperable with the railway.
Comparison of the Relevant Environment and the Demonstrated Environment	No significant differences
Technology Readiness Level Determination	TRL 9 (existing maglev systems)
Operational Requirement	Specific operational requirements depending on the type of maglev system
Test Results	Beijing Line S1, Birmingham maglev, Daejeon Expo Maglev, Fenghuang Maglev, Incheon Airport Maglev (Ecobee), Linimo, Chuo Shinkansen

Structure	Structure for Hybrid MDS interoperable with railway infrastructure
Technologies Reviewed:	The structure of the new vehicle is dedicated to operations as a hybrid MDS.
Function:	The component that enables transferring internal (e.g., from payload) and external (e.g., track dynamic responses, wind, etc.) forces and distributes them safely to maintain the vehicle's integrity. The structure affects both trainset and pod-type vehicles.
Relationship to Other Components	As the structure is the central component of the vehicle, a variety of other components can be attached to the structure. The main ones include linear motor mover, suspension, onboard electronics, safety systems, payload, etc. In a dedicated vehicle, the structure could be optimized for the best possible packaging of other elements and minimal mass.
Development History and Status	The structure itself as a frame has been known for centuries and has been used in railway systems and other transportation modes for a very long time. In a hybrid MDS vehicle, the structure will be similar to those well-known in maglev systems or the aerospace industry since it should be lightweight to improve the levitation parameters, if applicable.
Relevant Environment	The relevant environment is a railway network, which may be closed (like sidings or internal facility tracks) or open.

Structure	Structure for Hybrid MDS interoperable with railway infrastructure
Comparison of the Relevant Environment and the Demonstrated Environment	Demonstrated environment is a simplified straight railway track without railway switches where prototype vehicle – MDS vehicle bogie – is being tested. To achieve next step, full-scale MDS newly designed vehicle should be built and validated.
Technology Readiness Level Determination	TRL 5 (full-scale bogie)
Operational Requirement	The structure should be authorized to transfer the forces from linear motor operations safely, as well as meet all defined safety requirements. Also the structure should be lightweight, if applicable for levitation and high-speed systems.
Test Results	Full-scale bogie demonstrator tested by Nevomo in Nowa Sarzyna Test Track successfully. Levitation achieved over 70 km/h. Maximum speed reached was 130 km/h. Further tests are in progress.

Structure	Structure of Rail vehicle upgraded with MDS subsystems or technologies
Technologies Reviewed:	Retrofitted structure using existing rolling stock
Function:	The component that enables transferring internal (e.g., from payload) and external (e.g., track dynamic responses, wind, etc.) forces and distributes them safely to maintain the vehicle's integrity.
Relationship to Other Components	As the structure is the central component of the vehicle, a variety of other components can be attached to the structure. The main ones include linear motor mover, suspension, onboard electronics, safety systems, payload, etc.
Development History and Status	The structure itself as a frame has been known for centuries and has been used in railway systems and other transportation modes for a very long time. However, the existing structure adapted for a linear motor is something new, and currently, the technology is in the development phase (TRL5).
Relevant Environment	The relevant environment is a railway network. It may be closed (like sidings or internal facility tracks) or open.

Structure	Structure of Rail vehicle upgraded with MDS subsystems or technologies
Comparison of the Relevant Environment and the Demonstrated Environment	The structure itself is adapted for being utilized in a railway network environment. However, if the structure is upgraded with the linear motor mover, it must be authorized again, which has not been done yet.
Technology Readiness Level Determination	TRL 5
Operational Requirement	The structure should be authorized to transfer the forces from linear motor operations safely.
Test Results	Full-scale demonstrator tested by Nevomo in Nowa Sarzyna Test Track successfully. Vehicle - freight platform equipped with linear synchronous motor mover - reached 50 km/h. Further tests are in progress.

5.3.4.1.1 Propulsion – vehicle part

Propulsion – Vehicle part	Linear Induction Motor
Technologies Reviewed:	Linear Induction Motor (LIM) is an asynchronous electric machine that usually is made of two parts – active part that is a winding (usually 3-phase) that generates the electromagnetic field and the reaction plate where the eddy currents are generated. The active part in most cases is mounted on the vehicle. In the case of the Linear Induction Motor U-shaped armature (U-LIM), two geometries of the reaction plate can be designed, the flat shaped reaction plate, and the U-shaped reaction plate.
Function:	Component that enables acceleration and deceleration of the vehicle via applying the direct force to the vehicle-mounted part.
Relationship to Other Components	The vehicle part of the propulsion has the internal interfaces with the structure via some types of mounting and with onboard units (for LIM) that monitor the linear motor state. External interface is the infrastructure part of the linear motor. However, it is crucial to note that if the vehicle operates on the railway network also the relationships to the railway subsystems and constraints should be considered, e.g., structure gauge and EMC.

Propulsion – Vehicle part	Linear Induction Motor
Development History and Status	The linear motors are well known for over 50 years. They have been proven in such projects like M-Bahn, Transrapid 01-09, Chuo Shinkansen and other maglev systems since this is the principal propulsion for these modes of transport. Currently, the linear motors have TRL9 majority. The systems in a dedicated railway network were implemented on metro lines, first in Canada, then in Japan and recently in China, to cover today more than 500 km. (TRL 9).
Relevant Environment	The relevant environment for the railway-compatible MDS linear motors is a railway network or railway sidings.
Comparison of the Relevant Environment and the Demonstrated Environment	Railway-compatible prototype linear motor does not meet all the regulatory requirements (environmental conditions, EMC, etc.). Moreover, in the Demonstrated Environment no switches and road-rail crossings integration has been tested.
Technology Readiness Level Determination	Linear induction motors are generally chosen for Maglev applications and reached TRL9. At present, this motor is under use in Japanese HSST Maglev system that is a medium speed system and in Ecobee, M-Bahn and Linimo. Linear Induction motor for traction must satisfied the standard IEC 62520:2011 Railway applications - Electric traction - Short-primary type linear induction motors (LIM) fed by power converters.
Operational Requirement	Linear motors require additional power supply on the vehicle side on usual third rail or catenary. Due to the wear of the wheels and their reprofiling it is necessary to periodically adjust the air gap between the armature on the track and the inductor on board the vehicle. This adjustment is much less critical if the armature is U-shaped
Test Results	Several projects as Vancouver Skytrain, all metro lines in Japan and China have proven the technology to be fully operational on railway tracks. Full scale tests at Grenoble wheel test bench (Ø13m) 300km/h (U-LIM 6m lengh supplied by a PWM inverter 1MW-2kV corresponding to the traction/braking of a 20 tons vehicle. Few industrial U-LIMs are in operation from 5m/s to 360km/h.

Propulsion – Vehicle part	Linear Synchronous Motor (LSM) for Full Maglev systems
Technologies Reviewed:	Linear Synchronous Motor (LSM) possesses high force density along with high efficiency and high-power factor as compared to linear induction motors. Since it is a doubly excited motor, it incorporates a DC excitation source in its structure. To make the system contactless, generally permanent magnets are used for DC excitation and fitted in the translator. The translator forms the onboard part and moves with the vehicle. The distributed stator windings are laid on the tracks and energized with the help of ground converters which gives it a long stator configuration. Excitation of stator windings generates moving flux that moves at synchronous speed. DC magnets fitted on translator generate constant flux. When both of these fluxes interact, a magnetic locking is produced that impels the translator to move at synchronous speed.
Function:	Component that enables acceleration and deceleration of the vehicle via applying the direct force to the vehicle-mounted part.
Relationship to Other Components	The direct relationships and interfaces with other components include internal ones like vehicle structure as it is mounted directly there, and onboard sensors that monitor the gap, magnetic field, etc., and external ones e.g., the infrastructure part of the linear motor.
Development History and Status	The Linear Synchronous Motor has been used for several high-speed maglev applications and in urban transit.
Relevant Environment	The relevant environment for the LSM is a railway network with dedicated infrastructure.
Comparison of the Relevant Environment and the Demonstrated Environment	Railway-compatible prototype LSM does not meet all the regulatory requirements (environmental conditions, EMC, etc.).
Technology Readiness Level Determination	The linear motors in full maglev systems are on TRL 9.
Operational Requirement	This motor requires precise position monitoring to maintain synchronism with the moving flux generated by stator windings, which makes the track structure complex and costly. Also, use of double excitation sources increases its cost and losses. Vehicles propelled by linear synchronous motor have limitations such as accommodation of only one vehicle at a time in any track section. The other vehicle cannot enter the section unless the first one clears it to maintain the synchronism. Thus, operation of more trains needs more tracks that not only increases control and monitoring needs but also increases converter requirements.

Propulsion – Vehicle part	Linear Synchronous Motor (LSM) for Full Maglev systems
Test Results	It is under use in almost all the high-speed Maglev systems worldwide including Chinese Shanghai Maglev, Japanese SCMaglev, German Transrapid, etc (Prasad and Jain, 2023).

Propulsion – Vehicle part	Linear Synchronous Motor (LSM) for Hybrid MDS
Technologies Reviewed:	Linear Synchronous Motor (LSM) in a synchronous electric machine usually consisting of the mover – a vehicle-mounted set of NdFeB magnets in Halbach array and the stator (active part) – a 3-phase winding installed in the track.
Function:	Component that enables acceleration and deceleration of the vehicle via applying the direct force to the vehicle-mounted part.
Relationship to Other Components	The vehicle part of the LSM is called the mover, consisting of a set of NdFeB magnets arranged in the Halbach array. The direct relationships and interfaces with other components include internal ones like vehicle structure as it is mounted directly there, and onboard sensors that monitor the gap, magnetic field, etc., and external ones e.g., the infrastructure part of the linear motor. However, it is crucial to note that if the vehicle operates on the railway network also the relationships to the railway subsystems and constraints should be considered, e.g., structure gauge and EMC.
Development History and Status	The first tests of the permanent magnet linear synchronous motor were performed in 2019 when the lab-scale demonstrator proven that the Nevomo technology concept was working. The second iteration of the linear motor was done in 2021. for the first time in the final configuration with the railway tracks integration and full linear motor segmentation has been tested successfully. Currently, the third - full-scale - system has been built and the tests are ongoing. The linear motor demonstrator can accelerate the vehicles up to 130 km/h.
Relevant Environment	The relevant environment for the railway compatible MDS linear motors is a railway network or railway sidings.
Comparison of the Relevant Environment and the Demonstrated Environment	Railway-compatible prototype LSM does not meet all the regulatory requirements (environmental conditions, EMC, etc.). Moreover, in the Demonstrated Environment, no switches and road-rail crossings integration has been tested.

Propulsion – Vehicle part	Linear Synchronous Motor (LSM) for Hybrid MDS
Technology Readiness Level Determination	The linear motors interoperable with the railway system are on TRL 6-7.
Operational Requirement	Linear synchronous motors require an additional power supply on infrastructure side
Test Results	Regarding linear motor installed on the railway track – prototype tests have been accomplished successfully, however still operational, interoperability and safety aspects are to be tested.

Propulsion – Vehicle part	Lateral wheel-based propulsion/braking
Technologies Reviewed:	The technology is a traction/braking subsystem design option to be coupled with Ferromagnetic passive levitation technology or other magnetic levitation systems. It consists of multiple pairs of vertical axes wheels. The wheels are coupled with asynchronous, synchronous brushless electric motors.
Function:	The system has the purpose of delivering the traction/braking force applied on the guideways. It includes a control system to modulate the contact force. The system can also provide guidance function.
Relationship to Other Components	The system is connected to the levitation system, the vehicle control system and the electrical system. Lateral wheels are in contact with the guideways (rails).
Development History and Status	Electric traction wheels are a widely adopted, very efficient and robust solution for vehicle and transport applications. Ironlev is currently testing the integration of electric traction wheels with magnetic levitation technology to a 50E5 track.
Relevant Environment	Normal operating conditions. Electric motors and wheels are currently adopted in the railway environment.
Comparison of the Relevant Environment and the Demonstrated Environment	The application of lateral wheel-based propulsion and braking needs to configure vertical axes wheels in order to be coupled with the levitation system. For custom rail application, the wheels can be coupled with a rubber track for optimal traction and cooling integration.
Technology Readiness Level Determination	System under testing phase on a 2 km operating line.

Propulsion – Vehicle part	Lateral wheel-based propulsion/braking
Operational Requirement	One important feature is the efficiency and reliability of electric traction motors. Another feature is the possibility to span from low speed to very high speeds by using available and off-the-shelf robust components. Another feature is the possibility to provide high precision control positioning.
Test Results	Concepts, engineering design and prototype. Reference: Ironbox srl

Propulsion – Vehicle part	Electro-dynamic wheels (EDW)
Technologies Reviewed:	In an electro-dynamic wheel (EDW), a cylindrical PM Halbach array (typical design) is rotating to induce its field over a passive conducting surface. Then, eddy currents are generated inside the surface, and it opposes the field induced.
Function:	The EDW can generate levitation and thrust forces simultaneously, which makes it different from other suspension systems.
Relationship to Other Components	It can provide both levitation and propulsion, as well as braking when the wheels rolling in the opposite direction.
Development History and Status	One commercial activity developed the EDW solution with TRL 6-7, see video (LEVX, 2017)
Relevant Environment	Incorporating into the current maglev trains or replace the LIM with EDW.
Comparison of the Relevant Environment and the Demonstrated Environment	Currently, the scaled model and numerical model were built, based on which the EDW design was validated. Further studies are still needed at full-scale model test, as well as more studies on numerical modelling of EDW dynamic responses on high-speed railway. Currently the application of EDW is for freight transportation at ports (LEVX, 2017)
Technology Readiness Level Determination	TRL 6: laboratory test on scaled model and numerical simulations were performed. One application has been identified at port goods Transportation in USA.
Operational Requirement	Relatively lower requirement and track construction costs than LIM, which needs conductive surface, such as aluminium plate.
Test Results	Some test can be found in (Hijlkema, 2019), (Shi et al., 2023), (Bird and Lipo, 2006), (Noland, 2021), (LEVX, 2017)

5.3.4.1.2 Suspension

Suspension	Electrodynamic system (EDS)
Technologies Reviewed:	Electrodynamic system (EDS) employs magnetic repulsive force for accomplishing levitation. On-board magnets, when moving forward with the vehicle over the guideway consisting of inductive coils or conducting sheets, generate repulsive force due to interactions of onboard magnets with the currents induced in the guideway coils. This repulsive force provides the required levitation to the vehicle.
Function:	Subsystem that enables counteracting vertical load and/or maintaining the vertical position of the MDS vehicle.
Relationship to Other Components	For MLX 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.
Development History and Status	The main reference is the Chuo Shinkansen. Japan started its research and development on the maglev system in 1964. 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. On April 22, 2015, the Japanese superconducting maglev system L0 achieved a running speed of 603 km/h, a record for any guided vehicle. On the other hand, on December 31, 2000, the first crewed high-temperature superconducting maglev wagon was tested successfully at Southwest Jiaotong University, Chengdu, China. In 2021, The world's first locomotive prototype using high-temperature superconducting magnetic levitation technology (HTS Maglev) has been unveiled in Chengdu City, capital of southwest China's Sichuan Province.
Relevant Environment	This system uses superconducting magnets (SCMs) which are super-cooled at frigid temperatures using a cryogenic system. These magnets not only raise the cost of the system, but the strong magnetic field generated by such magnets penetrates inside the train car even after shielding, which can make the journey uncomfortable for passengers. This parasitic magnetic field was solved thanks to a new design and position under the car body of the cryogenic electro-magnet. However, the SCMs can conduct electricity during power failure.
Comparison of the Relevant Environment and the Demonstrated Environment	The Chuo Shinkansen and the HTS Maglev–ETT use this levitation technology. Chuo Shinkansen is in operation, but the HTS Maglev–ETT has been tested but is not jet in operation.

Suspension	Electrodynamic system (EDS)
Technology Readiness Level Determination	Based on the previous experiences, this technology reached a TRL 8 - 9
Operational Requirement	These systems can achieve levitation up to 10 cm. However, the inherent pitfall of this system is the requirement of rubber tires on which the train must roll initially until it reaches a lift-off speed of about 100 km/h.
Test Results	As mentioned, the Chuo Shinkansen and the HTS Maglev–ETT use this levitation technology. Chuo Shinkansen is in operation, but the HTS Maglev–ETT has been tested but is not jet in operation. Some references of test can be found in (Deng et al., 2017; Mamoru U, 2016)

Suspension	Electromagnetic system (EMS)
Technologies Reviewed:	This system uses magnetically attractive forces between the guideway and the on-board electromagnets installed below the guideway, for accomplishing levitation. This design produces levitation even at zero speed.
Function:	Subsystem that enables counteracting vertical load and/or maintaining the vertical position of the MDS vehicle.
Relationship to Other Components	The Shanghai Maglev, Korean UTM and Japanese HSST use this system with the levitation and guidance circuits completely integrated. However, in this arrangement, the interference between the two circuits increases with the increase in speed. Therefore, this integration is suitable for low-speed applications. The German Transrapid TR09 uses EMS technology with the levitation and guidance circuits completely separated, which makes it suitable for high-speed operation because of the absence of interference between the two circuits. But such arrangement increases the cost of the design due to the increase in number of power controllers used.
Development History and Status	There are several vehicles developed with this technology. As an example, we can mention the following ones: The Transrapid development began in 1969, with the construction of a test facility in Emsland, Germany, completed in 1987. The last Transrapid maglev train was completed in 2005. Today, the Transrapid technology is active only on Shanghai Maglev. The urban transit system known as Linimo has been in successful operation along the Tobu Kyuryo Line in Nagoya since the year 2005. The development of low-speed maglev systems in Korea began in the

Suspension	Electromagnetic system (EMS)
	mid-1980s, leading to the creation of the first prototype train in 1992. In 1993, a 1 km-long maglev track was constructed for a public demonstration during Expo 93 in Daejeon. This track is currently operational, serving as transportation between Expo Park and the National Science Museum. The development of Chinese urban maglev systems commenced in 1989, culminating in the completion of the first prototype in Chengdu by 1994. The first commercial urban maglev line became operational in Changsha in 2016, boasting an 18.5 km system length. A second urban maglev system in China, integrated into the Beijing Metro network, opened in 2017.
Relevant Environment	Unlike the EDS system, EMS system uses standard electromagnets, which conduct in the presence of electric power supply only. This results in magnetic fields of comparatively lower intensity inside the passenger compartment, making the travel more comfortable for the passengers.
Comparison of the Relevant Environment and the Demonstrated Environment	Most of the systems using this technology are in operation.
Technology Readiness Level Determination	Based on the previous experiences, this technology reached a TRL 9
Operational Requirement	Lower intensity of magnetic field produces a levitation air gap of 1 cm. A small levitation air gap makes the continuous controlling of the gap imperative because of the inherent instability of the suspension systems. Nevertheless, controlling the smaller air gap becomes more and more inconvenient with the increase in speed. This makes it suitable for low- to medium-speed applications.
Test Results	There are several systems using this technology such are Beijing Line S1, Changsha Maglev, Daejeon Expo Maglev, Fenghuang Maglev, Incheon Airport Maglev (Ecobee), Linimo, Shanghai Maglev. Some references of test can be found in (Feng et al., 2023; Ou et al., 2022; Wu and Hu, 2017). Also some test for slow speed vehicles (under 160 kph) for urban mass transportation in the United States can be found in (Federal Transit Administration Team, 2002)

Suspension	Electrodynamic systems (EDS) based on permanent magnets
Technologies Reviewed:	This system is a modified form of the conventional EDS system. It is a passive levitation system, also known as an Inductrack system based on the principle of magnetic repulsion. It uses permanent magnets at room temperature, arranged in the form of a Halbach array.
Function:	Subsystem that enables counteracting vertical load and/or maintaining the vertical position of the MDS vehicle.
Relationship to Other Components	Unlike a conventional EDS system, this system does not require any super-cooled magnets, neutralizing any cryogenic requirements. However, the system requires auxiliary wheels to accelerate the vehicle until it acquires some initial take-off speed, after which it starts levitating. The system is not integrated with the guidance system.
Development History and Status	The levitation technology referred to as "Inductrack", was developed by Dr. Richard Post of Lawrence Livermore National Laboratory (LLNL). In November 2002, construction of a 120-m long test track at the General Atomics Electromagnetics Systems facility in San Diego, California was initiated. The system is not in operation, but its fundamentals are being used in some Hyperloop projects.
Relevant Environment	In case of power failure, the train can slow down and rest on its auxiliary wheels.
Comparison of the Relevant Environment and the Demonstrated Environment	This technology has been under trial by General Atomics, USA, with suspension magnets separated from propulsion magnets. Other technology that uses super-conducting material levitating in a constant field of permanent magnets has also been under trial and research in Chengdu, China since 2002.
Technology Readiness Level Determination	Tests and trials have only been carried out and have achieved a TRL 5
Operational Requirement	The PM-EDS system employs a Halbach array formed with permanent magnets. This arrangement produces a sinusoidal magnetic field on the lower side of the array while cancelling it completely on its upper side. This magnetic field interacts with the insulated short-circuited coils forming the track to produce repulsive levitating force. As this design does not require any super-conductor, it is a low-cost design.
Test Results	Some test reports can be found in the following references: (Post and Ryutov, 1996; Saied and Al-Shaher, 2009; Zhang et al., 2021).

Suspension	Air levitation systems
Technologies Reviewed:	The air levitation suspension (or air cushion) 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.
Function:	Using powerful fans to create a cushion of air underneath them, effectively levitating the vehicle above the track.
Relationship to Other Components	In vehicles using air levitation suspension, propulsion is typically provided separately from the levitation system. This can be done using jet engines, linear induction motors or electrodynamic wheels. The system is integrated with the air-cushion technology-based guidance system.
Development History and Status	Air levitation technology has been studied since 1950s. 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). However, as with any innovative technology, air levitation for railway vehicles faces its own unique set of challenges. The main challenge is the propulsion of the Airlev train besides operational hurdles like noise management and energy efficiency. Understanding and overcoming these challenges is key to realizing the potential of air levitation technology in transforming the future of railway transportation. Following the French Aérotrain project using air levitation technology for sustentation and guidance, the system performance of the air levitation was demonstrated up to 430 km/h, over 100k km distance. The project was stopped in 1974 due to the lack of LIM propulsion. The power electronics necessary for the energy conversion was not ready yet. The French transportation research institute (IRT/INRETS) finally validated of the U-LIM technology in 1986 at 300km/h (Grenoble wheel test bench laboratory). Linear motors to propel air levitation vehicle needs compact power converter, the development of the power electronic switches started in 1970, but the high-performance power semiconductor switches (IGBT modules …) appeared on the market only at the end of the 1990s. Nowadays we have all the technologies bricks to achieve a very efficient air levitation transportation system.

Suspension	Air levitation systems
Relevant Environment	Airlev trains are from the hovercraft, which are meant to allow travelling over multiple environment conditions, like water, mud, and land. In addition, the requirement and construction cost for track is much lower than maglev train systems.
Comparison of the Relevant Environment and the Demonstrated Environment	Currently, there is no operating Airlev trains for commercial purpose. There are several lines using air-cushion suspension in the airport but with cable for propulsion. The intended environment, for example, incorporating in current rail systems, has not been performed or tested anywhere.
Technology Readiness Level Determination	For air-cushion suspension technology, it has been applied in many operating lines, however, the propulsion means have not been fully demonstrated or studied yet. The TRL for air-cushion suspension technology is 9, while TRL for corresponding propulsion is dependent on the types that will be applied.
Operational Requirement	The suspension air pad directs air into a chamber, generating a pressure differential that creates a mechanical force capable of lifting the vehicle. Meanwhile, guidance air pads located on both sides of the vehicle prevent any lateral contact with the supporting beam.
Test Results	In the former reports, such as French Aerotrain and American TALAV, the TRL can be 8.

Suspension	Ferromagnetic passive levitation technology
Technologies Reviewed:	The ferromagnetic passive levitation system is a patented Ironlev technology based on the coupling of a U-shaped magnetic slider which integrates passive permanent magnets with a ferromagnetic rail. The magnets are configured on the movable elements to provide vertical support. It is based on permanent magnets at room temperature and provides the levitation force both in static conditions as well as in dynamic conditions.
Function:	Subsystem that enables counteracting vertical load and/or maintaining the vertical position of the MDS vehicle.

Suspension	Ferromagnetic passive levitation technology
Relationship to Other Components	This system does not require any super-cooled magnets, neutralizing any cryogenic requirements, nor auxiliary systems like in EDS systems. The system is not integrated with the guidance system except for specific designs. It is coupled with guidance system for the lateral centring and rail interaction and its interface is the structure of the vehicle for load transfer purposes. Guidance system types compatible are lateral wheels and EMS systems. The system is not integrated with traction system. The latter can be integrated in the lateral wheel guidance system or can be a separate system.
Development History and Status	The Ironlev technology first patent was filed in 2016. Since then, many tests have been performed at different load scales, from few kgs up to tons. In 2017, the system was proven at full scale by applying a 10 tons max load platform on UNI60 railroad tracks to demonstrate the application on a railway track shape. In fact, the technology can work in combination with the standard railroad shape, magnetically interacting with the top head of the rail. Custom ferromagnetic rail is currently under development and testing for the use in separate structure or for auxiliary rail design applied to standard infrastructure. The technology is currently under testing phase for speed conditions and in combination with wheeled powered traction system, although it can be coupled with different traction technologies. The same technology is also applied and commercially available for different application fields, including sliding systems for windows & doors mechanisms, in industrial machinery and material handling systems and in the elevator domain.
Relevant Environment	Passive levitation technology can work seamlessly in static and dynamic conditions.
Comparison of the Relevant Environment and the Demonstrated Environment	Ironlev levitation technology has been tested in relevant industrial environment and under different environmental conditions, including temperature range and salt spray, demonstrating the technical solution viable for environmental resistance. Static and low speed tests have been carried out with different rail shapes, including railway track shapes UNI60 and 50E5. Custom rail is currently under development for high performance systems in terms of speed and energy efficiency.
Technology Readiness Level Determination	Test on Ironlev levitation system for railway application have been performed with TRL 5-6. For other application fields (elevator and industrial material handling) the technology is proven at TRL 9.

Suspension	Ferromagnetic passive levitation technology
Operational Requirement	The most important Ironlev enabling feature is to work in combination with steel/ferromagnetic rail and in particular to work with a rail shape compatible with railroad track shapes. In fact, the system is anchored to the top head of the iron rail, compatible with vertical wheel interaction. It opens to the possibility of full railway compatibility or with the possibility to have an iron-based low-cost infrastructure. Another system enabling feature is to be a passive levitation system working both in static condition (speed=0) and dynamic condition. It enables the elimination of additional or auxiliary systems. In addition, being a system based on permanent magnets, it does not require cryogenic systems. Another system enabling feature is the extreme energy efficiency if compared to other levitation systems and technologies. In fact, Ironlev technology is based on the minimisation of the eddy current effects along the rail. Another feature is the versatility of the technology and its combination with different guidance systems and/or traction systems.
Test Results	FEA simulations with different software, reports, charts (Deliverable 2.1) Reference: Ironbox srl

5.3.4.1.3 Guidance

Guidance	EMS/EDS
Technologies Reviewed:	For maglev systems, the physical contact between vehicles and guideway is avoided, so a magnetic force is also used for guidance to counteract the centrifugal force in curves and withstand any possible disturbances in the lateral direction. There are two guidance approaches corresponding to the Electromagnetic suspension (EMS), and to the Electro-dynamic suspension (EDS)
Function:	Electromagnetic suspension (EMS): For low-speed maglev systems, both the operational speed is low and the centrifugal force in curves is small. The EMS is self-centred, which means any lateral displacement between the magnetic rail and the electromagnet leads to a restoring force to pull the vehicle back to the centre position. The magnetic field can be adjusted to strengthen the restoring force by detecting the air gap. Therefore, there is no need to

Guidance	EMS/EDS
	have a specific guidance system onboard or in the infrastructure. However, for high-speed maglev system, the operational speed, centrifugal force and dynamic load are very high. In addition, the air gap between the vehicle and the infrastructure for the EMS system is small, so the restoring force is not strong and fast enough to centre the vehicle back to its original position. In order to acquire a high restoring force, another electromagnetic suspension is used in the lateral direction. The system works as the EMS for levitation. There are also sensors to detect the air gap in the lateral direction to control the electric current through the electromagnets. Electro-dynamic suspension (EDS): The repulsive force used for levitation by electro-dynamic suspension is very strong with speed increase and can maintain a large air gap between the infrastructure and the vehicle, so it is not necessary to place the magnets and the induced conductors right below the carbody. In order to provide the restoring force in the lateral direction for guidance, the EDS is placed on the two sides of the vehicle and the induced conductors are a bit below the magnets onboard. In that case, the same suspension system works for both vertical levitation and lateral guidance. Even though the suspension system becomes simple, the EDS does not work well in the low-speed range, so wheels or a special gear are needed not only right below the carbody but also on the two sides of the vehicle. In an emergency condition, they have to take over the EDS system to carry the train weight. The suspension systems, therefore, become relatively complex.
Relationship to Other Components	The system is strongly related to the levitation system
Development History and Status	CHSST uses EMS (Federal Transit Administration Team, 2002). In HSST, there is no active lateral control. The suspension is stable, but under-damped laterally. Some damping is provided laterally by airbags on the secondary side (module to car body), but HSST does not have data and analysis describing the damping ratio. Related to EDS, Japanese MLX technology integrates the guidance system with the levitation system, whereas Japanese MLU technology integrates the guidance system with the propulsion system. The German Transrapid also uses magnetic repulsive force between the on-board electromagnets and the side coils connected on either side of the train for accomplishing guidance.
Relevant Environment	EMS is used for operative maglev with lateral control and electronic systems (e.g. Shanghai maglev train).

Guidance	EMS/EDS
Comparison of the Relevant Environment and the Demonstrated Environment	The system is in operation in several projects.
Technology Readiness Level Determination	Based on the previous experiences, this technology reached a TRL 9
Operational Requirement	The maximum operating speed of HSST-100 is 100 kilometres per hour.
Test Results	For CHSST system, lateral guidance is accomplished passively; there is no active control of lateral position. Reported results show significant lateral oscillations during normal operation.

Guidance	Lateral wheels or traditional bogie guidance
Technologies Reviewed:	The system consists of the use of wheels to provide lateral centering and guidance. The system can be based on lateral wheels or traditional vertical bogie wheels.
Function:	The system has the guidance function. In some applications it provides also suspension at low speed (EDS systems).
Relationship to Other Components	Wheels can provide also traction/braking and be coupled with motors. The system interacts with the guideways and with the levitation and structure in order to transfer lateral loads. If the system integrates controlled elements, it is connected to the vehicle control system and to the vehicle electric system.
Development History and Status	Bogie guidance is currently adopted in the railway sector. Lateral wheel-based guidance is also adopted in monorail applications.
Relevant Environment	Railway standards or upgraded guideways
Comparison of the Relevant Environment and the Demonstrated Environment	Standard bogie already available. Lateral wheels adopted in monorail; Ironlev is currently testing dynamic conditions in a 2 km existing railway track.
Technology Readiness Level Determination	TRL 9 for standard bogie TRL 6 for Ironlev lateral wheels
Operational Requirement	One important feature is the lateral control on contact force that enables to increase the efficiency of the vehicle and reduces the wear of the guideway.

Guidance	Lateral wheels or traditional bogie guidance
Test Results	Test measurement of friction coefficient (Ironbox Srl)

Guidance	Air levitation technology-based guidance
Technologies Reviewed:	Because air levitation vehicles float above the ground, they need a guidance system to maintain their path. This can be achieved using physical guides (like walls or rails) or non-contact methods, such as magnetic or similar air-levitation technology-based guidance.
Function:	The air-levitation technology-based guidance is used to navigate the vehicle travelling along the guideway. It is also used to damp some lateral vehicle dynamics.
Relationship to Other Components	The air-levitation technology-based guidance usually gets air from the same centralised fan that also outputs air for air-levitation suspension.
Development History and Status	Summarize pertinent development activities that have occurred to date on the critical technology.
Relevant Environment	For tracked air levitation vehicles, like hovertrains, guidance systems include physical barriers or rails that ensure the vehicle remains on a predetermined path. For the guidance at switches, it is suggested to use the same structure that provides switches for maglev trains, such as steel bendable switches in Transprapid 08, but without the expensive electro or permanent magnets.
Comparison of the Relevant Environment and the Demonstrated Environment	Similar to the air-levitation suspension technology, by using the airpad vertically instead of horizontally.
Technology Readiness Level Determination	TRL 8: Full scaled prototype was developed as well as tested, already reaching one last step to commercial operation.
Operational Requirement	The air levitation technology-based guidance mainly relies on the air fender and its air pressure. In addition, it needs relatively flat surface for the air-blowing fender to resist on. Normal concrete slab track is suitable as tested in earlier projects, such as Aerotrain in France.
Test Results	The former project report as well as published papers have already proved the air levitation technology-based guidance, which can be found in the following references (Bailey, 1993; Ferreira and Stephan, 2019).

5.3.4.1.4 Braking

Braking	Linear motor
Technologies Reviewed:	In the Maglev trains, the traction motors must provide not only propulsion but also braking forces by direct electromagnetic interaction with the rails. This section covers both Linear Induction Motors and Linear Synchronous Motors and is closely related to the propulsion technology. To reduce the speed and stop rail vehicles with a magnetic suspension, the linear traction motors can operate as eddy current principle of the brakes. The Linear Induction Motor (flat and U shaped) can brake the vehicle using two modes, by regenerating energy in hyper-synchrone mode, or by DC current injection, which is the safety mode.
Function:	Linear motors are used for both traction and braking. The linear motor operates to propel the train forward, and when it is necessary to brake the train, the linear motor acts in reverse. This reversing of the linear motor converts the energy of the train into electrical energy which can be fed back into the electrical network. Linear motors can be used as service braking and for normal emergency braking and severe emergency braking, and also for regenerative braking.
Relationship to Other Components	The system is directly related with the propulsion system and also with the train control system.
Development History and Status	Since the beginning, the majority of the maglev systems use linear motors for propulsion and braking. For example, the Transrapid maglev system uses a synchronous long stator linear motor for both propulsion and braking. CHSST uses LIM for propulsion and service braking. The electric service brakes themselves operate in one of two modes dependent upon vehicle speed. The first mode is the regenerative mode, which normally operates at the higher vehicle speeds and the second mode is the dynamic brake mode, which normally operates at the lower speeds. In the regenerative mode, the energy produced by the kinetic energy of the vehicle is converted into electrical energy and is transferred to the trolley rails and power supply for use by other electric loads. In the dynamic braking mode, energy is supplied by the power supply and trolley rail and is dissipated within the LIM, which operates in the plugging or reversed phase mode. In the ECOBEE, for electrical braking mode, the LIM is controlled to operate as an electric generator converting the vehicle's mechanical

Braking	Linear motor
	energy into electrical energy; and furthermore, in dynamic mode, energy is supplied by the power supply for the plugging phase mode.
Relevant Environment	Service braking: Linear motors are used for both traction and braking. For example, in the Transrapid, the primary brake is initiated by the central control system, which controls the long stator propulsion motor to reverse vehicle thrust. Electrical energy generated during vehicle braking is dissipated in load resistors at the substation. An eddy current braking system provides secondary braking using longitudinal vehicle magnets to induce eddy currents in the nonlaminated track guide rails. Normal emergency braking: Normal emergency braking will occur when the vehicle is required to stop unexpectedly because of an unexpected fault condition, but the fault condition is within design limits. For this mode the linear motor should be capable of providing at least 0.25 g reverse thrust and, when the aerodynamic and magnetic drag are added, the total deceleration will be on the order of 0.3g. Severe emergency braking: For severe and very rare events, such as an unexpected and major earthquake, braking rates more than 0.5 g may be desirable (but not acceptable for human on stand up position, or even unfastened). Conventional high-speed trains do not have the ability to brake this rapidly, so some system designs do not include fast braking as a feature. However, the use of an active guideway LSM offers "dynamic braking" as an option that should be carefully considered by system designers. With dynamic braking there are resistors connected across the motor winding so that the voltage generated by the moving vehicle creates current and hence power loss in these resistors. This induced current does not have to flow through the inverter or any power limiting component so very high braking forces are possible. The only limits on braking force are the resistance and inductance of the winding and the mechanical strength of the winding and guideway structural members. This mode can be made fail safe because it does not require active control or a source of power. The power resistors and winding must not overheat during the deceleration, but this is a one-time process so there is plenty of time for these components to cool down after the braking event. An LSM for an EMS system cannot achieve enough force for rapid braking, so other mechanisms must be used. In the case of TR07 there

Braking	Linear motor
	are eddy current brakes which induce currents in the solid steel guidance rails. These eddy current brakes are used for all deceleration greater than about 0.5 m/s2. High speed trains have also been fitted with eddy current brakes that induce currents in the rails, and this braking method can be very reliable and not dependent on a friction force. Concerns about rail overheating have impeded the application of rail eddy current brakes, but it has been proven to give faster stopping in all weather conditions.
Comparison of the Relevant Environment and the Demonstrated Environment	The Transrapid maglev system uses a synchronous long stator linear motor for both propulsion and braking. The Superconducting Maglev is equipped with a braking system capable of safely stopping a train traveling at 311mph. 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.
Technology Readiness Level Determination	Tests and trials have only been carried out and have achieved a TRL 9 Regarding linear motor installed on the railway track – prototype tests have been accomplished successfully, however still operational, interoperability and safety aspects are to be tested.
Operational Requirement	Linear motors require additional power supply on the vehicle or infrastructure side
Test Results	Several projects (Transrapid, Chuo Shinkansen, Ecobee maglev, Vancouver Skytrain) have proven the technology to be fully operational on separated tracks. Some references can be found in (de Oliveira et al., 2013; Deng et al., 2010; Thornton R D et al., 1993) CHSST braking performance was extensively tested and reported on in several sections of the report (Federal Transit Administration Team, 2002)

Braking	Electro-dynamic wheels (EDW)

Technologies Reviewed:	In an electro-dynamic wheel (EDW), a cylindrical PM Halbach array (typical design) is rotating to induce its field over a passive conducting surface. Then, eddy currents are generated inside the surface, and it opposes the field induced. Rolling the EDW in the opposite direction will reduce the vehicle speed, which can be used as braking.
Function:	The EDW can generate thrust forces, which makes acceleration as well as deceleration of the vehicle.
Relationship to Other Components	It can provide both levitation, propulsion and braking, when the wheels rolling in the different direction.
Development History and Status	One commercial activity developed the EDW solution with TRL 6-7.
Relevant Environment	Incorporating into the current maglev trains or replace the LIM with EDW.
Comparison of the Relevant Environment and the Demonstrated Environment	Currently, the scaled model and numerical model were build based on which the EDW design was validated. One application has been identified for port freight transportation. Further studies are still needed at full-scale model test, as well as more studies on numerical modelling of EDW dynamic responses on high-speed railway.
Technology Readiness Level Determination	TRL 6-7: laboratory test on scaled model and numerical simulations were performed. One application has been identified for port freight transportation in USA.
Operational Requirement	Relatively lower requirement and track construction costs than LIM, which needs conductive surface, such as aluminium plate.
Test Results	From TUD-owned patent, as well as several published papers (Hijlkema, 2019), (Shi et al., 2023), (Bird and Lipo, 2006), (Noland, 2021), (LEVX, 2017)

5.3.4.1.5 Vehicle control system

Vehicle control system	On board control system
Technologies Reviewed:	The on-board control system is also known as TCMS. The Train Control Management System (TCMS) is the centralized supervision system for all train subsystems; doors, lights, air conditioning, brakes, communication with the outside, batteries, water tanks and much more. In the case of the maglev system, it will have to interact with the levitation control module. This supervision is not only made up of computing units but also of communication systems that interconnect these elements. It includes traditional communication channels such as MVB (Multifunctional Vehicle Bus) and CAN but also Ethernet networks with new generation protocols. Added to this set are many input / output devices and gateways, i.e. signal switching systems. The TCMS is therefore the brain and nervous system of the train and must be carefully designed, simulated and tested. The purpose of the TCMS is to operate the train efficiently, with the safety of passengers as the highest priority. The TCMS is usually interfaced with the main modules on board and moreover Air Gap sensors, speed sensors and position sensors for continuous controlling and monitoring of the air gaps and coil excitations.
Function:	The TCMS, having the task of controlling the entire train, has various interfaces to manage. Towards the signalling system ETCS must manage the requests for voltage change and movement of the pantographs, of the service brake by interacting with the brake control unit, the electric traction, the consent of the opening of the doors, the integrity of the train, the composition of the train, traction management by interacting with the control unit. The TCMS is involved in joining and splitting of the train, when in pick hours are needed more vehicles. Moreover, reliable and safe operation of maglev systems requires continuous controlling and monitoring of the air gaps and coil excitations. Various gap sensors, speed sensors and position sensors perform this task. Generally, in such systems, regulating the levitation and guidance forces maintains the position of the vehicle steady with respect to the guideway. This helps in maintaining the air gap constant, which further helps in maintaining the ride comfort. Other than this, signals given by the accelerometers and position sensors control the excitation of the linear motor. This further controls the speed, acceleration, deceleration and braking of the vehicle. Sensors acknowledge the changes in the vehicle dynamics due to the external factors and pass the signal to a control and logic unit (CLU).

Vehicle control system	On board control system
	This unit further compares the generated signal with the commanded value and transmits the error to the power-conditioning unit (PCU). The PCU then generates the supply of appropriate magnitude and frequency that further controls the winding excitations of the linear motors.
Relationship to Other Components	Modern TCMS have "standard" interfaces based on connections such as MVB (Multifunctional Vehicle Bus) and CAN but also Ethernet networks with new generation protocols. These links are subject to standardization. Furthermore, we are also moving towards the standardization of information exchange with systems installed wayside.
Development History and Status	Used in all the existing systems since the beginning. Pure maglev systems use their own TCMS
Relevant Environment	Usually the TCMS complies with the standards for the installation of on-board train systems. These standards also regulate the map of frequencies with which the system must comply. By introducing the maglev system, it is necessary to verify that these maps are always valid.
Comparison of the Relevant Environment and the Demonstrated Environment	No relevant differences
Technology Readiness Level Determination	System in operation TRL 9
Operational Requirement	It's necessary compatibility with TCMS for interoperability
Test Results	Some references can be found in (Kaye R J and Masada E, 2004; Otkun and Sefa Akpınar, 2017; Schultz et al., 2005; Shanghai Maglev Development Co.Ltd, 2005)

5.3.4.1.6 Electrical system

Electrical system	Current contact shoe and power rail
Technologies Reviewed:	For low-speed maglev systems, the energy transfer is very similar to metro systems, where a powered conductor (third rail) is built along the track. Since the maglev trains are lifted up and therefore lack contact with the rails, there is an additional rail for returning current. Therefore, two conducting rails are installed below the guideway. The current collectors are extended from the carbody to reach the two conducting rails on both sides. Due to limited dynamic performance, the system can only work within a low-speed range. This technology refers to both vehicle and infrastructure subsystems.
Function:	Providing electric power supply from the infrastructure to the vehicle, necessary for levitation, guidance, propulsion, onboard electrical equipment, battery recharging, etc.
Relationship to Other Components	The system is related to track sectioning, onboard batteries, Magnetic levitation and guidance, onboard auxiliary systems and traction power.
Development History and Status	Very established technology Latest research focuses on third rail materials for systems with big temperature changes, on efficient pad-rail contacts for improved efficiency, and alternative pad materials.
Relevant Environment	Low operational speed maglev systems. Limitations due to speed and voltage.
Comparison of the Relevant Environment and the Demonstrated Environment	For usage on conventional railway tracks (MDS), third rail would be necessary. If the vehicle does not have wheel-rail contact, a secondary cable or rail should be necessary for the returning current. Alternatively, a contact-shoe type system acting on the conventional rails.
Technology Readiness Level Determination	TRL 9 – widely used in conventional urban railway systems
Operational Requirement	Third rails are cheaper electrification options but are also less safe, as they are at track level and thus more accessible to people.
Test Results	Used in real life operation. Some references ca be found in (Han and Kim, 2016; Liu Z et al., 2022)

Electrical system	Pantograph and Overhead Catenary
Technologies Reviewed:	The catenary is a special power supply line built along the track to provide electrical energy for trains, as it is mainly composed of contact wires. The pantograph is the electrical equipment for any trains to obtain electrical energy from catenary, which is installed on the roof of the train. This technology refers to both vehicle and infrastructure subsystems.
Function:	Providing electric power supply from the infrastructure to the vehicle, necessary for levitation, guidance, propulsion, onboard electrical equipment, battery recharging, etc.
Relationship to Other Components	The system is related to track sectioning, onboard batteries, Magnetic levitation and guidance, onboard auxiliary systems and traction power.
Development History and Status	Very established technology. Used for high speed and high voltage AC system. Latest research and development involve dynamics at high-speeds, reduced wear and catenary breaks, better energy transfer efficiencies, and airless (non-pneumatic) pantograph mechatronics.
Relevant Environment	Conventional railway of virtually any type. Flexible cable catenary is widely used, but rigid overhead rail, aka. rigid catenary, is commonly used in tunnel sections as it is a more compact system.
Comparison of the Relevant Environment and the Demonstrated Environment	For usage on conventional railway tracks (MDS), catenary would be necessary. If the vehicle does not have wheel-rail contact, a secondary cable or rail should be necessary for the returning current. Alternatively, a contact-shoe type system acting on the conventional rails. Limitations in very high-speed operation.
Technology Readiness Level Determination	TRL 9 – widely used in conventional railways
Operational Requirement	Catenary systems can have a relatively high cost and are typically difficult to fit in tunnels where rigid catenaries are needed. In operation they can be affected by strong winds, and a cable break is more likely than failure of other components, completely blocking the system until repaired.
Test Results	Used in real life operation. Some references ca be found in (Han and Kim, 2016; Liu Z et al., 2022)

Electrical system	Wireless power transfer
Technologies Reviewed:	At high speeds, the maglev trains can no longer obtain power from the infrastructure by using mechanical contact. Therefore, high-speed maglev trains use non-contact methods to deliver the power to the vehicle from the infrastructure. A linear generator is therefore used, where the generator coils are onboard and induced by the change of magnetic flux from the guideway to provide electricity. German Transrapid train: linear generator integrated into the levitation electromagnets. Japanese MLX maglev system: linear generators are mounted on the two sides with the superconducting electromagnets. This technology refers to both vehicle and infrastructure subsystems.
Function:	Providing electric power supply from the infrastructure to the vehicle, necessary for levitation, guidance, propulsion, onboard electrical equipment, battery recharging, etc.
Relationship to Other Components	The system is related to track sectioning, onboard batteries, Magnetic levitation and guidance, onboard auxiliary systems and traction power.
Development History and Status	The German Transrapid train employs the use of a linear generator that is integrated into the levitation electromagnets. The linear generator derives power from the travelling electromagnetic field when the vehicle is moving. The frequency of the generator windings is six times higher than the motor synchronous frequency. The linear generator is mechanically contact-free, which is very positive for high-speed operation. For the Japanese MLX maglev system, beside a gas turbine generator, two linear generators are mounted on the two sides. On-board coils distributed along the vehicle form the coils of the distributed type of generator. These coils are fitted with on-board superconducting coils. In the concentrated type, generator coils are concentrated in the nose and tail part of the vehicle. Superconducting coils and generator coils form the upper and lower part of the on-board assembly, respectively.
Relevant Environment	High-speed maglev systems with specific track configuration.
Comparison of the Relevant Environment and the Demonstrated Environment	For usage on conventional railway tracks (MDS), it would be necessary to install an inductive plate in the infrastructure
Technology Readiness Level Determination	TRL 9 – used in operation in high-speed maglev systems

Electrical system	Wireless power transfer
Operational Requirement	These systems require a certain speed for generating electric energy at the vehicle side and are thus not able to transfer energy at standstill.
Test Results	Used in real life operation. Some references ca be found in (Han and Kim, 2016; Liu Z et al., 2022)

Electrical system	Battery onboard
Technologies Reviewed:	High current battery: Changsha Maglev Battery packs: Chuo Shinkansen, M-bahn, Sengenthal, Shanghai Maglev, SwissMetro, Transrapid 09
Function:	Store electrical energy for ensuring continuous and consistent power supply to every onboard electrical system.
Relationship to Other Components	The system is related to: • Energy transfer systems (pantograph, shoe, contactless) • Magnetic levitation and guidance • Onboard auxiliary systems • Traction power
Development History and Status	Established technology with quick development due to the electrification automotive industry. The most common batteries are Lithium-based (Lithium-Ion, LFP, lithium-iron-phosphate; LMO, lithium-manganese-oxide; LTO, lithium-titanate). Latest trends include modular packs including battery cells, charge and discharge control systems, monitoring and management systems for cell temperature, voltage, or extreme charges or discharges.
Relevant Environment	Onboard storage, so it should be light and compact. Safety considerations regarding overheating and fires.
Comparison of the Relevant Environment and the Demonstrated Environment	Widely used in conventional rail vehicles and many other systems.
Technology Readiness Level Determination	TRL 9 – used in operation in both maglev systems and conventional railway systems

Electrical system	Battery onboard
Operational Requirement	There are numerous existing norms, regulations, technical committees, etc. regarding battery-electric vehicles. E.g. ISO design standards for Li-Ion batteries, for tests, etc. Common operational issues with batteries are the influence of environmental temperatures on the efficiencies in different operational points and on self-discharge.
Test Results	Used in real life operation. ISO and other national standards for testing.

5.3.4.1.7 Monitoring & safety

Monitoring & Safety	Signalling, and Infrastructure and Vehicle Management
Technologies Reviewed:	They are systems that have the task of verifying the behaviour of the railway system in real time. These are divided into two areas of intervention that cooperate with each other. These are the trackside system and the On-Board system. In this area, diagnostic systems cooperate which have the task of verifying on the one hand the state of the infrastructure (tracks, fuel system for vehicles, switches, level crossings, stations) and on the other the state of the vehicle (propulsion, condition of the braking system, trolleys, wagons, etc). The signalling systems (both national ones and CBTC and ERTMS/ETCS) use the information coming from the diagnostic systems indicated above to harmonize traffic and choose the safest solution for the transport of people and goods.
Function:	For the Trackside: • Track status monitoring • Monitoring of catenary status • Power system status monitoring • Exchange status monitoring • Level crossing status monitoring • Monitoring of platform status in the station For the On Board: • Traction system status monitoring • Braking system monitoring • Auxiliary system monitoring

Monitoring & Safety	Signalling, and Infrastructure and Vehicle Management
	• Boogie status monitoring • Monitoring pantograph status • Wagon status monitoring Signalling systems: • Safe distancing of trains • Safe management of train routes • Management of degraded conditions • Intervention for time-table management
Relationship to Other Components	There is a hierarchy in managing these systems. The monitoring and diagnostic part works in parallel with the signalling part. All the information flows into the TMS Train Management System (or equivalent) which defines the train routes and which routes are best based on the monitoring and diagnostic data received. The signalling part then takes care of taking charge of this information and leading the vehicles safely to their destination.
Development History and Status	There are different states of automation in the process indicated above, also due to the complexity of the line to be managed. In the case of metropolitan lines that have no intersection and interoperability with others, and are often inaccessible by people and vehicles, except in stations, the automation of the function has reached a higher level. For railway lines where the complexity increases exponentially both due to the number of intersections of the lines and the possible access to the lines by other vehicles (cars, trucks, etc.), this management becomes very complicated and currently there are few examples of extensive automation.
Relevant Environment	The context in which the solution to be tested will be developed is the railway sector which is subject to many constraints related to interoperability between the various vehicles circulating on the line and the systems installed trackside. One of the most relevant aspects in the railway sector is the demonstration of non-intrusiveness of the new system adopted towards existing systems. Therefore, before introducing a system into the field it is necessary to carry out a series of preliminary checks to ensure its compatibility. This necessary but not sufficient phase is then followed by field tests to

Monitoring & Safety	Signalling, and Infrastructure and Vehicle Management
	verify its actual compatibility and interoperability. What must be demonstrated is that the behaviour of the new systems does not alter the functioning of the existing ones, and that there are no side effects on the infrastructure used that could jeopardize its functioning or premature deterioration of the same.
Comparison of the Relevant Environment and the Demonstrated Environment	By defining the line that will host the new system, comparisons can be made with the previous configuration.
Technology Readiness Level Determination	TRL 9 – used in operation in both maglev systems and conventional railway systems
Operational Requirement	The new technology must comply with the TSI in force as well as with the national rules applied in the country where the introduction will take place.
Test Results	All tests carried out in the past for analogue applications on railway lines must be collected.

5.3.4.2 TRA Report for MDS Infrastructure

Guideway	Dedicated separate infrastructure
Technologies Reviewed:	Structure that supports both guidance and levitation systems
Function:	Maglev is a system in which the vehicle runs levitated from the guideway by using electromagnetic forces between superconducting magnets on board the vehicle and coils on the ground. The levitation coils are installed on the sidewalls of the guideway. The guideway is the structure that maglev vehicles move over it and are supported and guided by it. Its main roles are to direct the movement of the vehicle, to support the vehicle load, and to transfer the load to the ground. It is the function of the guideway structure to endure applied loads from the vehicle and transfer them to the foundations. Guideway can be mounted either at-grade or elevated on columns and consists of individual steel or concrete beams. Elevated guideways occupy the least amount of land on the ground. Moreover, with such systems there is guarantee of meeting no obstacle along the route.
Relationship to Other	It supports the propulsion, suspension and guidance system. It is related to the vehicle and all its main sub-systems, as well as to the

Guideway	Dedicated separate infrastructure
Components	energy and train control system.
Development History and Status	Most of the existing maglev systems use at this moment separate infrastructure.
Relevant Environment	The infrastructure is the main cost component and has a direct impact on the spatial integration of the electromechanical components in order to decrease the total investment cost. Because the air gap is small between the vehicle and the infrastructure, the structural misalignment in the construction and the structural deformation during operation should be kept as small as possible to maintain the clearance. Guideway provides guidance for the movement of the vehicle, to support the vehicle load, and to transfer the load to the ground. Guideway consists of superstructures and substructures. A guideway consists of a beam (girder) and two levitation (guidance) rails. Guideways can be constructed at grade (ground-level) or elevated including columns with concrete, steel, or hybrid beams. Maglev elevated guideways minimize land occupation and prevent collision with other forms of traffic at-grade intersections. Guideways are designed and constructed as single or double tracks. Guideways can be U-shaped, I-shaped, T-shaped, Box, Truss, and so forth. A majority of cross-sections of guideway girders are also U-shaped.
Comparison of the Relevant Environment and the Demonstrated Environment	Each system has its particular implications. For example: For the Swissmetro, the tunnel structure naturally imposes to have horizontal vehicle arms supporting the levitation, the guidance inductors and the motor on board parts. Simultaneously, the active forces (levitation, guidance, propulsion) act very closely to the gravity horizontal centreline. The mechanical vehicle structure leads to a frame similar to an airplane frame, light and flexible, of 3 m inside diameter. Furthermore, the small tunnel inside diameter and the total length of the vehicle requests a deformation in the axial direction in order to guarantee the guiding air gap in the curves. Flexible joints assure this function. For the Transrapid, a concrete V block allowing a rotation on its bottom summit defines the vehicle spatial position. This permits to consider curves with an inclined guide way without changing the concrete columns supporting the V block. This optimization leads to vehicle arms going under knee the concrete V block. As a result, the total vehicle height increases to 4.16 m. Advantageously, the V block structure limits the overall cross section of the complete concrete structure thus permitting to consider the Transrapid at different ground level heights (O to 17.7 m height). New V block structure

Guideway	Dedicated separate infrastructure
	considers steel guide way instead of concrete in order to decrease total cost. MLX is based on a U concrete shape, which supports the lateral levitation, guidance and propulsion stator windings, offers a compromise for both uses: essentially at ground level and underground compatibility. The Inductrack system is based on a concrete U shape, each vertical branch of the U contains the reactive coils of the super conducting magnets (Halbach types), assuring both levitation and guidance reactive surfaces. These infrastructure differences emphasize the problem of the vehicle configuration if the MAGLEV has to perform simultaneously in underground tunnels and on ground conditions depending on the market requests.
Technology Readiness Level Determination	There are a lot of facilities in operation, so TRL 9 is reached
Operational Requirement	For low-speed maglev systems, both the operational speed is low and the centrifugal force in curves is small. The EMS is self-centred, which means any lateral displacement between the magnetic rail and the electromagnet leads to a restoring force to pull the vehicle back to the centre position. The magnetic field can be adjusted to strengthen the restoring force by detecting the air gap. Therefore, there is no need to have a specific guidance system onboard or in the infrastructure. However, for high-speed maglev system, the operational speed, centrifugal force and dynamic load are very high. In addition, the air gap between the vehicle and the infrastructure for the EMS system is small, so the restoring force is not strong and fast enough to centre the vehicle back to its original position. There are also sensors to detect the air gap in the lateral direction to control the electric current through the electromagnets.
Test Results	The vast majority of existing and described maglev systems include test results.

Guideway	Existing or upgraded conventional railway infrastructure
Technologies Reviewed:	Railway infrastructure upgraded with the linear synchronous motor installed between the rails and the levitation modules at the sleepers' edges, if needed. Suitable for operation of hybrid MDS and retrofitted vehicles with MDS technologies i.a. subsequently MagRail and MagRail Booster
Function:	The guideway is used for MDS vehicles movement. The main function of the guideway is enabling safe acceleration and deceleration of the vehicle (linear motor stator mounted within the guideway), also lateral and vertical guidance of those.
Relationship to Other Components	The guideway is closely connected to the propulsion component on the infrastructure side – it may be a stator of the linear motor. Similarly, the mechanical connection is between guideway and levitation and guidance components. Last part are the trackside CCS devices and switch point machines that may be installed within the guideway.
Development History and Status	The interoperable MDS guideway has been described a few times in the past, however no tests have been performed before Nevomo test tracks have been built. First test of the MagRail Booster guideway in scale (1000mm railway gauge) has been conducted in 2020. Then, once the Nowa Sarzyna Test Track has been opened for tests in 2023, the guideway was under several tests.
Relevant Environment	The relevant environment includes open or closed railway network with separated MDS segments.
Comparison of the Relevant Environment and the Demonstrated Environment	The demonstrated guideway was a straight 720 meters long railway track on concrete sleepers and S49 rails without the curves, point machines, trackside CCS devices. These components are missing in relation to the operational environment.
Technology Readiness Level Determination	TRL 6 – demonstrated guideway works, however still some critical components are missing for operational tests.
Operational Requirement	The same requirements as railway tracks.
Test Results	The guideway has been tested successfully in 2023. Vehicles were safety accelerated and decelerated, guidance system works well.

Switches	Dedicated separate infrastructure
Technologies Reviewed:	Maglev systems use particular solutions. Two possibilities are described below.

Switches	Dedicated separate infrastructure
Function:	As an example of high-speed maglevs, the Transrapid vehicle changes tracks using bending switches or transfer tables. Bending switches are used in mainline and off-line situations for smooth transition between tracks. They consist of welded steel, multi-span, bending beams with electro-mechanical, rack and pinion drive units mounted on every second support of the bending switch. Locking mechanisms ensure the positioning of the steel beam. Both low-speed and high-speed switches are available for use on the Transrapid system. Low speed Maglev systems use other different systems. For example Maglev Changsha Airport Express Line, the switch is a kind of 3-girder-switch. Each girder has a fixed rotating center.
Relationship to Other Components	The system is related to vehicle, suspension, guidance and propulsion
Development History and Status	Maglev systems use particular solutions.
Relevant Environment	Dedicated maglev infrastructure
Comparison of the Relevant Environment and the Demonstrated Environment	No significant differences
Technology Readiness Level Determination	TRL 9
Operational Requirement	For the Transrapid, the low-speed switch, typically used near stations and maintenance facilities, has a total beam weight of 300 tons and a total beam length of 78 m. In the turnout position, speeds are restricted to 100 km/h, while full operating speed is allowed in the straight position. The high-speed switch, typically used on a mainline portion of a system, has a weight of 600 tons and a total beam length of 148 m. It allows a turnout speed of 200 km/h and permits full speed in the straight position. Bending switches are available in both two-way (switching between two tracks) and three-way (switching between three tracks) versions. The bending switches are designed for a service life of approximately a million cycles, or twenty to thirty years of typical service. Transfer tables are used in off-line situations (e.g. maintenance areas) for compact access of multiple tracks. They consist of welded steel, multi-span, straight beams with electro-mechanical, rack and pinion drive units mounted on every second support of the transfer

Switches	Dedicated separate infrastructure
	table. Locking mechanisms ensure the positioning of the steel beam. With the vehicle resting on top, the transfer table shifts laterally to access parallel segments of guideway.
Test Results	Some references cab be seen in (Fontana R and Flaherty A J, 1993; The Monorail Society, n.d.; Yuan et al., 2018)

Switches	Existing or updated conventional railway infrastructure (Hybrid MDS)
Technologies Reviewed:	The technology reviewed is a system that enables to switch guideways from one track to another. It can be a standard railway system based on tapering rails and electromechanical systems that move laterally the points in two alternative positions or it can be a customised system for MDS upgrade.
Function:	The function is to change the guideway configuration of the rail track, enabling change from one track to another in order to change route direction or platform.
Relationship to Other Components	Switches are part of infrastructure. They are connected with the substructure, the guideways and the ballast. During operations, it is also in contact with vehicle wheels. In MDS upgraded switches, the system could interact with stator in case of linear motor and magnetic levitation systems.
Development History and Status	Standard railway switches are a consolidated and widely adopted system. In case of MDS upgrade, some examples of TRL-9 systems are railway systems upgraded with LIM. For LSM integration, the systems are at a conceptual level on TRL2.
Relevant Environment	Railway environment – infrastructure part
Comparison of the Relevant Environment and the Demonstrated Environment	For standard switches integrated with LIM, the demonstrated environment is similar to the relevant one. The main difference could be another CCS system that should be taken into account while implementing such a switch in, e.g., open railway network. Regarding LSM switches, no demonstrated environment has been established yet since the component is at the conceptual phase.
Technology Readiness Level Determination	TRL-9 for standard railway switches. TRL-9 for LIM integration TRL-2 for LSM integration.

Switches	Existing or updated conventional railway infrastructure (Hybrid MDS)
Operational Requirement	Switches are subject to loads in vertical and lateral directions (guidance loads). They also shall guarantee propulsion and braking operations during switch crossing. In case of MDS upgraded systems, they shall interact with levitation systems by providing support and/or guidance.
Test Results	Standard switches widely adopted. Other examples: LIM Vancouver SkyTrain, Japanese lines. For LSM the upgraded railway switches are currently in the research phase by Nevomo.

Propulsion – infrastructure part	Specific infrastructure
Technologies Reviewed:	Propulsion system included in the infrastructure side, corresponding to the linear motors. This section covers stator with multi-phase winding, long stator synchronous linear motor, LIM stator (armature) and U-LIM (U shape armature)
Function:	For the Linear Induction Motor (LIM), there are two types. For the short primary type (SP) stator coils are on board and conducting sheets are on the guideway. And for the Long primary type (LP), stator coils are on the guideway and conducting sheets are on board as shown. For the Linear Synchronous Motor (LSM), there are also two types, equivalent to the LIM (LP and SP type).
Relationship to Other Components	The system is related to the vehicle subsystem and with the energy and control systems
Development History and Status	Most of the existing systems have developed technology in this field: Chuo Shinkansen, Transrapid high-speed Maglev system, Yokohama subway, Osaka subway, Sendai subway, Skytrain, Toei Oedo subway, Vancouver Skytrain.
Relevant Environment	The LIM-based propulsion systems are a mature and extensively accepted dominating candidate for maglev transit systems. High-speed Maglev trains prefer the LSM because it has a higher efficiency and power factor than the LIM. The economic efficiency of the electric power consumption is very important for high-speed operation.

Propulsion – infrastructure part	Specific infrastructure
Comparison of the Relevant Environment and the Demonstrated Environment	Railway-compatible prototype linear motor does not meet all the regulatory requirements (environmental conditions, EMC, etc.). Moreover, in the Demonstrated Environment no switches and road-rail crossings integration has been tested.
Technology Readiness Level Determination	Linear motors in general reached TRL 9
Operational Requirement	Linear motors require additional power supply on the vehicle or infrastructure side. The LIM is generally not preferred as compared to the LSM for speeds more than 300 km/h, because of its lower efficiency, higher eddy current losses, lower propulsion force density and lower power factor.
Test Results	Some results can be found in (Prasad et al., 2019) Test results are also available for Chuo Shinkansen, Transrapid high-speed Maglev system, Yokohama subway, Osaka subway, Sendai subway, Skytrain, Toei Oedo subway, Vancouver Skytrain.

Propulsion – infrastructure part	Existing or upgraded conventional railway infrastructure (Hybrid MDS)
Technologies Reviewed:	Linear Synchronous Motor (LSM) in a synchronous electric machine usually consisting of stator (active part) – a 3-phase winding installed on the track and the mover installed on the vehicle.
Function:	The primary function of the LSM is to convert electrical energy into mechanical motion along a track. The term "synchronous" indicates that the motion of the motor is synchronized with the frequency of the applied electrical power. In an LSM, the mover moves in sync with the changing magnetic fields of the stator, maximizing efficiency.

Propulsion – infrastructure part	Existing or upgraded conventional railway infrastructure (Hybrid MDS)
Relationship to Other Components	The vehicle part of the LSM is called the mover, consisting of a set of NdFeB magnets arranged in the Halbach array. The direct relationships and interfaces with other components include internal ones like vehicle structure as it is mounted directly there, and onboard sensors that monitor the gap, magnetic field, etc., and external ones e.g., the infrastructure part of the linear motor. However, it is crucial to note that if the vehicle operates on the railway network also the relationships to the railway subsystems and constraints should be considered, e.g., structure gauge and EMC.
Development History and Status	The first tests of the permanent magnet linear synchronous motor were performed in 2019 when the lab-scale demonstrator proven that the Nevomo technology concept was working. The second iteration of the linear motor was done in 2021. for the first time in the final configuration with the railway tracks integration and full linear motor segmentation has been tested successfully. Currently, the third - full-scale - system has been built and the tests are ongoing. The linear motor demonstrator can accelerate the vehicles up to 130 km/h.
Relevant Environment	The relevant environment for the railway-compatible MDS linear motors is a railway network or railway sidings.
Comparison of the Relevant Environment and the Demonstrated Environment	Railway-compatible prototype LSM does not meet all the regulatory requirements (environmental conditions, EMC, etc.). Moreover, in the Demonstrated Environment, no switches and road-rail crossings integration has been tested.
Technology Readiness Level Determination	The linear motors interoperable with the railway system are on TRL 6-7.
Operational Requirement	Linear synchronous motors require an additional power supply on infrastructure side.
Test Results	Regarding linear motor installed on the railway track – prototype tests have been accomplished successfully, however still operational, interoperability and safety aspects are to be tested.

Propulsion – infrastructure part	U-LIM (U shape armature)
Technologies Reviewed:	Propulsion system included in the infrastructure side, corresponding to the linear induction motors. This section covers short stator with multi-phase winding using U shaped armature. The U-LIM acronym is for U shaped Linear Induction Motor.
Function:	For this short primary stator, coils are on board and conducting sheets are on the guideway. The magnetic field is confined withing the steel magnetic part armature, so the vertical sides of the U-shaped armature can be used as magnetic guidance system (EMS guidance type).
Relationship to Other Components	The system is related to the vehicle subsystem and with the energy and control systems. The U-LIM is powered on several section with each one connected to an independent traction inverter.
Development History and Status	U-LIM original technology and the flat LIM has been compared in the research frame of the French Aérotrain program. The first patent was registered in 1979 by the engineer Jean Guimbal. This technology is now up graded with the latest innovative materials and optimized with the most compact power invertor.
Relevant Environment	The U-LIM based propulsion systems are a mature used on few industrial applications. U-LIM characteristics has a much higher efficiency and power factor compared to the flat LIM. The U-LIM ratio thrust/weight is the highest and offer a very compact subsystem which is a strong advantage for the vehicle design.
Comparison of the Relevant Environment and the Demonstrated Environment	U-LIM can meet the regulatory railway requirements (gauge, environmental conditions, EMC, etc.) but validation tests are still to be performed on real railway tracks. Switch and railroad crossing can be satisfied by locally removing the U-shaped armature.
Technology Readiness Level Determination	U shaped Linear induction motors reached TRL9 in industrial application and reach TRL8 on railway track as it has not been tested yet on railway environment.
Operational Requirement	U-LIM require additional power supply on the vehicle (or infrastructure side in specific application). The U-LIM is generally preferred compared to the LSM for speeds up to than 300 km/h, because of its highest efficiency, higher power factor and mainly for its lower cost due to the simplest passive track. This motor offers features such as simplicity, reliability, robustness,

Propulsion – infrastructure part	U-LIM (U shape armature)
	low maintenance.
Test Results	Some results can be found in (Fintescu and Pascal, 1986). Currently the U-LIM79 still propelled the Grenoble wheel test bench (Ø13m).

Substructure	Structural components
Technologies Reviewed:	The rails are fixed on wooden or concrete sleepers, placed on ballast resting on a reinforced foundation to support the standardized ground load gauge (EU STI). MAGLEVs guideways are either tunnel or elevated placed on pillars, made of pre-stressed concrete profile.
Function:	The guideways sizing satisfies the vertical forces (22.5t at the axle) and lateral forces (radiuses of curvature of the track, lateral winds, etc.). MAGLEVs require a specific design due to the particular constraints of very high-speed including propulsion and guidance technologies, which are integrated into the track.
Relationship to Other Components	The integration of the wound stator of the synchronous linear motor into the track imposes a specific restrictive structure, which might satisfy the railway gauge for MDS but not compatible with the conventional MAGLEVs system (Transrapid, LO Shinkansen). Asynchronous linear motors offer possible integration because they simply consist of a flat or U-shaped steel/copper or steel/aluminum lamination fixed in the centre of the track. This traction technology remains compatible with the existing railway gauge and switches, for the LIM armature can be interrupted locally. The U-shaped armature provides the dual function of traction and magnetic guidance on the vertical sides of the U.
Development History and Status	For around 200 years the structure has undergone numerous improvements, the ballast around 1850, more recently the concrete track. Specific tracks for Aerotrain and Maglev systems date from the 1960s. Linear motor metro rail tracks were proposed in the 1990s. Today, the concept of MDS track is now in its design period and needs to be demonstrated in its functional version .

Substructure	Structural components
Relevant Environment	The structure of the MDS tracks must be interoperable with railway rolling stock, it is then necessary to respect the standardized gauge by the TSIs concerning rolling stock and the track.
Comparison of the Relevant Environment and the Demonstrated Environment	The MDS track structure must be interoperable with railway rolling stock, it is then necessary to respect the standardized gauge by the TSIs concerning rolling stock and the track. Given climate change, the railway track design temperature limit of 45°C may be exceeded in the coming years; the superstructure of the MDS system will have to be designed to adapt to the geometric variations generated. These new thermo-mechanical constraints are not yet integrated into demonstration projects.
Technology Readiness Level Determination	Maglev substructure is working since more than 20 years: TRL 9. Linear induction railway applications are existing in operation since about 30 years: TRL9.
Operational Requirement	MDS substructure will require a very accuracy civil engineering building to satisfy the airgap geometry of the linear motor and of the guidance technology.
Test Results	LSM technology using electrodynamic sustentation and magnetic guidance are tested on full scale model on short distance railway track. Flat LIM technology based on rail/wheel contact for sustentation and guidance are working for 30 years in Canada, Japan and China. U-LIM technology using rail/wheel contact was used on specific applications since few years.

5.3.4.3 TRA Report for Energy System

Power supply	Infrastructure power supply
Technologies Reviewed:	Power supply covers the components between the high voltage (110KV) AC public power grid, and the electric energy system at track or catenary level. This might include step-down transformers, rectifiers, step-ups, cables, switch stations, and more. For classic railways, some signal conditioning is done between pantograph and traction system. For Maglev or MDS systems this is done at infrastructure level, as stator of the traction linear motor is built into the tracks. Alternative names for classic railway electrical substations are traction substation, traction current converter plant, rectifier station or traction power substation (TPSS). There are many types of substation types used in existing railway systems depending on the provision from the network and the needs from the railway system, e.g. converting three-phase 50 or 60 Hz AC for feeding single-phase AC systems at a lower frequency; or rectifying AC from the network into DC for traction equipment. In Europe the standard railway voltages are 1500V & 3000V DC, 25kV-50Hz, and 15kV-16,7Hz. High speed train (300km/h) use 2x25kV-50Hz. For MDS linear motor systems, the 110KV public power grid is stepped down to 20KV and 1.5KV via step-down transformer, then converted into direct current via rectifier, converted back to variable frequency AC current between 0 and 300Hz via rectifier. After step-up, the current is fed to long stator winding on the guideway via guideway cables and switch stations.
Function:	The power supply system includes substations, trackside feeder cables, switch stations and other power supply equipment. Power supply system feeds the power to the trackside long stator with 3 phase AC power required for the train propulsion according to the working conditions. Railway electrical substations convert electric power from the electrical grid for public utility service to an appropriate one that rail vehicles can use; usually appropriate type of current, voltage, and frequency.

Power supply	Infrastructure power supply
Relationship to Other Components	Coupled to the public power grid (110 kV power supply). Coupled to the infrastructure side of the electric traction system (track stator for MDS systems, catenary or third rail for classic systems) For MDS systems with linear motors, coupled to the system's sensing and communication system for adapting the required output power and frequency at the stator.
Development History and Status	Already in use. AC and DC power supply is used in conventional railways depending on the country, with varying levels of voltage and/or frequency. DC power supply is used in Low-speed maglev systems too. High-speed maglev systems use Variable Voltage Variable Frequency energy conversion (Transrapid, Chuo Shinkansen - TRL9), Nevomo (TRL 7). For Transrapid, at the outputs of the substation (high voltage switching equipment with step-down transformers), the inverters energize the stator sectors of the motor. The corresponding AC bus, which sees the same frequency (0 - 215 Hz, for 400 km/h) than the motor synchronous frequency, assures the transfer of energy along the track. Sectors with switches permit to decrease the energized motor section length. There are only inverters at the substation, none along the track. A disadvantage is the line effect of the AC high voltage cable bus, which limits the distance between two consecutive substations. JR-Maglev (MLX) presents a very similar strategy to Transrapid power supply approach. In the power supply of the Swissmetro, the 125 kV, 50 Hz corresponds to the surface grid. The substation (125 kV/6 kV) is in an underground substation. After the three level rectifier, a DC bus (-5, 0 , 5 kV) supplies the different motor stators. The DC bus permits to transfer energy on long distance with low Joule losses. For the Japan HSST and Korean Incheon Maglev, both systems are supplied by a DC catenary of 1500 V. The DC bus is usually put on one side of the track.
Relevant Environment	The rectification equipment, conversion equipment and motor stators etc. of the maglev system are all installed on the ground. No strict requirements for the volume, weight, and anti-vibration of the equipment are available. Technology is different depending on the maglev system.

Power supply	Infrastructure power supply
Comparison of the Relevant Environment and the Demonstrated Environment	Mature technology. There is no difference between the two environments.
Technology Readiness Level Determination	TRL 9; already in operation
Operational Requirement	The fed AC frequency and voltage are related to the working condition of the maglev trains (e.g., speed). No other special requirement. For a MDS, integration in the existing electrification system is needed. Numerous existing norms, regulations, technical committees, etc. regarding electric substations (European STIs regulation). A common challenging operational requirement is when power peaks are needed from the vehicle side that cannot be met by the electrical subsystem. For MDS systems this could occur when linear motors are used to provide extra power to freight vehicles going uphill.
Test Results	Mature technology; already in use. Some references can be found in (Cassat and Bourquin, 2011)

Sensing and communications	Components used to monitor and control the state of the energy system
Technologies Reviewed:	Remote sensing units monitor the whole operation of the system through an optical fibre cable-based signalling and monitoring system which sends signals to a semi-automatic centralized control unit and to track signalling control unit. This centralized unit not only controls the supply of the system, but it also monitors the operation and maintenance of the whole system. In order to reach the most efficient and stable traction performance, the traction system needs to control the current phase of the 3-phased windings to make the traveling magnetic field be synchronized with the magnetic field of the electromagnets. In this process, the precise relative position between the electromagnets and the long stator is a prerequisite. Considering the dimensional accuracy of the tooth-slot structure of the long stator, high precision positioning can be achieved by detecting the tooth-slot structure based on non-destructive detection technology.

Sensing and communications	Components used to monitor and control the state of the energy system
Function:	The sensing and communication systems are used to monitor and control the state of the energy system, especially the operation of the linear motor. Sensors gather information about the train position, the currents, voltages and phases, and send it back to the motor control device. The information is sent to a centralized control unit for train operation and power supply.
Relationship to Other Components	It is related to signalling system, power supply, segment switches, and train driving.
Development History and Status	Mature technology, already in use.
Relevant Environment	There are no strict requirements available regarding environment.
Comparison of the Relevant Environment and the Demonstrated Environment	Mature technology. There is no difference between the two environments
Technology Readiness Level Determination	TRL 9
Operational Requirement	There are no strict requirements available.
Test Results	Mature technology, already in use.

Segment switches	Dedicated separate infrastructure
Technologies Reviewed:	The stator winding loss can also be reduced significantly because power is only supplied to the segment over which the train just passes. Therefore, when the train is about to leave the current stator section, the power supply should be switched off timely. And the power must be transferred to the next stator section. Such a process can result from turning off and online switches (vacuum breakers) along the guideway. Since the stator current should be adjusted up or down during stator section changing, the thrust will also be affected. The electric power from the substation can be transferred through line switches to the corresponding stator motor sections where a train is located. If the train is leaving a segment, the line switch connected to that stator section will be opened subsequently. After the segment has been disconnected from the power source, the new segment can receive the power by closing its associated line switch.

Segment switches	Dedicated separate infrastructure
Function:	High-speed maglev systems use trackside long-stator linear motor. In order to reduce energy loss and to keep an acceptable power factor at the infrastructure side, the trackside stator is split into many stator segments. When the maglev train is running within the segment, the segment switches energize the segment. When the train leaves the segment, the segment switches turn the power to the segment off.
Relationship to Other Components	The segment switches work according to the position of the maglev train, which is detected and transmitted by sensing and communication system. The segment switches control the length of the energized section of the trackside stators.
Development History and Status	German Transrapid used this system.
Relevant Environment	No strict requirements are available.
Comparison of the Relevant Environment and the Demonstrated Environment	Mature technology. There is no difference between the two environments
Technology Readiness Level Determination	TRL 9
Operational Requirement	There is only one maglev train allowed to run within one segment. It is for high-speed maglev system.
Test Results	Mature technology; already in use.

Segment switches	Existing or upgraded railway infrastructure
Technologies Reviewed:	Segment switches are commonly used in maglev and maglev derived systems (MDS), which use a long stator linear motor. Segment switches are supplied with three-phase AC voltage, which is applied to the stator through power electronics circuits. Segment switches allow powering selected parts of the linear motor stator, only those in the area of which the mover vehicle is located. Therefore, there are no power losses in the linear motor section, which are not directly involved in propelling the vehicle. This makes it possible to significantly increase the energy efficiency of the system. What is more such a solution also makes it possible to significantly reduce the cost of the power electronics infrastructure.

Segment switches	Existing or upgraded railway infrastructure
Function:	Segment switches release the appropriate AC voltage to selected sections of the linear motor. This voltage is previously properly controlled by the inverter. The use of segment switches makes it possible to reduce the number of inverters required for installation along the system route. Instead of using multiple inverters for the stator section of the linear motor, it is possible to use fewer of them while using segment switches, directly supplying the motor stators. What is more solution allowing to significantly reduce losses in the motor.
Relationship to Other Components	Switch segments work directly with inverter systems and linear motor stator sections. The inverter circuits provide the appropriate voltage (characterized by amplitude, frequency and phase shift), which is distributed to the linear motor stator through the segment switches.
Development History and Status	Technology for MDS is being developed by Nevomo since 2019. In 2023 it has been successfully tested for vehicle achieving velocity of ca. 150 km/h. The technology has been filed for a patent procedure in 2021 (Michalczuk M et al., 2021)
Relevant Environment	No strict requirements are available.
Comparison of the Relevant Environment and the Demonstrated Environment	The main difference is that technology is designed for vehicles above 300 km/h. So far, it has only been tested up to 150 km/h.
Technology Readiness Level Determination	TRL 6
Operational Requirement	There is only one MDS train allowed to run within one segment.
Test Results	The technology has been tested successfully up to speeds of 150 km/h. Tests for lower speeds are described in the reference (Michalczuk et al., 2021)

5.3.4.4 TRA Command and Control

TMS	Existing Command and Control Signalling System in railway systems
Technologies Reviewed:	If national systems are excluded, there are two families of CCS systems. These are CBTC and ERTMS/ETCS. The big difference between these is that ERTMS/ETCS was created to make the railway system interoperable throughout Europe and therefore has solutions that must be interoperable and applicable in all European countries. CBTC, on the other hand, was created mainly to meet the needs of metropolitan lines and is not intended to be interoperable. For implementations that include maglev traction, compliance testing must be performed. This is a normal procedure that applies to all modifications made to rolling stock. While for CBTC systems it is possible to define the Ad Hoc solution and select the critical parts of competence to guarantee the functioning of the entire system (in short, modifications are possible), for ERTMS/ETCS applications there is greater attention because the system is already defined and compliance must be verified but changes cannot be made to the ETCS system. Many tests have already been done and checks regarding the compatibility in adopting maglev traction in ERTMS/ETCS environments.
Function:	The main areas where there may be consequences regarding CCS are: • Radio communications • the transponders used (EUROBALISE) • the Train Detection System systems (when used) Radio Communications Depending on the type of CCS is used (CBTC or ERTMS/ETCS) radio communications use different frequencies. Preventive analyses and then field tests will have to be carried out to demonstrate that the maglev does not produce any side effects on radio communications. The effect would have consequences on the regularity of the service. EUROBALISE Eurobalises are transponders that are installed on track slippers. then on the Rolling Stock side there is an antenna that powers and reads the message sent by the balise. It is therefore necessary to check that there is no electromagnetic and mechanical interference. The reference specifications and tests to be performed are already defined at European level. It is therefore necessary to carry out the

TMS	Existing Command and Control Signalling System in railway systems
	appropriate analyses and carry out the associated certification. Train Detection System: When required, CCS systems use systems to independently verify the presence of the train along the tracks. These systems can be of different nature. the main ones are i) the axle counters which count the number of axles that pass over the sensor; ii) track circuits that send a current onto the track and read back its presence to determine whether or not there is a rolling stock between a receiver and a transmitter. For these two macro types of TDS it is necessary to verify compatibility with the maglev systems used. Since they can be different depending on the country in which you operate, it is necessary to carry out a broader check that covers different applied technologies.
Relationship to Other Components	At the on-board system level there could be (but it should be a remote situation) possible interference. It should be verified during the integration phase of the maglev vehicle.
Development History and Status	All maglevs are based on an automatic operation, even at high speed as Transrapid or ev JR-Maglev (MLX). No ERTMS/ECTS implementations have been done for maglev systems. Lo Shinkansen Maglev will use the Japanese ATC system already use for the Shinkansen rolling stock high speed train. In SHIFT2RAIL IP2 and EU Rail R2DATO (EURAIL R2DATO, n.d.) there are activities linked to ETCS Level 3 and ATO up to GoA4.
Relevant Environment	The most interesting case is the railway environment where it is necessary to guarantee interoperability with trains that use different traction systems.
Comparison of the Relevant Environment and the Demonstrated Environment	The environment where the tests will be carried out will be a dedicated railway line where all the railway systems will be present in addition to the presence of trains with different traction.
Technology Readiness Level Determination	TRL 9 in existing ERTMS (ETCS and ATO) systems
Operational Requirement	The operational aspects are the same as those applied to the railway lines in use, therefore the same Use Cases applicable to traditional lines and high-speed lines must be carried out

TMS	Existing Command and Control Signalling System in railway systems
Test Results	For ERTMS/ETCS systems the interoperability tests are already defined and will have to be applied. They concern tests to be performed on rolling stocks and tests to be performed on lines.

TMS	Specific TMS used in Maglev systems
Technologies Reviewed:	The TMS (Train Management System) has the task of regulating the movement of all trains in its area of competence. It has the task of making the trains arrive on time according to a defined timetable. It has no particular connection with maglev solutions. The TMS collects the information arriving from the different systems operating on the line, signalling systems and diagnostic systems and chooses the best route for each train. In the railway sector there is no specific associated solution.
Function:	The TMS manages the movement of all trains between stations. Resolves conflicts when they arise due to delays and unexpected events due to various events.
Relationship to Other Components	The TMS interfaces mainly with interlocking and with ATO, as well as with the diagnostic systems manager.
Development History and Status	All maglevs are based on an automatic operation, even at high speed as Transrapid or JR-Maglev (MLX). See (Cassat and Bourquin, 2011)
Relevant Environment	There are no relevant comments on the matter. It is a Railway environment.
Comparison of the Relevant Environment and the Demonstrated Environment	No specific issue
Technology Readiness Level Determination	It is possible to use existing TMS
Operational Requirement	The operational aspects are the same as those applied to the railway lines in use, therefore the same Use Cases applicable to traditional lines and high-speed lines must be carried out
Test Results	The same checks envisaged for the use of the TMS on other railway areas

Virtual coupling	Virtual coupling
Technologies Reviewed:	Virtual coupling (VC) is a promising solution for a more flexible mode of transport with better headway and a high degree of modularity in the trains' composition because it significantly increases the capacity of a line and provides a more flexible mode of operation than conventional signalling systems.
Function:	VC is a train-centric next generation signalling system that enables multiple trains to operate in a formation just like one train or decouple separately, either on the run or at station, flexibly or as planned. VC is an evolution of the current MBSs, similar to the way in which road vehicles operate, where vehicles run at a safe distance from the vehicle in front and the driver reacts to the brake lights of the vehicle in front, and this safe distance is far shorter than the braking distance required for a complete stop, as considered in current moving block systems. VC is based on the concept of relative braking model.
Relationship to Other Components	It interfaces with vehicle, communications and command and control system
Development History and Status	The first VC concepts appeared in 1999 and these concepts were consolidated until 2006. However, their freight-oriented approach and the limitations of existing technology at that time may have prevented them from reaching their potential. Thus, the concept of VC, which is undoubtedly novel and disruptive, did not progress. Only when the European Research Initiative Shift2Rail appeared did VC receive a new impulse, mainly motivated by the need to increase the capacity of passenger rail lines in mass transit and by advances in communication technology. Both the EU, initially through Shift2Rail and currently through Europe's Rail Joint Undertaking, and various Chinese research programs, have actively supported research in the field of VC. Considerable research has also been performed within academia, often in connection with the aforementioned projects.
Relevant Environment	From a technological perspective, the main challenges for VC were identified with regard to aspects such as safety, control technology, interlocking, vehicle-to-vehicle communication, cooperative train protection and control, and integrated traffic management.
Comparison of the Relevant Environment and the Demonstrated Environment	The system is underdevelopment. Only are available implementations made on test track.
Technology Readiness Level Determination	Only small implementations have been made on test track, so TRL 4-5 is reached.

Virtual coupling	Virtual coupling
Operational Requirement	Mobile block infrastructure with high performance communications. Train-to-train communications and distance control are required.
Test Results	EU-funded projects X2RAIL-3 and MOVINGRAIL SCOTT and InsecTT EU projects tested the integration of track and train information in a centralized cloud-based platform. Safe4Rail3 project has proposed a demonstration of Wireless link between two consists for virtual coupling. (Felez and Vaquero-Serrano, 2023)

Control centre	Operations Control Centre
Technologies Reviewed:	Operation control system is the fundamental guarantee for the normal operation of the entire maglev system. It includes all the equipment to be used in security guarantee control, execution and plan and includes the equipment to be used in communication among the equipment. Operation control system consists of operation control centre, communication system, decentralized control system and on-board control system.
Function:	The Operations Control Centre (OCC) is the brain that manages the daily activities of transport operators. It is a system that is present both in the subways and in the railway world. The OCC must ensure that scheduled service times are met when unexpected events occur. The OCC must provide a coordinated response, in a timely manner, to reduce and recover from operational disruptions and to minimize the impact on passenger service. Some of the main OCC functions include: • Monitoring operations • Anticipate problems • Manage the schedule of scheduled operations • Minimize service interruptions • Conflict resolutions At the same time, the OCC is responsible for maintaining performance and providing quality of service, as well as reducing operational costs. In other words, the OCC is responsible for executing a daily program, as scheduled, without going over budget. Communication services are the cornerstone of an effective OCC. These vital services enable collaborative coordination of various stakeholders in the OCC. They can improve visibility of incoming

Control centre	Operations Control Centre
	information and reduce recovery times. Communications are critical for the OCC to ensure operations and user safety. A foundation based on reliable/secure communications can: • Support complementary services such as receiving/sending calls • Enable coordination and collaboration between stakeholders • Improve information awareness • Provide openness to easily integrate with different OCC functional blocks Modern OCC systems (in railways they are called TMS) have various interactions, they receive the status of the line by interfacing with the interlocking, up to the automation part to ensure that everything proceeds correctly. From the ATO system it receives the precise position of the train along the line and knowing the status of the line it can choose where to route the train to ensure that the expected timetable is respected. It also interacts with the Passenger Information System (PIS) so that the public is informed of any changes
Relationship to Other Components	The Control Centre (OCC) usually resides in dedicated rooms attended only by authorized personnel. It does not have a direct contact other than the railway lines, the information are exchanged through the dedicated communication network. The OCC (or TMS) receives the position of each vehicle in the area of competence from the trackside signalling system or directly from on-board systems.
Development History and Status	The OCC (or TMS) is not a system defined exclusively for Maglev technology. Currently there are various systems that regulate traffic both in the railway and metropolitan areas. Also within the EU Rail MOTIONAL (EURAIL MOTIONAL, n.d.) project there is a development for a modern TMS for the railway sector.
Relevant Environment	Control Centre (OCC) computers usually reside in dedicated and often climate-controlled areas.
Comparison of the Relevant Environment and the Demonstrated Environment	The OCC is usually installed in dedicated rooms. It also manages timetables and resolves conflicts if there are causes that prevent the defined timetables from being respected. It does not have a close connection to Maglev technology. Perhaps there may be travel time requirements on acceleration and braking curves.

Control centre	Operations Control Centre
Technology Readiness Level Determination	In all the project there is a TRL7 up to TRL9
Operational Requirement	The OCC is based on communication between vehicles and the control centre to identify the correct position of each vehicle on the lines. So, a functioning communication network is needed. Furthermore, the OCC uses the defined timetable as a reference for traffic regulation.
Test Results	In this case, the tests are performed on the entire system created, with multiple real or simulated trains. The tests will produce conflicts in circulation and the OCC will have to resolve them following the expected KPIs.

Monitoring and safety	Control and diagnosis system
Technologies Reviewed:	Today, rail networks across the world are getting busier with trains travelling at higher speeds and carrying more passengers and heavier axle loads than ever before. The combination of these factors has put considerable pressure on the existing infrastructure, leading to increased demands in inspection and maintenance of rail assets. The monitoring and diagnostic systems applicable for railway and metro lines can be divided into different families. TRACK MEASUREMENT • Track Geometry • Turnout & Crossing • Rail Profile • Rail Corrugation • Ride Quality • Tunnel & Clearance TRACK INSPECTION • Track Inspection • Head Check • Fishplate / Joint Bar • Internal Rail Flaw CATENARY MEASUREMENT • Geometry & Contact Wire Wear • Electric Parameters • Pantograph Interaction • Electric Arc Detection

Monitoring and safety	Control and diagnosis system
	• Thermal Scanning CATENARY INSPECTION • Longitudinal Defects Detection • Transversal Defects Detection • Pole Detection TRAIN MONITORING • Train Profile • Train Temperature • Pantograph Parameters • Brake Parameters • Shoegear Wear • Wheel Parameters • Wheel Impact Load • Weight-in-Motion These systems can then be connected to a management system that automatically provides the status of the line. This can be used for both maintenance and circulation reasons. For example, it can be connected to the OCC or TMS to provide information on the status of the line and allow the control system to choose the best/efficient line for the service provided. Monitoring and diagnostic systems have safety implications because they cooperate to reduce the possibility that an accident can occur. These systems are complementary to the signalling systems with which they coexist.
Function:	Monitoring and diagnosing of the various system components
Relationship to Other Components	The monitoring and diagnostic systems interface with the maintenance manager and the TMS
Development History and Status	The Control and Diagnostic System is not a system defined exclusively for Maglev technology. Currently there are various systems that work on the railway and metro environment. Also within the EU Rail IAM4RAIL (EURAIL IAM4RAIL, n.d.) project there is a development for a modern Control and Diagnostic System for the railway sector.
Relevant Environment	They are systems that have sensors or elements that are directly installed on the rolling stock or on the line. Therefore, they are subject to all possible electromagnetic interactions. The Maglev systems must verify their coexistence and compatibility tests must

Monitoring and safety	Control and diagnosis system
	be carried out, especially for railway lines
Comparison of the Relevant Environment and the Demonstrated Environment	If the existing systems are not suitable and new systems have to be developed to be installed along the line or on board the vehicle dedicated to Maglev technology, in this scenario then a dedicated project must be carried out. Otherwise, existing systems will be used.
Technology Readiness Level Determination	Depending on the previous point it is possible to have TRL4 up to TRP9
Operational Requirement	The purpose of the Control and Diagnostic System is to detect problems with the infrastructure and the vehicle. Therefore, considering the reference railway system, systems connected to the Control and Diagnostic System must be installed. The correct management of possible simulated or real problems will be verified.
Test Results	In the railway reference area, the types of faults will be defined and the Control and Diagnostic System will have to manage them in the expected manner and within the established times. Tests will be performed for each detection system connected to the Control and Diagnostic System.

Communication systems	Existing communication systems in railway systems
Technologies Reviewed:	The train-to-ground and train-to-train communication scenarios in the rail domain are based today on wireless communication system. It is used to transport the information between the train and the ground and between trains for train operation. The radio-based communication system is a key element of the control and command system of the train. The communication systems are also needed for maintenance (transfer of the maintenance information from the train to a control centre) and it is also considered for passenger information. Generally, one can distinguish the communication system for safe applications and the communication system for the non-safe applications. Several technologies exist today for safe applications or mission critical applications. The GSM-R is deployed on 150 000 km at European level among them 23 000 km are high-speed lines in the context of ERTMS/ETCS. GSM-R is based on 2G standard GSM phase 2+. It is a so called "circuit" mode system. It allows safe voice and data transmissions with a maximal bitrate of 9.6 kbits/s. GPRS is an evolution of GMS standard that introduce IP technology to enhance data rate and optimise the use of radio resources. 2x4 MHz are allocated for Railways in the 900 MHz band. GSM-R will be obsolete in 2030. It will be replaced by FRMCS based on 5G standard and the

Communication systems	Existing communication systems in railway systems
	two systems will coexist. Wi-Fi-derived systems are considered for CBTC applications for metros. Wi-Fi standard is widely considered by railway industry to build proprietary solutions for the radio system of several CBTC in the world. In general, starting from COTS, specific layers are added to enhance safety and security but also performance. The American version IEEE 802.11p and the European one ITS-G5 have been designed specifically for automotive applications and offer a good basis for railway applications. Inside the trains, the communication system is using Ethernet network (Ethernet Train Backbone). Wi-Fi is deployed inside trains for passenger services. TETRA (cellular professional radio) is also deployed for some specific safety related applications. Public or private LTE are considered in some countries for non-safety related applications
Function:	One specific communication system is used for the control and command of the vehicle. It will disseminate information needed for the train control and command (for example position and speed). Other communication systems are used for maintenance and passenger information.
Relationship to Other Components	The communication system is a key component for train operation and control and command and for the maintenance and for passenger information

Communication systems	Existing communication systems in railway systems
Development History and Status	In existing maglev systems as German Transrapid Maglev test line and Shanghai line the 3G radio communication has been adopted to transmit data for the vehicle control security, and synchronous traction. The passenger information and communication are transmitted through another radio communication channel. Existing communication systems deployed for conventional high-speed trains can be used for MDS. There are some ongoing projects related to communication for railways. FRMCS is under development and evaluation in several projects: • in IP2 of Shift2Rail program: X2RAIL1, X2RAIL3, X2RAIL5 have developed the first FRMCS adaptable communication system, • In H2020 ICT program the projects 5GRAIL, 5GMED are evaluating in labs and on tracks FRMCS prototypes. The project S5LECT has been selected in the EUSPA program for the use of IRIS2 satellite constellation in combination with FRMCS specifically for secondary line. • EU Rail R2DATO (EURAIL R2DATO, n.d.).
Relevant Environment	No need for specific environment except the railway context
Comparison of the Relevant Environment and the Demonstrated Environment	No issue – Railway environment
Technology Readiness Level Determination	TRL 9 - The GSM-R is deployed on 150,000 km at European level among them 23,000 km are high-speed lines in the context of ERTMS/ETCS FRMCS is today near TRL9 for some applications
Operational Requirement	There are no strict requirements available except FRMCS requirements.
Test Results	Generally, specific key performance indicators (KPI) are defined and should be respected. KPI generally refer to throughputs, packet error rate, latency, jitter, time for handover between two radio access points, resistance to Doppler, resistance to interference... The tests to be done in MDS context should be the same than for high-speed trains.

Communication systems	Future communication systems used in railway systems
Technologies Reviewed:	GSM-R will be obsolete in 2030 will be replaced by FRMCS based on 5G private networks. The FRMCS is under tests within several projects in Europe. FRMCS can be used for MDS. LTE was tested in the framework of various projects but 5G was chosen for FRMCS. It has been used for signalling communication on few metro systems (new Zhengzhou-metro). Ethernet backbone for TCMS will be also replaced by wireless technology. Demonstration has been done in the Safe4rail3 project considering LTE V2X, ITS-G5 and mmWave system. Developments are ongoing in IAM4RAIL project. Wireless communications in the millimetric bands are also under study for light trains Europe and for MDS in China. Some papers in the literature refer to optical solutions for high-speed connectivity on high-speed trains in Japan for Internet on board. Satellite communication systems (Low Earth Orbit constellation) are foreseen also as a complement to FRMCS particularly for rural areas where it will be very expensive to deploy 5G. Satellite systems can be considered for MDS (S5LECT project has started in EUSPA framework).
Function:	Communications for the control and command (critical mission), for maintenance applications, for passengers. The same functions than for conventional high-speed trains
Relationship to Other Components	The communication system is a key component for train operation and control and command and for the maintenance and for passenger information
Development History and Status	Research and development activities are ongoing at international level for the use of millimetric waves and satellite and future 6G networks for railway applications mainly for maintenance and passengers.
Relevant Environment	No specific environment to be considered for MDS compared to HST
Comparison of the Relevant Environment and the Demonstrated Environment	No issue – Railway environment
Technology Readiness Level Determination	Depending on the technology the TRL will vary. Generally, when demonstrators are available, we can consider that the technology is TRL6

Communication systems	Future communication systems used in railway systems
Operational Requirement	There are no strict requirements available except existing FRMCS requirements.
Test Results	Generally, specific key performance indicators are defined and should be respected. KPI generally refer to throughputs, packet error rate, latency, jitter, time for handover between two radio access points, resistance to Doppler, resistance to interference… The tests to be done in MDS context should be the same than for high-speed trains.

Positioning systems	Positioning systems used in conventional railways
Technologies Reviewed:	The existing technologies in conventional railways for positioning are mainly Eurobalise, KVB and track circuits for control and command applications. GPS is used for non-safety related applications (passengers, freight, maintenance) In the near future, GNSS based solutions (multi sensor + GNSS) are foreseen and are under development. Several demonstrators have been already made with several European and national projects. A European solution is under development in ERJU R2DATO project and other European projects. Several projects are testing prototypes for railways in the framework of EUSPA program.
Function:	To provide safe position of the train to the control and command system. The positioning information is obtained on board, then transmitted to the control centre.
Relationship to Other Components	Relation with communication system, control and command, maintenance, passenger information
Development History and Status	Mature technology, already in use. There are some projects ongoing for the train positioning along railway lines. Some of these projects are in SHIFT2RAIL IP2, X2RAIL-2 and X2RAIL-5 and in EU RAIL R2DATO WP21 and WP22. These projects are studying to use additional sensors for positioning scope.
Relevant Environment	No issue – same than conventional high-speed trains Analysis of the influence of the magnetic field on the positioning system

Positioning systems	Positioning systems used in conventional railways
Comparison of the Relevant Environment and the Demonstrated Environment	There are no relevant comments on the matter. It is a Railway environment
Technology Readiness Level Determination	TRL 9 for Eurobalise, KVB, track circuits TRL 6 for some demonstrated solution based on GNSS and multi sensors.
Operational Requirement	Positioning accuracy along the line, resilience to interferences, availability of the information
Test Results	The tests to be done are the same than for conventional high-speed trains

Positioning systems	Specific positioning systems based on the maglev technology
Technologies Reviewed:	When the train is running, it is necessary to make the control system sense its exact location and speed. Hence, a set of positioning system should be attached in the train. The function of positioning system is realized by devices installed in the train and track.
Function:	In the Transrapid, the vehicle's location on the track is identified using an on-board system that detects digitally encoded location flags on the guideway. A radio transmission system is used for communication between the central control centre and the vehicle. In the Ecobee, speed detection and absolute distance detection use the pattern belt installed on the centreline of the guideway.
Relationship to Other Components	All positioning and speed data are firstly obtained on board, and then they are transmitted to the ground operation control and traction system for conducting the operation of trains. Therefore, the mobile communication between the ground and the moving vehicle is needed. Both German TVE Maglev test line and Shanghai line adopt the 3G radio communication to transmit data for the vehicle control, security, and synchronous traction. The passenger information and communication are transmitted through another radio communication channel.
Development History and Status	German Transrapid Maglev test line and Shanghai line adopted this technology
Relevant Environment	Devices installed in the train and track

Positioning systems	Specific positioning systems based on the maglev technology
Comparison of the Relevant Environment and the Demonstrated Environment	Mature technology; there is no difference between the two environments
Technology Readiness Level Determination	This system has been tested and implemented in German Transrapid Maglev test line and Shanghai line and Ecobee system, so TRL 9 is reached.
Operational Requirement	Maglev lines with LIM
Test Results	See reference (Liu et al., 2015)

5.4 TRA Report Findings and Conclusions and comparison of the different systems

TRA reports should provide useful information to identify technology maturity gaps, decide when and how technology development efforts should move forward, consider whether backup or alternative technology solutions should be considered, and obtain information as a source of input for other analyses, such as updating a program risk management plan, or revising cost and schedule risk assessments.

In this case, the TRA report will serve to propose the constituent technologies which fits best to the different MDS identified, as well as evaluating the overall TRL for each MDS system. The TRA report will also provide data about each Maglev-Derived System's development status and pipeline of future works, outlining the possible expected evolution for the sector.

In the following, the findings and the comparison of the different systems can be further divided into the four main components of an MDS system: vehicle, infrastructure, energy system and TMS. This section also identifies and discusses significant development gaps and proposes the technical characteristics of the MDS that are best suited to the future needs of the railway system.

5.4.1 Regarding the vehicle

For propulsion, linear motors are the key technology most used. At present, linear motors are mostly at TRL 9, and several projects have demonstrated that the technology is fully operational on separate tracks. However, conventional rail-compatible systems are still under development (TRL 6-7). The LIM is generally not preferred over the LSM for speeds above 300 km/h due to its lower efficiency, higher eddy current losses, lower power density and lower power factor.

Linear motors are used as a service brake and for emergency braking (TRL equivalent to the traction), but also in combination with mechanical braking for redundancy.

Nowadays railway-compatible linear motors prototypes do not meet all the regulatory requirements (environmental conditions, EMC, etc.). Moreover, the test environment where demonstrations were performed did not include critical infrastructure components such as switches and road-rail crossings.

In addition, technologies such as lateral wheel-based propulsion/braking systems are under development (TRL 5-6) and show potential for rail-compatible systems as they can provide not only traction/braking but also guidance. Other technologies, such as electro-dynamic wheels, are at an early stage of development (TRL 6-7).

Suspension and guidance are very closely related. EMS and EDS are the most used technologies.

The EMS system (TRL 9) has been widely used in technical applications, such as the Japanese HSST magnetic levitation train, the German Transrapid magnetic levitation train operating in Shanghai, and some low-speed magnetic levitation systems in the world. For low-speed systems, it is not necessary to have a special guidance system on board or in the infrastructure, but for high-speed maglev systems another electromagnetic suspension must be used in the lateral direction. The EMS needs proprietary infrastructure and is so far not compatible to existing railway infrastructure.

As for the EDS system (TRL 5-8), although the suspension is simple, it does not work well at low speeds, so wheels or a special gear are needed either directly under the body or on both sides of the car. It also requires specific infrastructure adaptions to be integrated into an existing railway infrastructure.

When comparing the two systems, EDS seems to be more flexible and useful for railway compatible systems, although, as of today, EDS systems remain energy intense for operative use and have material compatibility challenges for infrastructure integration due to the use of conductive material such as aluminium.

Ferromagnetic passive levitation technology (TRL 6-7) can work on a standard railway shape with auxiliary integration systems for low to moderate speed or it require a specific infrastructure for the integration for high-speed applications. Its benefit as a suspension system is the possibility to have high levitation efficiency if compared to the other available technologies and the use of low-cost steel guideways.

Air levitation technology (TRL 5-8) has been confirmed to be used for both vehicle suspension as well as vehicle guidance with the high level of technology readiness level (8-9). This can be supported by the almost commercialised French Aerotrain and US tracked air- levitation vehicle (Guigueno, 2008; Zurek, 1978). The problem identified in vehicles using air- levitation technology is propulsion due to the levitation by compressed air.

In relation to the vehicle structure, it is interesting to consider which technologies can be used to adapt or complement conventional rail vehicles to the new specific requirements. Some of the above-mentioned technologies influence the design of the vehicle structure and therefore exclude their use in systems that are to be compatible with the existing railway system.

On the other hand, although rail systems have been designed on trainsets, as a vision for the future, it is also very interesting to consider their potential application on more flexible systems such as pods with or without virtual coupling.

Finally, vehicle control systems and monitoring and safety systems are horizontal technologies that are used in all railway systems.

Regarding the Train Control System (TCS), current systems use specific ATOs. For the future, however, it is desirable to move towards standardized and interoperable systems such as ERTMS/ETCS.

In any case, both the control systems and the monitoring and safety systems will have to consider the specificities of the levitation technology used, since the reliable and safe operation of maglev systems requires, for example, continuous control and monitoring of air gaps and coil excitations.

5.4.2 Regarding the infrastructure

The infrastructure is the main cost component and has a direct impact on the spatial integration of the electromechanical components for both levitation and traction capabilities.

Unlike other trains, which can be purchased and installed on existing tracks, maglev trains require their own unique infrastructure (TRL 9). This means that the entire railway system would have to be replaced with maglev tracks before it could be put into service. Not only does this take a long time, but it's even more expensive to finance.

As the objective of this work is to find MDS alternatives that can be run or adapted to the conventional railway network, the construction of Maglev tracks is disregarded as a possible solution. For rail-compatible (hybrid) systems an interesting solution can be supplementing the existing tracks with a linear motor installed between the existing rails (TRL 6-7) and levitation plates mounted on the sides of the track (TRL 6-7), which address specific shortcomings of classic adhesion-based systems like e.g. adhesion limits, rolling resistance, or noise and vibrations.

5.4.3 Regarding the energy system

Regarding the electrical system, one of the main constraints is the current collector. If systems are to be compatible with the existing railway system (TRL 9), the existing electrification system must be taken into account. There are promising solutions used in maglev trains such as wireless power transfer that can also be used if the infrastructure is adapted, with a TRL 9 for maglev infrastructure and substantially lower TRL for wireless energy transfer solutions adapted to conventional railways.

For hybrid solutions where linear traction motors have the stator integrated in a conventional railway track, the energy needs at vehicle level are reduced to auxiliary systems and the charging of on-board batteries for redundancy, reducing the energy transfer needs into the vehicles, which would make wireless energy transfer more attractive. These type of traction motors have a TRL of 5-7.

5.4.4 Regarding the command and control

As previously mentioned, regarding the TCS, current systems use specific ATOs (TRL 7-9). For the future, however, it is desirable to move towards standardized and interoperable systems such as ERTMS/ETCS (TRL 9).

In the same way, communications technology is also horizontal, so, when using shared infrastructure, the tendency should be to use the same as in the existing rail system. Technologies such as LTE, 5G, FRMCS, or satellites will be key to the development of these systems (TRL 6-9).

Additionally, there is technology developed in existing maglev systems, such as positioning systems or speed measurement systems, which can be used in MDS to improve performance and accuracy or as redundancy, most TRL 9, with TRL 6 solutions based on GNSS and multi sensors.

5.5 System development status and pipeline of future works

The previous section has provided data about each maglev-derived system's development status. This section complements the analysis with the pipeline of future works, outlining the possible expected evolution for the sector.

5.5.1 Context and current status

The White Paper on Transport issued by the European Commission in 2011 sets an important framework of goals with the objective to reduce CO_2 emission from transport sector by 60% in 2050 compared to 1990. In order to achieve this goal, 30% of the modal share of freight road transport travelling more than 300 km should be diverted to rail by 2030 and 50% by 2050. Moreover, the high-speed passenger network should triple its length by 2030.

In 2020, the Commission adopted the Sustainable & Smart Mobility Strategy, that raises the transport emission reduction objective 2050 vs. 1990 to -90% by four main strategies: zero-emission for collective line transport under 500 km by 2030; multi-modal trans-European TEN-T network fully operational by 2050; rail freight traffic +50% by 2030 and +100% by 2050 (vs. 2015); passenger rail traffic +100% by 2030 and +200% by 2050 (vs. 2015).

At the same time, the European institutions are refining the new European Regulation for the trans-European TEN-T network and the new Regulation on the use of railway infrastructure capacity, that are expected to be adopted by 2024. They both aim to enforce a smooth environment for customers to access rail transport, by providing a performant and completely interoperable European rail network that makes convenient for both passenger and freight traffic to shift to rail. The first Regulation concentrates on the infrastructural harmonisation on different countries, whereas the latter provides a regulatory supernational framework that ensures that throughout Europe uniform and customer-oriented procedures are applied to capacity allocation.

Member States are therefore working hard to meet the common standards set for the TEN-T network, overcoming national specificities to attain a continent-wide standardized network that enables inter-modal and intra-modal competition. For freight, that means enabling the lines to standardised gauge, gabarit, weight and train length values, also by financing new lines, pursuing the adoption of a common performant signalling system, limiting the number of electric supply systems, and adopting continent-wide certification systems for rolling stock. For passenger traffic, particular care is applied in setting a regulatory environment that encourages competition from newcomers, also by the adoption of standardised characteristics for the rolling stock admitted. This standardization effort involves a momentous commitment of financial and operational resources, that should enable the environment-friendly rail transport mode to overcome the gap with the road transport.

In order to meet the above-mentioned sustainability goals set by the Sustainable & Smart Mobility Strategy, and to set rail transportation at the centre of a multi-modal, efficient, and sustainable in the long-term European transportation network, the railway sector is called to opening the door to new and different technological standards, whose viability is justified in the of case of game-changing and non-marginal benefits.

Subsystems and technologies derived from traditional maglev systems could potentially provide game-changing benefits that would signify a radical change in the European transport system, shifting demand from other modes that are less aligned with the European Green Deal goals, towards railways or track bound collective transportation systems.

The benefits of traditional maglev systems are hard to dispute. By replacing wheels and supporting mechanisms with electro- or superconducting magnets, hovering trains can reach higher speeds. Preventing interactions between wheels and rails also means less noise, no vibration, and no mechanical damage. It uses 30 percent less energy than conventional trains. A traditional maglev train at a speed of 420 km/h uses half the primary thermal energy per passenger-kilometre than a car at 100 km/h, and only a quarter of what is used by airplanes. Those trains use only electricity, which can come from renewable energy sources; therefore, it reduces pollution and carbon emissions, enables greater and safer mobility at lower costs, and reduces dependence on hydrocarbons.

The lack of moving parts also implies that these trains need less maintenance. Since they are not in contact with the rails, there is no wear on the trains or rails. Maintenance is minimal, and the vehicles follow a maintenance schedule closer to that of aircraft than that of traditional trains, meaning that their maintenance schedules are based on hours of operation rather than distance travelled. Maglevs are also immune to weather since their tracks are not subject to heat deformation or freezing, reducing traditional constraints placed on rail travel. This makes the technology ideal for any location with extreme weather.

Lastly and most importantly, linear motors allow maglevs to accelerate and decelerate to and from high speeds in a short distance. This makes them both ideal for rapid inner-city travel since this means that they can accelerate to their top speeds even when stations are close together.

Despite all of these advantages of maglevs over conventional rail, there are still many challenges that must be overcome in order to win the battle for prominence on the rails.

The main problem facing the realisation of maglev technology has always been high costs. It requires an exceptional and dedicated infrastructure, including substations and power supplies. Unlike traditional high-speed trains, these maglev systems cannot be integrated into existing railway transport systems as it can operate only on its unique tracks, unable to switch and run onto thousands of miles of conventional train paths.

5.5.2 MDS future possibilities

The possible use of MDS operating in existing railway infrastructure tries to deal with this issue. The primary advantage of integrating MDS into existing infrastructure lies in its incremental implementation, where each step offers standalone benefits. Unlike pure maglev systems that necessitate entire new lines or networks, often incurring high costs in the billions of euros, the MDS can be introduced gradually. This stepwise approach initiates an evolution within the traditional railway system, commencing with smaller and localized applications utilising existing railway infrastructure and eventually, establishing a European MDS network embedded in the existing railway infrastructure to support the railway system as the backbone of transport and mobility.

The initial stages of this application could involve the adoption of new propulsion systems from MDS in specific regions such as ports, terminals, or even industrial zones. These areas, characterized by less stringent requirements compared to open network lines, can witness immediate benefits with a manageable number of retrofitted wagons. The results of the TRA have shown, that from a technological point of view it might be feasible to commence first pilot projects within the next 5 years, even when no concrete implementations in Europe are decided yet.

The subsequent stage may focus on enhancing the efficiency of the railway network at critical junctures on major rail lines. For instance, assisting freight trains in overcoming steep inclines could improve section-wise line capacity and operational efficiency. Similarly, for passenger transport, individual implementations could increase capacity and service quality on heavily congested lines in major cities, particularly at stations with frequent train stops.

The prefinal step in this phased approach could involve the comprehensive integration of MDS on key routes to maximize positive impacts on crucial connections. This could be the complete implementation of additional propulsion systems along a complete line, emphasizing improvements for freight traffic, such as enhanced performance, higher flexibility, and automation. Additionally, existing conventional high-speed lines could be transformed into hybrid MDS lines to strengthen passenger services, thereby positively affecting travel time, quality, and flexibility. Moreover, this transition also opens avenues for incorporating freight transport on high-speed lines.

The gradual development of MDS systems in local applications, stations, and entire lines will lead to a critical proportion of MDS systems integrated with the existing TEN-T network. This stepwise growth strategy would ensure that each implemented project brings positive effects by itself. The final vision is a shared interoperable network where the strengths of the different systems, both conventional and MDS, are used to their fullest potential for specific operations, revolutionising existing railway operations with powerful and flexible infrastructure.

6 Definition of the different use cases for the different technologies and identification of the MDS to be evaluated in the technical-economic feasibility study

This section defines the MDS to be considered in WP7. For this purpose, a study has been carried out, segmented according to the application of MDS to the passenger or freight sector and according to the type of traffic (considering urban, interurban, high-speed, etc.) or local applications (e.g. ports, intermodal hubs, etc.). This study was carried out using the Promethee multi-criteria analysis method (Brans and Mareschal, 2005).

Afterwards, a SWOT analysis has been carried out taking into account the TRA and scalability of each system.

A selection process has been defined where a set of criteria has been identified to facilitate the selection of the MDS to be analysed in WP7.

For each type of MDS chosen, the most appropriate technologies and operating conditions have been identified based on the technological maturity and feasibility of implementing this technology/feature in the chosen type of service/application.

6.1 Definition of the different use cases for the different technologies

The purpose of this section is to proceed to the definition of the different use cases for the different technologies. For this purpose, the systematic methodology called morphological analysis will be used by means of morphological charts.

6.1.1 Selection of the different MDS depending on the types of services/application.

Based on the results of WP2 (MaDe4Rail D2.1, 2023) and the technological maturity analyses developed in WP6, a morphological chart of the MDS can be established using several criteria in order to define the possible uses cases.

For this purpose, the morphological chart is segmented according to the type of vehicle, system configuration, type of service/application and compatibility with existing infrastructure. This chart (**Figure 8**) will serve to establish the different criteria to be taken into account in the multi-criteria analysis (MCA) carried out to select the different MDS use cases to be studied in WP7.

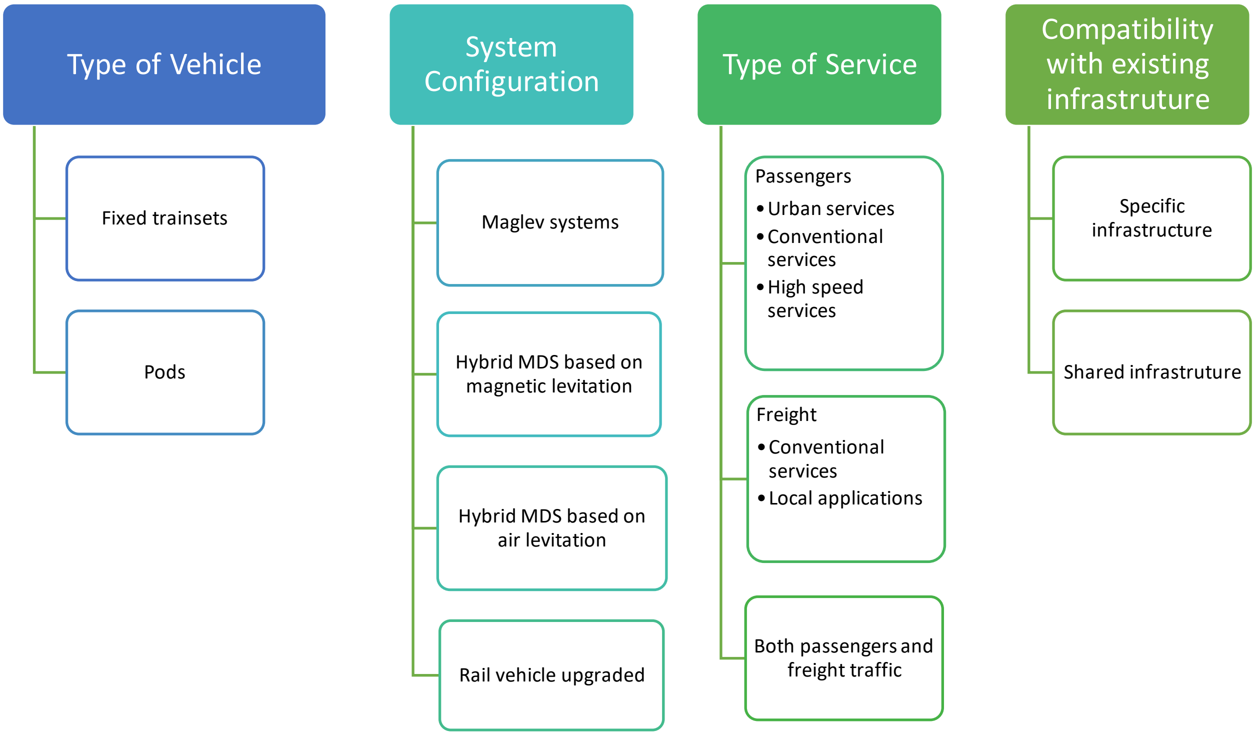


Figure 8. Classification and criteria for identifying the different MDS.

In **Figure 8**, we consider the following definitions:

Maglev system refers to maglev systems as transportation systems adopting methods and principles of magnetic levitation to suspend carriages, counteracting gravitational forces by means of magnetic fields.

Maglev-derived system (MDS) is defined as innovative, fast track-bound transportation system for rail application that use levitation-based technologies, such as linear motors with magnetic or pneumatic levitation, as their foundation.

Air-levitation system refers to MDS with suspension and/or guidance system based on aerodynamic forces. We refer to systems that utilize a cushion of air to lift the vehicle.

Pure maglev system refers to maglev systems that use specific and dedicated infrastructure, not compatible with the existing railway infrastructure.

Pure air-levitation system refers to air levitation systems that use specific and dedicated infrastructure, not compatible with the existing railway infrastructure.

Hybrid MDS refers to systems that are compatible with railway infrastructure.

Hybrid MDS based on air levitation refers to air levitation transport systems that are compatible with railway infrastructure.

Hybrid MDS based on magnetic levitation refers to magnetic levitation systems that are compatible with railway infrastructure.

Rail vehicle upgraded are conventional rail vehicles upgraded with MDS sub-systems or technologies.

Fixed trainset refers to a fixed formation that can operate as a train; it is by definition not intended to be reconfigured, except within a workshop environment.

Pod refers to "small vehicles" that can move independently but coordinated along a railway line. The POD system can be described as a decentralized, autonomous intermodal transport system.

Urban services, also called **Metro and other urban transit** in (MaDe4Rail D2.1, 2023) refers to transportation of large numbers of people especially within urban areas. Only systems and services under the rules of classical railways, interoperable and connected to the traditional railway network are taken into account.

Conventional services refer to passenger or freight transport on a route between cities, as opposed to a route providing commuter or metro services.

High-speed services refer to passenger trains that generally travel at over 250 km per hour.

Ports and Intermodal hubs refer to central locations where cargo containers can be easily and quickly transferred between different transport modes.

Passengers refers to the movement of people using inland transportation systems on a given network.

Freight refers to the use of inland transportation systems to transport cargo as opposed to human passengers.

Specific infrastructure refers to MDS that operate on a specific and dedicated infrastructure, with specific vehicles and without technical integration with the existing railway system.

Shared infrastructure refers to MDS that can operate integrated with existing rail infrastructure and new or retrofitted vehicles.

Also, from the technological point of view, taking into consideration aspects such as the TRA, scalability, adaptability, impact on the existing infrastructure or possibility of integration with existing railways, the following criteria included in **Figure 9** have been considered.

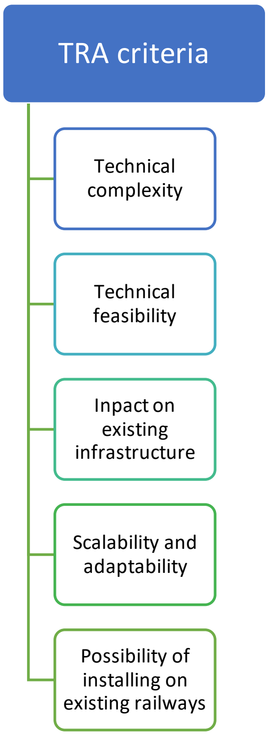


Figure 9. Criteria to be used from the TRA.

6.1.2 Criteria for selection of the possible use cases

For the selection of the possible use cases to be considered in the following steps, a multi-criteria analysis has been carried out using the Promethee method (Brans and Mareschal, 2005).

The Preference Ranking Organization METHod for Enrichment of Evaluations and its descriptive complement geometrical analysis for interactive aid are better known as the Promethee and Gaia methods.

Based on mathematics and sociology, the Promethee and Gaia method was developed at the beginning of the 1980s and has been extensively studied and refined since then.

It has particular application in decision making and is used around the world in a wide variety of decision scenarios.

The basic data related to such a problem can be written in a table containing evaluations. Each row corresponds to a criterion and each column corresponds to an action.

Table 6. Criteria and data used for the MCA.

CRITERIA		SUB-CRITERION				System configuration			
Definition	Weight (%)		Definition	Unit of measurement	Weight (%)	Pure Maglev	Hybrid Air-levitation	Hybrid Mag levitation	Rail vehicle upgraded
TECHNOLOGY	40,00	1.1	Technical Complexity	Range [1(Low)-5(High)]	10,00	5	4	4	3
		1.2	Technical Feasibility	Range [1(Low)-5(High)]	30,00	5	2	4	4
		1.3	Impact on the existing infrastructure	Range [1(Low)-5(High)]	30,00	5	2	2	2
		1.4	Scalability or Adaptability	Range [1(Low)-5(High)]	10,00	1	4	4	5
		1.5	Possibility of installing on existing railways	Range [1 (Yes) or 0 (No)]	20,00	No	**Yes**	**Yes**	**Yes**
INTEROPERABILITY	20,00	2.1	Interoperable with existing Service	Range [1 (Yes) or 0 (No)]	90,00	No	**Yes**	**Yes**	**Yes**
		2.2	Interoperability with future hyperloop	Range [1 (Yes) or 0 (No)]	10,00	**Yes**	No	**Yes**	No
TYPE OF SERVICE	30,00	3.1	Passengers: Urban services	Range [1 (Yes) or 0 (No)]	16,67	**Yes**	**Yes**	**Yes**	**Yes**
		3.2	Passengers: Conventional services	Range [1 (Yes) or 0 (No)]	16,67	**Yes**	**Yes**	**Yes**	**Yes**
		3.3	Passengers: High speed services	Range [1 (Yes) or 0 (No)]	16,67	**Yes**	**Yes**	**Yes**	**Yes**
		3.4	Freight: Conventional services	Range [1 (Yes) or 0 (No)]	16,67	No	No	**Yes**	**Yes**
		3.5	Freight: Local applications	Range [1 (Yes) or 0 (No)]	16,67	No	**Yes**	**Yes**	**Yes**
		3.6	Both passengers and freight traffic	Range [1 (Yes) or 0 (No)]	16,67	No	**Yes**	**Yes**	**Yes**
TYPE OF VEHICLE	10,00	4.1	Fixed trainsets	Range [1 (Yes) or 0 (No)]	50,00	**Yes**	**Yes**	**Yes**	**Yes**
		4.2	Pods	Range [1 (Yes) or 0 (No)]	50,00	**Yes**	**Yes**	**Yes**	No

Table 6 shows the different criteria used. Firstly, from a technological point of view, aspects such as TRA, scalability, adaptability, impact on existing infrastructure and the possibility of installation on existing railways have been considered. These criteria will help to choose the most suitable MDS that can be considered for use on existing railway lines. The type of vehicle has also been taken into account.

The interoperability criterion serves to analyse the feasibility of the different systems to be interoperable with existing and future railway systems, such as the hyperloop.

Finally, the service type criterion will be used to select the appropriate services for each MDS.

The explanation of the meaning of each criterion is shown in **Table 7**.

The System Configuration columns represent the four possible vehicle configurations depending on the technology used (MaDe4Rail D2.1, 2023): Pure Maglev, Hybrid Air-levitation, Hybrid magnetic levitation, and Rail vehicle upgraded.

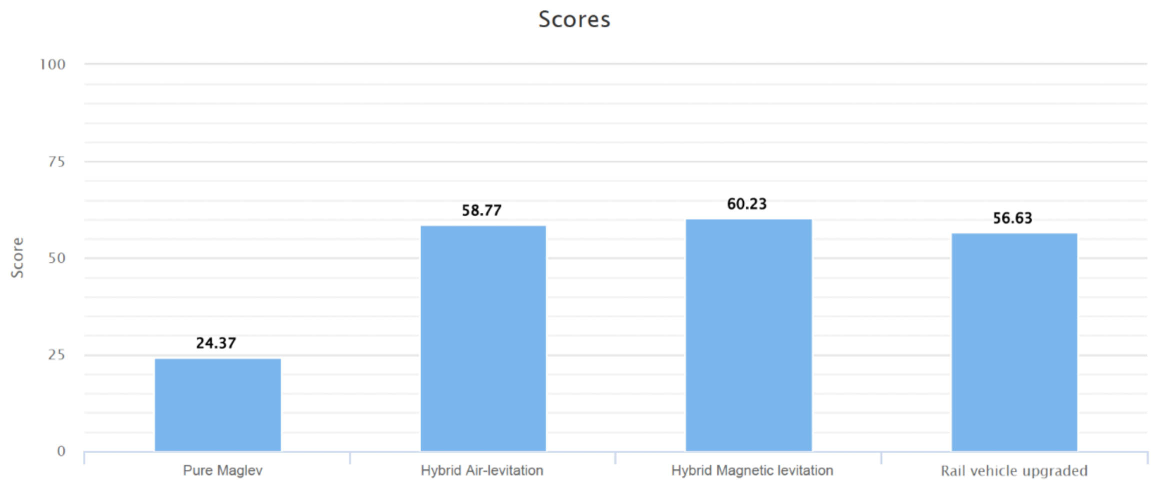
Table 7. TRA general description and contents

	CRITERION	DEFINITION
1.1	Technical Complexity	The different use cases request different technical solutions. The more components (e.g. propulsion, levitation, automation, …) must be implemented, the higher the technical complexity will be. The most complex use case will get the value 5 the one with the lowest the value 1. All other are sorted in between.
1.2	Technical Feasibility	The different use cases request different technical solutions in different environments. The combination of technical complexity and environmental issues (e.g. closed industrial zone, public terminal or yard, regional line, main line) will result in a subjective estimation of feasibility. The most feasible use case will get the value 5 the one with the lowest feasibility the value 1. All other are sorted in between.
1.3	Impact on the existing infrastructure	All use cases will cause needed adaptions on the existing infrastructure. Some need only very few adaptions (value 1) other will need complete new lines (value 5). All other are sorted in between.
1.4	Scalability or Adaptability	The scalability of use cases is estimated on behalf of the number of possible places, where the solution can be implemented independent from the actual demand. The use case with the smallest number of possible implementations in Europe gets the value 1, the use case with the potential highest number of implementations the value 5. All other are sorted in between.
1.5	Possibility of installing on existing railways	Is there a possibility of installing a technical solution on existing railways for the specific use case? Decision between yes or no.
2.1	Interoperable with existing Service	Is there a possibility of installing a technical solution interoperable with existing railway services for the specific use case? Decision between yes or no.
2.2	Interoperability with future ultra-high speed guided transport systems	Is there a possibility of installing a technical solution interoperable with future ultra-high speed guided transport systems based on vacuum-tube application services for the specific use case? Decision between yes or no.

With the selected criteria and their weights, the results presented in **Figure 10** and following are obtained. From this analysis, it appears that the MDS configurations with the greatest potential for use in today's rail infrastructure are the hybrid magnetic levitation and the air levitation MDS, closely followed by the rail upgraded vehicles. In contrast, the systems that are the most challenging to use on the current infrastructure are the existing pure maglev systems.

Figure 10 shows the scores obtained in the MCA and **Figure 11** presents the criteria contribution in the MCA. A more detailed information about the multicriteria analysis results can be seen in Annex 2.

Ranking



Rank	Alternative	Score
1	Hybrid Magnetic levitation	60.233
2	Hybrid Air-levitation	58.767
3	Rail vehicle upgraded	56.633
4	Pure Maglev	24.367

Figure 10. Scores obtained in the MCA.

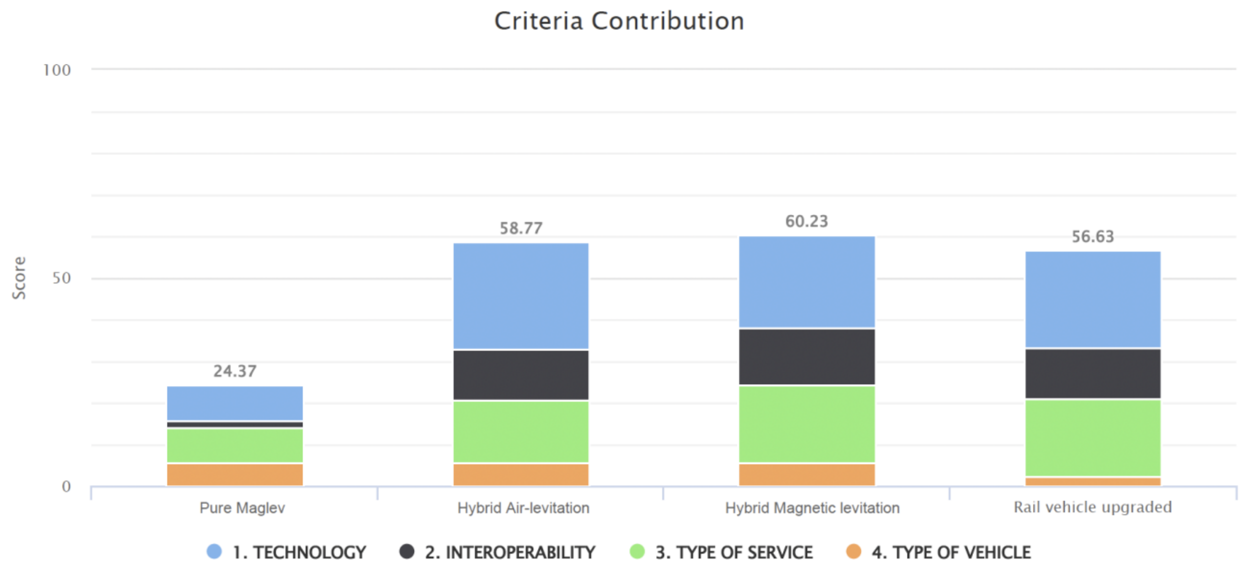


Figure 11. Criteria contribution in the MCA.

Thus, in order to analyse possible use cases, only hybrid magnetic levitation and air levitation

MDS, and rail upgraded vehicles will be considered, excluding pure maglev systems.

In **Figure 12**, the selection criteria for the possible use cases are shown, highlighting in green those that will be obtained with good scored in the MCA and in orange those that obtained low scores. In this figure Yes/No means that the System configuration is or is not feasible due to technical and/or operational conditions.

CRITERIA	System Configuration					
Definition	Definition		Pure Maglev	Hybrid Air-levitation	Hybrid Mag levitation	Rail vehicle upgraded
3. TYPE OF SERVICE	3.1	Passengers: Urban services	Yes	Yes[1]	Yes[1]	Yes
	3.2	Passengers: Conventional services	Yes	Yes	Yes	Yes
	3.3	Passengers: High speed services	Yes	Yes	Yes	Yes
	3.4	Freight: Conventional services	No	No	Yes	Yes
	3.5	Freight: Local applications	No	Yes[1]	Yes[1]	Yes
	3.6	Both passengers and freight traffic	No	Yes	Yes	Yes
4. TYPE OF VEHICLE	4.1	Fixed trainsets	Yes	Yes	Yes	Yes
	4.2	Pods	Yes	Yes	Yes	No

Figure 12. Criteria for selection of possible use cases.

[1]For the services 3.1 and 3.5 the major benefits might come from installing a linear propulsion system ("rail vehicle upgraded") with focus on stronger acceleration, electrification and automation potentials. For urban services which are very strong interlacing and where the different lines are very dependent from each other (vehicles are running on all different lines), the benefits of levitation can only be secured when complete networks were updated. However linear propulsion systems can gain benefits even with particular implementations. For local freight applications (3.5) the additional component of levitation will probably only bring small additional benefits, if its only installed in such areas. In both cases, the costs will probably not be compensated by the possible benefits, which makes those weaker than others. For this reason, these possible use cases are highlighted in light green, instead of the other more feasible use cases highlighted in dark green.

6.1.3 Identification of use cases for possible MDS application

After the selection of MDS configurations based on the selected criteria, a set of possible use cases for the application of MDS was defined. **Table 8** includes the different use cases considering key operational parameters that the specific use cases would require, as well as the estimated time horizon for their implementation and possible applications.

In this table Short-term means less than 5 years, Medium-term between 5 and 10 years, and Long-term more than10 years.

Table 8. Use case description

Nº	USE CASE DESCRIPTION	KEY OPERATIONAL PARAMETERS		TIME HORIZON short/medium/long term	POSSIBLE APLICATIONS
		Fixed trainsets	Pods		
1	Hybrid air-levitation MDS for urban services	Upgraded trainset with installing air fenders to carry part of loads with wheel-rail as propulsion; New trainset with complete train levitation by air fender and electro-dynamic wheels for propulsion (low infrastructure cost: very low requirement for track and low changes to existing slab track. Low track maintenance. More capacity).	Higher speed; better vehicle dynamics; lower travel or transport time; higher frequency and flexibility; on demand services; higher line capacity	medium	Metro/tram lines with severe rail corrugation.
2	Hybrid air-levitation MDS for Conventional Passengers services	Upgraded trainset with installing air fenders to carry part of loads with wheel-rail as propulsion; New trainset with complete train levitation by air fender and electro-dynamic wheels for propulsion (low infrastructure cost: very low requirement for track and low changes to existing slab track. Low track maintenance. More capacity).	Higher speed; better vehicle dynamics; lower travel or transport time; higher frequency and flexibility; on demand services; higher line capacity	long	Intercity connecting two big cities. City centre to suburb. Railway line near living area or nature area needs low noises.
3	Hybrid air-levitation MDS for High speed Passengers services	Upgraded trainset with installing air fenders to carry part of loads with wheel-rail as propulsion; New trainset with complete train levitation by air fender and electro-dynamic wheels for propulsion (low infrastructure cost: very low requirement for track and low changes to existing slab track. Low track maintenance. More capacity).	Higher speed; better vehicle dynamics; lower travel or transport time; higher frequency and flexibility; on demand services; higher line capacity	long	Updating High Speed Line; on demand service; High speed railway lines connecting EU capital cities.
4	Hybrid air-levitation MDS for Local Freight applications	Upgraded trainset with installing air fenders to carry part of loads with wheel-rail as propulsion; New trainset with complete train levitation by air fender and electro-dynamic wheels for propulsion (low infrastructure cost: very low requirement for track and low changes to existing slab track. Low track maintenance. More capacity).	Higher speed; better vehicle dynamics; lower travel or transport time; higher frequency and flexibility; on demand services; higher line capacity	medium	From sea port to cities. Freight centre to cities.

Nº	USE CASE DESCRIPTION	KEY OPERATIONAL PARAMETERS		TIME HORIZON short/medium/long term	POSSIBLE APLICATIONS
		Fixed trainsets	**Pods**		
5	Hybrid air-levitation MDS for Both passengers and freight services	Upgraded trainset with installing air fenders to carry part of loads with wheel-rail as propulsion; New trainset with complete train levitation by air fender and electro-dynamic wheels for propulsion (low infrastructure cost: very low requirement for track and low changes to existing slab track. Low track maintenance. More capacity).	Higher speed; better vehicle dynamics; lower travel or transport time; higher frequency and flexibility; on demand services; higher line capacity	medium	Metro/tram line to carry goods during night and early morning, such as freight centre to cities.
6	Hybrid magnetic levitation MDS vehicle for urban services	Upgraded trainsets is an additional option which can also profit from installed propulsion system (higher speed; better vehicle dynamics, lower travel time) and/or magnetic suspension systems. Low energy consumption, low track maintenance.	Higher speed; better vehicle dynamics; lower travel time; higher frequency; on demand services; higher line capacity, low noise and emissions urban transit	long	Complete Metro systems or dedicated urban lines
7	Hybrid magnetic levitation MDS for conventional passenger services	Upgraded trainsets is an additional option which can also profit from installed propulsion system (higher speed; better vehicle dynamics, lower travel time) and/or magnetic suspension systems. Low track maintenance.	Higher speed; better vehicle dynamics; lower travel time; higher frequency; on demand services; higher line capacity	long	Reactivating regional lines; upgrading conventional lines; on demand passenger services
8	Hybrid magnetic levitation MDS for high-speed passenger services	Upgraded trainsets is an additional option which can also profit from installed propulsion system (higher speed; better vehicle dynamics, lower travel time) and/or magnetic suspension systems on maglev corridors. Low track maintenance.	Higher speed; better vehicle dynamics; lower travel time; higher frequency; on demand services; higher line capacity	long	Updating High Speed Line; on demand service
9	Hybrid magnetic levitation MDS for Conventional Freight services	Upgraded trainsets can also profit from installed propulsion system (higher speed; higher train weight; better vehicle dynamics; lower travel time) and/or magnetic suspension systems. Low track maintenance.	Higher speed; better vehicle dynamics; lower transport time; higher flexibility; on demand services; higher line capacity	long	Flexible pods as on demand freight service

Nº	USE CASE DESCRIPTION	KEY OPERATIONAL PARAMETERS		TIME HORIZON short/medium/long term	POSSIBLE APLICATIONS
		Fixed trainsets	Pods		
10	Hybrid magnetic levitation MDS for Local Freight applications	Upgraded trainsets can also profit from installed propulsion system (higher speed; higher train weight; better vehicle dynamics; lower travel time) and/or magnetic suspension systems. low energy consumption, low track maintenance.	Higher mean speed; better vehicle dynamics; lower travel or transport time; higher frequency and flexibility; on demand services; higher line capacity	long	Flexible pods as on demand local freight service
11	Hybrid magnetic levitation MDS for Both passengers and freight services	Upgraded trainsets can also profit from installed propulsion system (higher speed; higher train weight; better vehicle dynamics; lower travel time) and/or magnetic suspension systems. low energy consumption, low track maintenance.	Higher speed; better vehicle dynamics; lower travel or transport time; higher frequency and flexibility; on demand services; higher line capacity	long	Upgrade HSL and open it for high-speed cargo pods
12	Rail vehicle upgraded for urban services	Additional traction; better acceleration and deceleration; better accuracy; better quality of service (e.g. punctuality); accuracy in stopping; low energy consumption, low track maintenance.	n.a.	medium	Improvement of accuracy and/or train dynamics at stopping points (e.g. stations) upgrade of a complete urban line
13	Rail vehicle upgraded for Conventional Passengers services	Additional traction; better acceleration and deceleration; better accuracy; better quality of service (e.g. punctuality); higher line capacity; low track maintenance.	n.a.	medium	Electrification without catenary (limited visual impact and only small limitation of clearance), reactivating regional lines
14	Rail vehicle upgraded for High-speed Passengers services	Additional traction; better acceleration and deceleration; better accuracy; better quality of service (e.g. punctuality); higher line capacity; low track maintenance.	n.a.	medium	Partial upgrade High Speed Lines (e.g higher maximum speed, better acceleration)
15	Rail vehicle upgraded for Conventional Freight services	Additional traction; higher train weight; better train dynamics; higher capacity	n.a.	short	Steep inclines; passing tracks (improvement of acceleration after stopping); electrification of diesel lines
16	Rail vehicle upgraded for Local Freight applications	Automated operation; less complexity of operation; electrification	n.a.	short	Terminal electrification; shunting automation

Nº	USE CASE DESCRIPTION	KEY OPERATIONAL PARAMETERS		TIME HORIZON short/medium/long term	POSSIBLE APLICATIONS
		Fixed trainsets	Pods		
17	Rail vehicle upgraded for Both passengers and freight services	Additional traction; better acceleration and deceleration; better quality; higher line capacity; higher train weights; better line clearance	n.a.	medium	Electrification of tunnels, reactivating regional lines open for freight trains

6.2 Selection of the use cases for MDS applications to be evaluated in the technical-economic feasibility study

After the selection of the three MDS configurations through the MCA and the analysis of the possible use cases where they could be applied; an early selection of the most interesting use cases was made in terms of applicability of the MDS technology to the specific use case and a "reality check" of the identified use cases against the actual existing needs for transport infrastructures or services across Europe.

This primary selection is composed of six use cases where, in order to cover a wide range of possibilities, it took into account the inclusion of the three MDS configurations that emerged from the Promethee method (see section 6.1.2) and the three time horizons defined for the analysis (short, medium and long term). It was also considered important to select use cases for both passenger and freight applications in order to maintain a broad idea of where the MDS can be implemented.

Thus, the set of use cases chosen for the SWOT analysis consists of three use cases for passenger services and three for freight services. On the other hand, the six cases include two for each configuration (Hybrid MDS based on air levitation, Hybrid MDS based on magnetic levitation and Rail vehicle upgraded). Finally, three of the cases correspond to long-term horizon, two to medium-term and one to short-term.)

The preliminary selection of use cases is presented in **Table 9**.

Table 9. Preliminary selection of use cases for MDS applications.

	Freight application	Passenger application
Hybrid MDS based on air levitation	Local freight applications (Medium-term)	Conventional passenger services (Long-term)
Hybrid MDS based on magnetic levitation	Conventional freight services (Long-term)	High speed passenger services (Long-term)
Rail vehicle upgraded	Local freight applications (Short-term)	Conventional passenger services (Medium-term)

After the preliminary selection, a Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis was performed for each one of the use cases. A SWOT analysis is a tool used for preliminary evaluation of a project under a strategic planning vision. It aims to identify internal and external factors that affect in both positive and negative ways the project (Gürel, 2017). The 4 elements of the SWOT analysis were adapted to the specific analysis object of the MaDe4Rail project as follows:

- Strengths: characteristic inherent to the MDS and the expected operational parameters that give the system advantages compared to other solutions.
- Weaknesses: characteristic inherent to the MDS and the expected operational parameters that give the system disadvantages compared to other solutions.
- Opportunities: External elements to the MDS that could be used to its advantage.
- Threats: External elements to the MDS that could trouble their eventual implementation.

The results of the SWOT analysis performed for the 6 selected use cases is presented in the following sections.

6.2.1 Hybrid MDS based on air levitation for local freight applications

This use case foresees the application of a Hybrid MDS based on air levitation system using existing rail infrastructure for local freight applications, which could connect freight ports or centres to urban areas.

The results of the SWOT analysis are summarised in the table below.

Table 10. SWOT analysis for the MDS based on air levitation for local freight application use case

Strengths	Weaknesses
– Limited visual impact for electrification – Lower damages to track. – Higher capacity – Lower noises when passing living/nature areas. – Technology in the train not in the track, leading to low rebuilding/construction costs. – Good integration with existing track.	– There is a need for rebuilding tracks within existing railway lines. – Less flexibility at warehouse/ports. – Higher operational costs (trains more expensive, than classical wagon). – Higher infrastructure investment costs compared to traditional railways. – New regulations and standards needed for hybrid systems (e.g. gauging).

Opportunities	Threats
– Integrating in on service tram/metro lines – Improving freight transportation flexibility by building new warehouse along/near the freight lines (normally only connecting ports) – Expected reduction of life cycle cost of vehicle by lowering building and maintenance cost	– Transportation authorities in some countries could have a conservative approach towards traditional railways, considering also that the railway system in Europe is vast and rebuilding existing track is challenging. – The mutual influence/impact with other new types of transportation means (e.g., self-driving automated car, hyperloop) – Secure the compliance and compatibility to the existing railway system and all its subsystems

6.2.2 Hybrid MDS based on air levitation for conventional passenger services

This use case foresees the application of a hybrid MDS based on air levitation system using existing rail infrastructure for conventional passenger services, which could be used as an alternative to electrification of lines with catenary and could improve the performance characteristics of the passenger services.

The results of the SWOT analysis are summarised in the table below.

Table 11. SWOT analysis for the MDS based on air levitation for conventional passenger services use case

Strengths	Weaknesses
– Limited visual impact for electrification – Lower damages to track – Higher capacity – Lower noises when passing living/nature areas – Technology in the train not in the track, leading to low rebuilding/construction costs – Good integration with existing track	– There is a need for rebuilding tracks within existing railway lines – Less flexibility at warehouses/ports – Higher operational costs (trains more expensive, than classical wagon) – Higher infrastructure investment costs compared to traditional railways – New regulations and standards needed for hybrid systems (e.g. gauging).
Opportunities	**Threats**
– Integrating in on service tram/metro lines	– Secure the compliance and compatibility to the existing railway system and all its subsystems

– Improving freight transportation flexibility by building new warehouse along/near the freight lines (normally only connecting ports) – Expected reduction of life cycle cost of vehicle by lowering building and maintenance cost	– Need to define new safety standards – In case of significant speed increase in the line, it's necessary to check that passenger comfort is maintained –

6.2.3 Hybrid MDS based on maglev for conventional freight services

This use case concerns the application of a hybrid MDS based on maglev on existing railway lines, focused on conventional freight services. In this case, the MDS freight vehicles/pods will utilise the existing infrastructure and will operate with conventional trains on the same lines. Therefore, such application could lead to a flexible and automated cargo MDS pods network.

The results of the SWOT analysis are summarised in the table below.

Table 12. SWOT analysis for the hybrid MDS based on maglev for conventional freight services use case

Strengths	Weaknesses
– Flexibility of services – Higher speeds which translate in lower transport time – The system could provide “door to door services” as Pods could run independently – Automation of freight services – less investment costs due to utilisation of existing infrastructure/brow field approach – Low noise and emissions	– Higher vehicle investment costs (pods more expensive, than classical wagon) – Higher complexity of operations, because of higher number of vehicles – Higher infrastructure investment costs compared to traditional railways – New regulations and standards needed for hybrid systems (e.g. EMC, gauging).
Opportunities	**Threats**

– Possibility to provide "on demand services" – Shift freight demand to rail/guided transportation systems. – Possibility to directly adapt "new state of the art" communication systems (e.g., FRMCS or other systems used for CBTC if there is no connexion with conventional trains)	– Development of dedicated freight pods – Development of new ATO and TMS adjustment for self-driving automated pods – Secure the compliance and compatibility to the existing railway system and all its subsystems – New safety standards and approvements for operations and retrofitted vehicles

6.2.4 Hybrid MDS based on maglev for high-speed passenger services

This use case pertains to the application of a hybrid MDS based on maglev on existing high-speed railway passenger lines. In this case, the MDS will utilise the existing infrastructure and will operate with conventional trains on the same lines.

The results of the SWOT analysis are summarised in the table below.

Table 13. SWOT analysis for the hybrid MDS based on maglev for high-speed passenger services use case.

Strengths	Weaknesses
– Higher speeds result in shorter travel times – Better quality of service (e.g., punctuality, frequency of connections) – Higher line capacity because of shorter headways – Lower infrastructure investment costs due to utilisation of existing infrastructure/ brownfield approach – Improved aeroacoustics design of pod-like vehicles without rotating components. – Low noise and emissions	– Higher vehicle investment costs (pods more expensive, than classical wagon) – Development of new ATO and TMS adjustment for self-driving automated pods – Higher complexity of operations, because of higher number and diversity of vehicles (conventional trains and pods) – Higher infrastructure investment costs compared to traditional railways – New regulations and standards needed for hybrid systems (e.g. EMC, gauging).
Opportunities	**Threats**

– Increase of comfort due to new vehicle concepts – Shift of “short distance” air and individual vehicle modal share to rail/guided transportation systems due to the expected higher speeds compared to HST. – Possibility to directly adapt “new state of the art” communication systems (e.g., FRMCS or other systems used for CBTC if there is no connexion with conventional trains) – Possibility to provide “on demand services” – Reduction of noise barrier walls due to improved aeroacoustics, in particular for high-speed sections	– Development of dedicated passenger pods/vehicles – Development of new ATO and TMS adjustment for self-driving automated pods – Secure the compliance and compatibility to the existing railway system and all its subsystems – Ensure that the acceleration and deceleration and curve dynamics is compliant with passenger comfort – New safety standards and approvements for operations and retrofitted vehicles

6.2.5 Rail vehicle upgraded for local freight applications

This use case focuses on the application of a rail vehicle upgraded with MDS technologies for local freight applications. Therefore, the trains/wagons will be retrofitted and equipped with MDS technologies to improve its performance. Such solution would be best applied to terminal electrification and shunting automation.

The results of the SWOT analysis are summarised in the table below.

Table 14. SWOT analysis for the rail vehicle upgraded for local freight applications use case.

Strengths	**Weaknesses**
– Reduce transport time due to reduction of complexity in rail freight service in terminals and yards – Only way to electrify terminal tracks – Automation of freight transportation	– Relevant number of retrofitted vehicles needed to bring the positive effects – Higher infrastructure investment costs compared to traditional railways – New regulations and standards needed for hybrid systems (e.g. EMC, gauging).
Opportunities	**Threats**
– Automation can lead to a reduction of human errors and therefore a higher safety level – Possibility to directly adapt “new state of the art” communication systems (e.g., FRMCS or other systems used for CBTC if there is no connexion with conventional trains)	– New operational rules and ATO needed for automated vehicle operations – New safety standards and approvements for operations and retrofitted vehicles – Losing operating time of the vehicle while it’s getting retrofitted

6.2.6 Rail vehicle upgraded for conventional passenger services

This use case focuses on the application of a rail vehicle upgraded with MDS technologies for conventional passenger services. Therefore, the trains/wagons will be retrofitted and equipped with MDS technologies to improve its performance. Such solution would be best applied to electrification without using the catenary and to possible reactivation of regional lines.

The results of the SWOT analysis are summarised in the table below.

Table 15. SWOT analysis for the rail vehicle upgraded for conventional passenger services use case.

Strengths	Weaknesses
– Limited visual impact for electrification – Only small limitation of clearance (e.g., for the electrification of tunnels) – Utilisation of existing infrastructure/brown field approach (e.g., electrification of tunnels) – better rail service corresponding to the demands of people	– Economical consideration of needed investments and benefits only positive on relations with high demand (main lines) – Higher infrastructure investment costs compared to traditional railways – New regulations and standards needed for hybrid systems (e.g. EMC, gauging).
Opportunities	**Threats**
– Automation can lead to a reduction of human errors and therefore a higher safety level – Possibility to provide “on demand services” – Possibility to reach outer regions by electrified rail freight services – Possibility to directly adapt “new state of the art” communication systems (e.g., FRMCS or other systems used for CBTC if there is no connexion with conventional trains)	– Losing operating time of the vehicle while it’s getting retrofitted – Coordination of construction works on main lines with bad detour possibilities (tunnel electrification)

6.2.7 General remarks on the SWOT analysis

The SWOT analysis was performed to obtain a preliminary assessment of the 3 selected configurations of MDS and their applicability to the identified use cases, considering their technology readiness assessment and the potential benefits they could bring through the identified key operational parameters.

For all the use cases for which the SWOT analysis was performed, potential strengths and opportunities were identified, regarding the enhancement of existing railway systems, taking advantage of their existing benefits (e.g. collective and sustainable transportation systems), and reducing their criticalities (e.g. through higher flexibility and automation of operations); which would result in non-marginal benefits that could push a shift to rail of the existing demand for both passengers and freight, encouraging more sustainable mobility solutions and contributing to reaching the European Green Deal goals.

However, there are some challenges to face. The most important weaknesses and threats regard the vast efforts needed to adapt existing infrastructures and vehicles to the new technologies, especially considering the high costs it would require, the need to develop the technologies up to their commercialization (TRL 9) and the time needed to adapt the existing infrastructures. Other important consideration relates to the need to transform the transportation environment to adapt the existing safety and security standards and the regulatory framework.

7 Conclusions

The objective of this document is to provide set of possible use cases to be analysed, based on a comprehensive technology readiness assessment on the technical maturity of the technologies involved in MDS.

The benefits of traditional maglev systems are hard to dispute. By replacing wheels and supporting mechanisms with electro- or superconducting magnets, hovering trains can reach higher speeds, less noise, no vibration, and no mechanical damage, and less energy consumption (maglevs use 30 percent less energy than conventional trains).

Despite all these advantages of maglevs over conventional rail, there are still many challenges that must be overcome to win the battle for prominence on the rails. The main problem facing the realisation of maglev technology has always been high costs. The possible use of MDS operating in existing railway infrastructure tries to deal with this issue. The primary advantage of integrating MDS into existing infrastructure lies in its incremental implementation, where each step offers standalone benefits. Unlike pure maglev systems that necessitate entire new lines or networks, often incurring high costs in the billions of euros, the MDS can be introduced gradually.

This document first has provided a comprehensive technology readiness assessment of the technical maturity of the technologies involved in MDS based on the development of a well-known methodology such is the TRA. Then, this first task has performed the TRA of each technology constituent and has served to propose which of them fits best to the different MDS, as well as evaluating the overall TRL for each MDS.

The TRA concluded with the findings and comparison of the different systems, considering the four main subsystems of an MDS: vehicle, infrastructure, energy system and TMS, by comparing the different systems and identifying and exploring significant development gaps.

Regarding the vehicle, for propulsion, linear motors are the key technology most used. At present, linear motors are mostly at TRL 9, and several projects have demonstrated that the technology is fully operational on separate tracks. However, rail-compatible systems are still under development (TRL 6-7).

Technologies such as lateral wheel-based propulsion/braking systems are under development and show potential for rail-compatible systems as they can provide not only traction/braking but also guidance. Other technologies, such as electro-dynamic wheels, are at an early stage of development.

Suspension and guidance are very closely related. EMS and EDS are the most used technologies. Both technologies require specific infrastructure adaptions to be integrated into an existing railway infrastructure.

When comparing the two systems, EDS seems to be more flexible and useful for railway compatible systems, although, as of today, EDS systems remain energy intense for operative use and have material compatibility challenges for infrastructure integration due to the use of conductive material such as aluminium.

Ferromagnetic passive levitation technology can work on a standard railway shape with auxiliary integration systems for low to moderate speed, or it requires a specific infrastructure for the integration with high-speed applications. Its benefit as a suspension system is the possibility to have high levitation efficiency if compared to the other available technologies and the use of low-cost steel guideways.

Air levitation technology has been confirmed to be used for both vehicle suspension as well as vehicle guidance with the high level of technology readiness level (8-9). The problem identified in vehicles using air-cushion technology is propulsion due to the levitation by compressed air.

Finally, vehicle control systems and monitoring and safety systems are horizontal technologies that are used in all railway systems. Regarding the Train Control System (TCS), current systems use specific ATOs. For the future, however, it is desirable to move towards standardized and interoperable systems such as ERTMS/ETCS.

In any case, both the control systems and the monitoring and safety systems will have to consider the specificities of the levitation technology used.

Regarding the infrastructure, the infrastructure is the main cost component and has a direct impact on the spatial integration of the electromechanical components in order to reduce the total investment cost.

Nevertheless, it would be advantageous to introduce magnetic levitation and propulsion technology on the existing railway infrastructure itself, adapting it where necessary. Solutions involving the addition of a linear motor between the existing rails and levitation plates mounted on the sides of the track are possible approaches.

Regarding the electrical system, one of the main constraints is the current collection. If systems are to be compatible with the existing railway system, the existing electrification system must be taken into account, but promising solutions such as wireless power transfer can also be used if the infrastructure is adapted.

Finally, regarding the TCS, current systems use specific ATOs. For the future, however, it is desirable to move towards standardized and interoperable systems such as ERTMS/ETCS.

In the same way, communications technology is also horizontal, so, when using shared infrastructure, the tendency should be to use the same as in the existing rail system. Technologies such as LTE, 5G and beyond, 5G based FRMCS, or Low earth Orbot satellites for mission critical applications will be key to next developments.

Additionally, there is technology developed in existing maglev systems, such as positioning systems or speed measurement systems, which can be used in MDS to improve performance and accuracy or as redundancy.

After the TRA, and based on its results, an analysis of the state of development of each MDS and the pipeline of future work has been carried out to outline the possible expected evolution for the sector.

Subsystems and technologies derived from traditional maglev systems could potentially provide game-changing benefits that would signify a radical change in the European transport system, shifting demand from other modes that are less aligned with the European Green Deal goals, towards railways or track bound collective transportation systems.

The next step, also based on the TRA results, has been to analyse different use cases for the different technologies and to identify and propose a set of uses to be evaluated in further work packages. To this end, a multi-criteria analysis (MCA) was carried out to select the various MDS use cases that would be most suitable for consideration in further work packages for use on existing railway lines. Several criteria have been used. From a technological point of view, aspects such as TRA, scalability, adaptability, impact on existing infrastructure and the possibility of installation on existing railways were considered. The type of vehicle and system configuration were also considered. Finally, the criterion of the type of service has been used to select the appropriate services for each MDS.

With the selected criteria and their weights, the MCA showed that the MDS configurations with the greatest potential for use in today's rail infrastructure are the hybrid magnetic levitation and the air levitation MDS, closely followed by the rail upgraded vehicles. In contrast, the systems that are the most challenging to use on the current infrastructure are the existing pure maglev systems. Thus, to analyse possible use cases, only hybrid magnetic levitation and the air levitation MDS, and rail upgraded vehicles have been considered, excluding pure maglev systems.

After the selection of MDS configurations based on the selected criteria, a set of possible use cases for the application of MDS was defined (17 in total), considering the key operational parameters that the potential specific use cases would require, as well as the estimated time horizon for their implementation and possible applications.

From this set of potential use cases, an early selection of the most interesting use cases was made in terms of the applicability of the MDS technology to the specific use case and a "reality check" of the identified use cases against the actual existing needs for transport infrastructure or services across Europe.

This selection resulted in a final set of six use cases by combining the system configuration (hybrid air-levitation, hybrid magnetic levitation or upgraded rail vehicle) and the application (passenger or freight) for different services, with a balance between the type of services and applications.

Finally, a SWOT analysis was carried out for each of the use cases. The results of the SWOT analysis carried out for the selected use cases will facilitate the selection of the MDS to be analysed in further WPs.

For all the use cases for which the SWOT analysis was performed, potential strengths and opportunities were identified, regarding the enhancement of existing railway systems, taking advantage of their existing benefits (e.g. collective and sustainable transportation systems), and reducing their criticalities (e.g. through higher flexibility and automation of operations); which would result in non-marginal benefits that could push a shift to rail of the existing demand for both passengers and freight, encouraging more sustainable mobility solutions and contributing to reaching the European Green Deal goals.

However, there are some challenges to face. The most important weaknesses and threats regard the vast efforts needed to adapt existing infrastructures and vehicles to the new technologies, especially considering the high costs it would require, the need to develop the technologies up to their commercialization (TRL 9) and the time needed to adapt the existing infrastructures. Other important consideration relates to the need to transform the transportation environment to adapt the existing safety and security standards and the regulatory framework.

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9 Appendices

9.1 Annex1. Technology readiness levels (TRL)

Where a topic description refers to a TRL, the following definitions apply, unless otherwise specified:

TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in lab
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

9.2 Annex 2. MCA Analysis

This annex includes the comprehensive results of the MCA presented in 6.1.1.