Deliverable D 2.1

Functional, technical, operational, and economical overview of conventional rail systems, traditional maglev systems, and innovative maglev-derived systems

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1 Executive Summary

The objective of Deliverable 2.1 is to provide a detailed overview of existing Maglev-Derived Systems (MDS), categorise the various types of MDS, and delineate their maturity levels and the technologies employed in their subsystems (Chapter 5). After the first overview, a comprehensive analysis is drawn, including the main functional, technical, operational, and economic parameters of conventional railways, established maglev systems, and emerging MDS (Chapter 6). Throughout these analyses, the merits and limitations of the various technologies are discussed, aiming to identify potential ways in which MDS could not only be integrated but also prove advantageous to the existing railway network within the European Union (EU). The concluding segment of the activities detailed in this deliverable focuses on the formulation of a standardised MDS architecture and nomenclature along with the technology enablers, serving as a foundational reference for the subsequent Work Packages of the MaDe4Rail project, and the further development of MDS (Chapter 7).

The deliverable highlights various existing transport systems like Chinese and Japanese maglevs and metro systems, all using linear motors, but not designed for EU railway compatibility. However, emerging interoperable MDS like MagRail, MagRail Booster, Ironbox subsystems, etc. show promise. Despite different types of suspension—magnetic levitation, wheels, air cushions—all systems primarily employ linear motors. Thus, the focus remains on linear motor compatibility with railways, emphasising on proven types of suspension like wheels and levitation. Some of the analysed MDS could operate within current railway infrastructure. However, non-interoperable MDS reveal potential compatibility for some of their subsystems and may be beneficial for urban applications. The analysis of MDS that are interoperable with railway systems can set a foundation for future regulatory frameworks.

The initial phase of the MDS framework has been established, setting the groundwork for subsequent advancements. Future directives emphasise a comprehensive exploration of railway regulations, aiming to discern overlaps and distinctions with MDS. A pivotal step will involve pinpointing the interconnections among MDS components, scheduled for the ensuing project WPs. Of utmost importance is to identify and select a set of MDS configurations. These configurations, marked by their interoperability, have been assessed for their technical, regulatory, and economic viability, ensuring they present the greatest potential for successful integration.

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
ACV	Air Cushion Vehicle
APM	Automated People Mover
ART	Advanced Rapid Transit
ASCI	Advanced Speech Calls Items
ATO	Automatic Train Operation
ATP	Automatic Train Protection
AVE	Alta Velocidad Española (Spanish high-speed)
BTS	Base Transceiver Stations
CAPEX	Capital Expenses
CBTC	Communication Based Train Control
CCM	Change Control Management
CCS	Continuous Control System
CCTV	Closed Circuit Television
CPU	Central Processing Unit
CRL	China Railway
DMI	Driver Management Interface
EDS	Electrodynamic Suspension
EDW	Electro-Dynamic Wheels
EMC	Electromagnetic Compatibility
EML	Electro-Magnetic Levitation
eMLPP	Multi-Level Precedence and Pre-emption Service
EMS	Electromagnetic Suspension
EMU	Electric Multiple Unit
ERTMS	European Railway Traffic Management System
ETCS	European Train Control System
ETT	Evacuated Tube Transport
EU	European Union
EVC	European Vital Computer
FRMCS	Future Railway Mobile Communication System
GHG	Greenhouse gases
GPRS	Global Packet Radio System
GPS	Global Positioning System
GSM-R	Global System for Mobile Communications-Railway
GTO	Gate turn-off thyristors
HEMS	Hybrid Electromagnetic Suspension
HSR	High-Speed Rail
HST	High-Speed Trains

HTS	High Temperature Superconductors
ICE	Intercity Express
ICTS	Intermediate Capacity Transit System
IGBT	Insulated-Gate Bipolar Transistor
IMU	Inertial Measurement Unit
JAL	Japan Airlines
JU	Joint Undertaking
LASUP	Laboratory of Applications of Superconductors
LEM	Linear Electric Machines
LEU	Lineside Electronic Unit
LIM	Linear Induction Motor
LMS	Low and Medium Speed
LSM	Linear Synchronous Motor
LSRM	Linear Synchronous Reluctance Motor
LTE	Long-Term Evolution
MA	Movement Authority
MDS	Maglev-derived system
OHSGT	Office of High-Speed Ground Transportation
OPEX	Operational Expenses
PM-EDS	Permanent Magnet Electrodynamic Suspensions
PMLSM	Permanent Magnet Linear Synchronous Motor
PRT	Personnel Rapid Transit
PTACV	Prototype Air Cushion Vehicle
PWM	Pulse Width Modulation
RBC	Block Center
TACRV	Tracked Air Cushion Research Vehicle
TACV	Tracked Air Cushion Vehicle
TGV	Trains à Grande Vitesse (High Speed Trains)
TMS	Traffic Management System
TRL	Technology Readiness Level
TSB	Transport System Bögl
TTC	Transportation Technology Center
UFRJ	Federal University of Rio de Janeiro
UIC	International Union of Railways
UTACV	Urban Tracked Air Cushion Vehicle
UTDC	Urban Transportation Development Corporation
WOS	Web of Science
WPT	Wireless Power Transfer
YBCO	Yttrium Barium Copper Oxide

3 Background

The present document constitutes the Deliverable D2.1 “Functional, technical, operational, and economical overview of conventional rail systems, traditional maglev systems, and innovative maglev-derived systems” in the Europe’s Rail Flagship Area 7 Project “Maglev-Derived Systems for Rail” from the innovation pillar, as described in the Europe’s Rail (EU-RAIL) Multi-Annual Work Programme (MAWP).

4 Objective/Aim

This document has been prepared to provide a comprehensive state-of-the-art overview of MDS including literature analysis of existing systems, subsystems, and technologies, setting a baseline for the subsequent activities of the MaDe4Rail project, with the aim to narrow the potential solutions for interoperable MDS that could be introduced to the railway system in the EU.

Furthermore, an exhaustive comparative analysis of the existing end emerging system from functional, economic, operational, and technical perspectives has been performed that is crucial for Work Stream 2 of the MaDe4Rail project, to perform the next activities such as the feasibility studies and cost-benefit analyses.

Last objective covered within the D2.1 is to create a common system complemented by a compendium of essential definitions required for further activities within WP3, WP4 and WP5, where a defined framework is vital. Specifically, this framework will facilitate hazard identifications and risk assessments in WP3, the formulation of detailed breakdown structures pertinent to vehicular aspects in WP4, and an analysis of the MDS's congruence with the System Pillar in WP5.

5 Overview of the Maglev-Derived System

5.1 Definitions and methodology

To harmonise the considerations regarding MDS, it is advantageous to establish the definition of such systems and the method employed to analyse them.

Maglev-derived system is defined as an innovative, fast track-bound transportation system for rail application that use maglev-based technologies, such as linear motors with magnetic or pneumatic levitation, as their foundation. It can be a stand-alone system with its own dedicated infrastructure and vehicles or can be, in principle, integrated within the existing railway infrastructure. The possible interoperability is within the particular interest of MaDe4Rail project since investigations of MDS that could be interoperable within the EU railway network are one of the goals of the whole project. More detailed considerations about classification of MDS regarding i.e., the levels of interoperability or compatibility with the railway system is a subject of further WPs.

The methodology of the MDS overview was based on a few steps.

First, the state-of-the-art analysis for MDS has been performed. The main principle that MDS have in common is the linear motor. Based on this, four groups of MDS have been recognized:

- Maglev systems based on magnetic suspension,
- Air-cushion transport systems based on pneumatic suspension,
- Wheeled MDS moving on railway or dedicated infrastructures,
- Hyperloop systems that refer to MDS operating in low-pressure environment.

Next step was to define the areas in which the systems will be compared. To make a relevant comparison for next Work Packages, general, technical and operational/cost/lifecycle aspects have been covered. General features refer to the system parameters, existing implementations, and maturity level. Technology has been recognized in the following areas: propulsion, guidance, braking, infrastructure, power supply, communication and command, control and signalling systems. Operations were divided into operating speed, acceleration and deceleration limits, specific energy consumption, vehicle and line capacity, climate robustness, CAPEX and OPEX costs split between the infrastructure and the vehicle, and the system deployment speed, defined as the measure of how fast the system can be installed in a specific location.

Second, the literature overview regarding MDS was prepared. Scientific paper analysis has been carried out for the preparation of a review. A wide variety of tools and applications facilitate this task with different search methods. The following search and data analysis applications were used: Inciteful, Web of Science (WOS), and Scopus. The bibliographic search is carried out based on this keyword. Each application provides a series of files of the publications available in its database. The files provided are exported to an Excel file to obtain the raw data and import them into the corresponding analysis tools. With the data obtained from the different databases, the VOS viewer application was also used to analyse the most relevant or frequently used keywords and the groups of related authors and co-authors. As a result of the operations and analyses carried out, the bibliographic list that appears in the "Bibliography" section has been generated.

5.2 Literature overview

Having in mind the specific goals of the project "Development of business case analysis, including feasibility studies and use cases", and specifically the Objective 5 "Technological readiness assessment on the technical maturity of the technologies and identification of possible use cases or operational context", a literature overview has been performed.

As a result of this paper review and data analysis, a list of references has been generated to prepare for the execution of the next WPs. Finally, from the references, a proposal for a data study was made to assess the technical maturity of the technologies and to identify possible use cases or operational contexts.

5.2.1 Methodology

In this task, data analysis has been carried out for the preparation of a review. There are a wide variety of tools and applications that facilitate this task with different search methods. Of these, the following search and data analysis applications were used:

- **Inciteful** (Inciteful, 2023)**.**
- **Web of Science, (WOS)** (WoS, 2023)**.**
- **Scopus** (Scopus, 2023)**.**

The bibliographic analysis provided a series of files of the publications available in its database. The files provided are exported to Excel to obtain the raw data and to import them into the corresponding analysis tools.

The following sections describe the search activity and the results of the analyses carried out in each application or tool.

With the data obtained from the different databases used, the VOSviewer (VOSviewer, 2023) application was also used to analyse the most relevant or frequently used keywords and the groups of related authors and co-authors.

As a result of the operations and analyses carried out, the bibliographic list that appears in the "Bibliography" section has been generated.

5.2.2General search and data analytics

The bibliographic search is started with the keyword:

MagLev Train

The following reference, cited in 577 other publications, is obtained and selected:

H.-W. Lee, K.-C. Kim, and J. Lee, "Review of Maglev train technologies". IEEE Transactions on Magnetics, Vol. 42, No. 7, July 2006. 0018-9464/$20.00 © 2006 IEEE. D.O.I.: 10.1109/TMAG.2006.875842

Starting from the previous publication, the ***Inciteful*** application obtains different sets of publications related to the first publication initially taken.

Each set is shown as relevant according to different criteria. These datasets are exported into the corresponding files to have the complete data. Figures 1-6 show the results of the analysis of the ***Inciteful*** application.

The results of the first search with Inciteful are available at the following link:

https://inciteful.xyz/p/W2153028751

The results of the second search for the most cited papers are available at the following link:

https://inciteful.xyz/p?ids%5B%5D=W1970973192&ids%5B%5D=W2065614005&ids%5B%5D=W2105693977&ids%5B%5D=W2052236484&ids%5B%5D=W2139593900&ids%5B%5D=W3127517162&ids%5B%5D=W2560304951&ids%5B%5D=W2053956221&ids%5B%5D=W2059935921&ids%5B%5D=W2767129165&ids%5B%5D=W2153028751

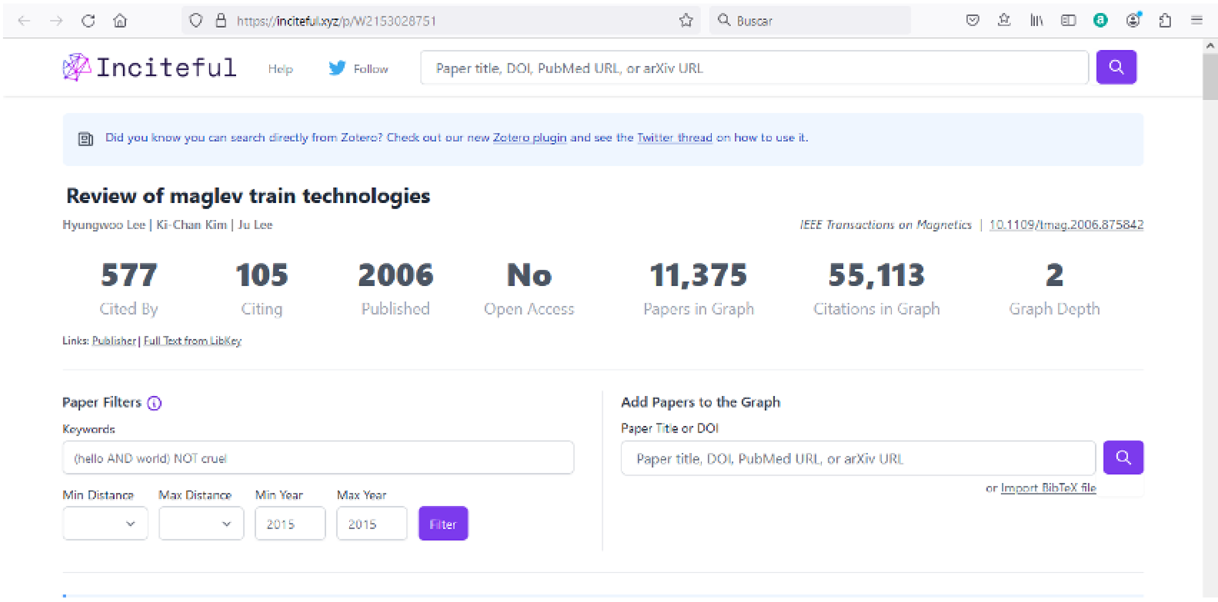


Figure 1.- Result of the first search in Inciteful. (Source: Inciteful)

Seed Papers

TITLE	FIRST AUTHOR	YEAR	CITED BY
A SELF-CONTROLLED MAGLEV SYSTEM	Francesca Di Puccio	2012	10
Prospects and Challenges of the Hyperloop Transportation System: A Systematic Technology Review	Jonas Kristiansen Noland	2021	27
Methods of Transport Technologies: A Review On Using Tube/Tunnel Systems	W M Shibani	2016	5
The high speed Maglev transport system TRANSRAPID	J. Meins	1988	48
Electromagnetic suspension and levitation	B.V. Jayawant	1981	59
Conventional Indian railways and the advanced transportation systems: A comparative review	V. Shirish Murty	2016	2
Korea's Urban Maglev Program	Doh-Young Park	2009	30
A new MAGLEV system for magnetically levitated carrier system	M. Morishita	1989	143
Review of maglev train technologies	Hyungwoo Lee	2006	577
Japan's superconducting Maglev train	M. Ono	2002	108
The Inductrack: a simpler approach to magnetic levitation	Richard F. Post	2000	105

Figure 2.- Seed papers from the first search. The most cited papers by in Inciteful. (Source: Inciteful)

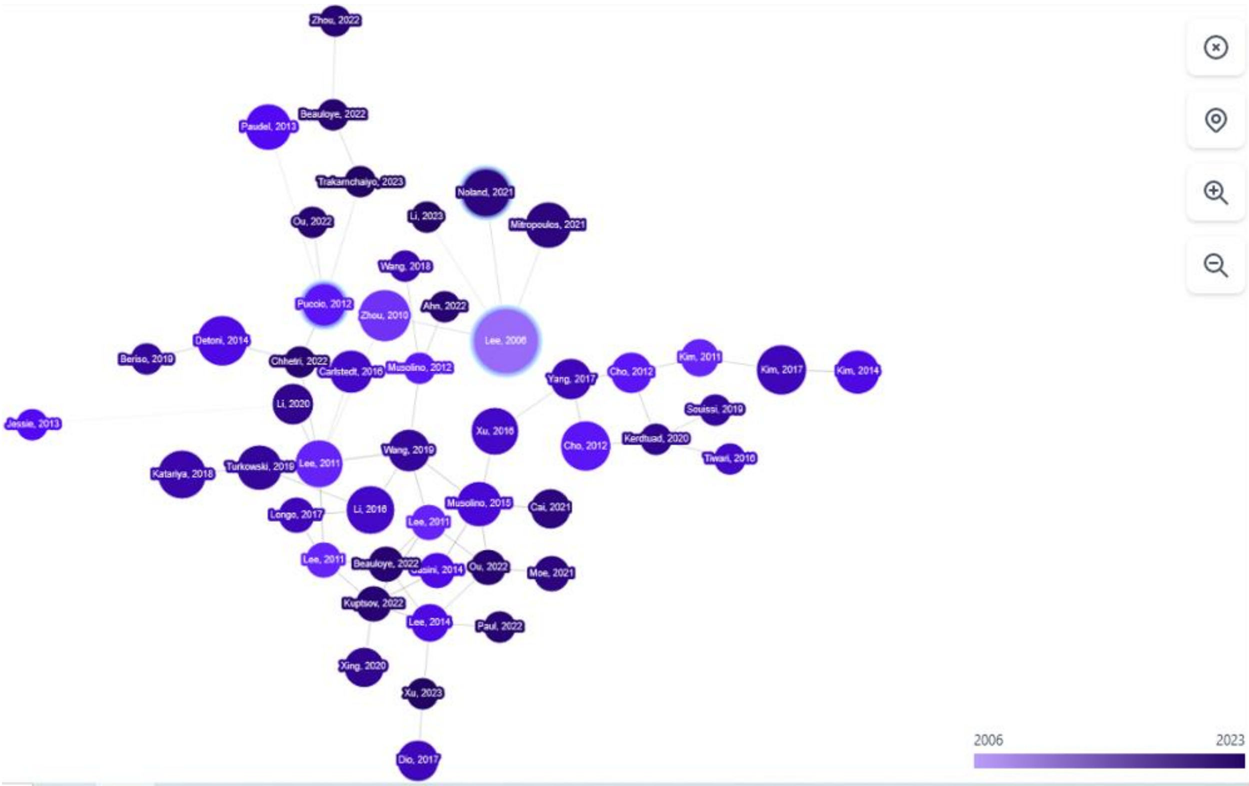


Figure 3.- Map of authors in Inciteful. (Source: Inciteful)

Top Authors

This section tries to identify the top authors in the network.

	total_page_rank	num_papers
Ju Lee	14.495404	9
Hyungwoo Lee	13.656645	3
Ki-Chan Kim	13.69847	2
Nobumichi Tamura	1.104857	2
S. Kanda	1.104857	2
T. Azukizawa	5.154106	2
M. Morishita	1.162312	2
T. Yokoyama	1.012312	1
B.V. Jayawant	8.139629	8
Richard F. Post	4.587115	4

Figure 4.- Top Authors list from Inciteful. (Source: Inciteful)

Institutions

This section tries to identify the top institutions in the network.

	total_page_rank	num_papers
Hanyang University	43.740962	9
Korea Railroad Research Institute	42.492046	8
Southwest Jiaotong University	21.451314	88
Toshiba	16.660329	4
National University of Defense Technology	15.729207	73
Railway Technical Research Institute	14.403564	8
Korea Institute of Machinery and Materials	10.757384	23
Tongji University	9.93328	43
Central Japan Railway	9.669225	4
Saitama University	8.683445	28

Figure 5.- Top Institutions list from Inciteful. (Source: Inciteful)

Top Journals

This section tries to identify the most relevant journals for this research area

	total_page_rank	num_papers
IEEE Transactions on Magnetics	128.059266	119
IEEE Transactions on Applied Superconductivity	38.870241	61
Journal of Applied Physics	18.352465	13
IEEE Transactions on Vehicular Technology	18.031778	6
Proceedings of the IEEE	8.806043	10
IEEE Instrumentation & Measurement Magazine	7.874851	1
IEEE Access	6.751403	26
Reports on Progress in Physics	6.525705	1
Proceedings of the Institution of Electrical Engineers	5.956111	11
Systems and Computers in Japan	5.59586	1

Figure 6.- Top journals in Inciteful. (Source: Inciteful)

Doing a more refined search in Web of Science (WOS) and Scopus, using the keyword "***Maglev + Train",*** a total of 5,267 documents were obtained and analysed as shown in the figures 7-14.

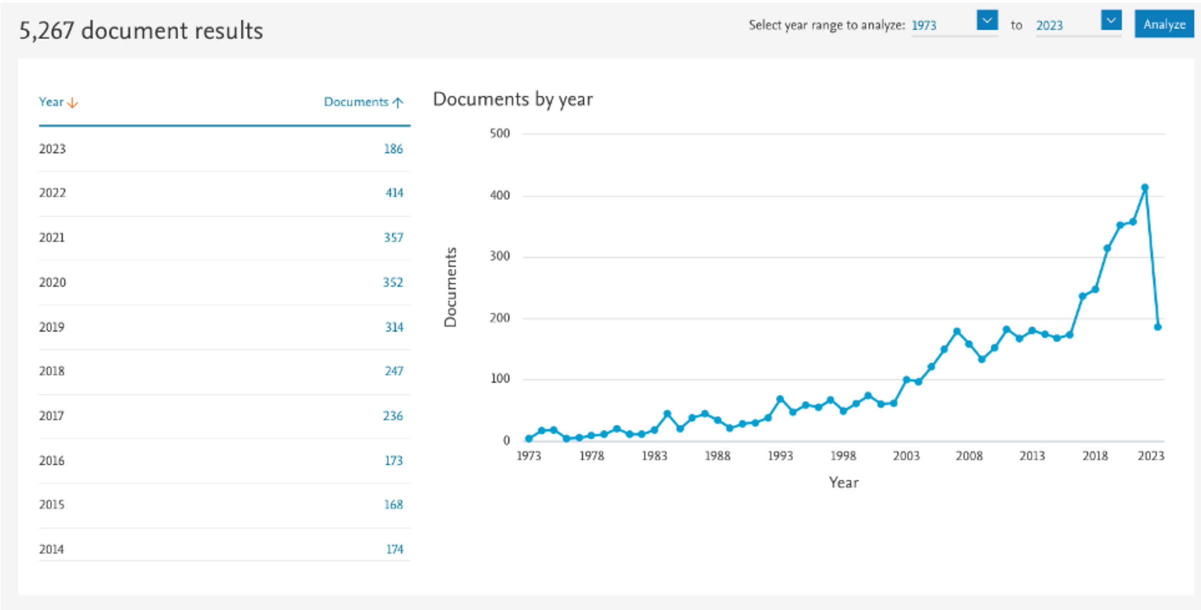


Figure 7.- Documents by year (source Scopus).

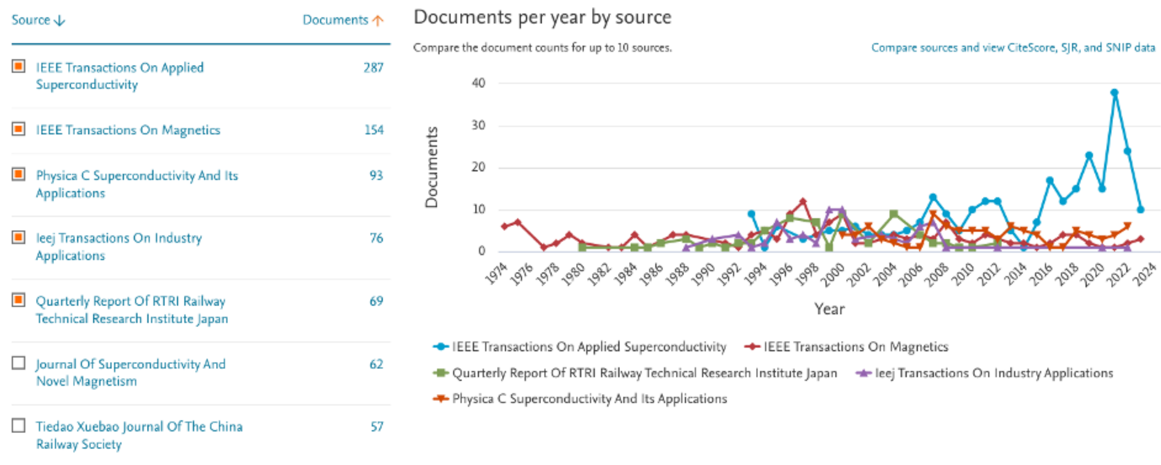


Figure 8.- Documents per year by source (source Scopus).

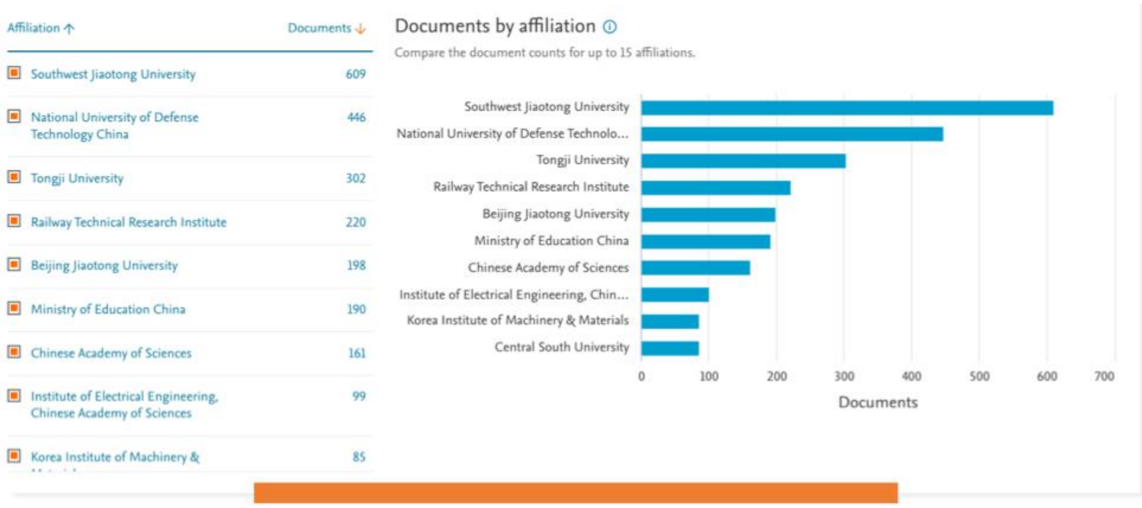


Figure 9.- Documents by affiliation (source Scopus).

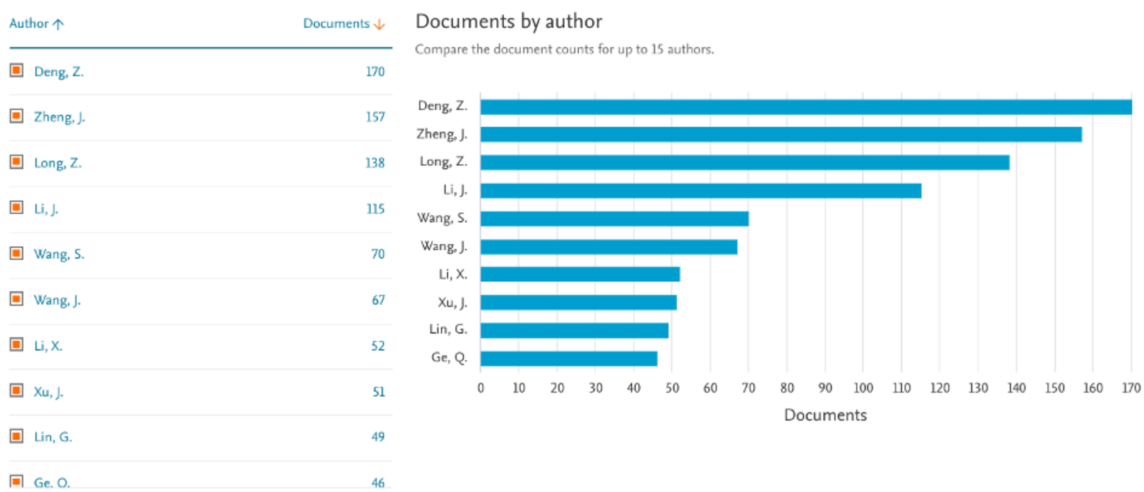


Figure 10.- Documents by author (source Scopus).

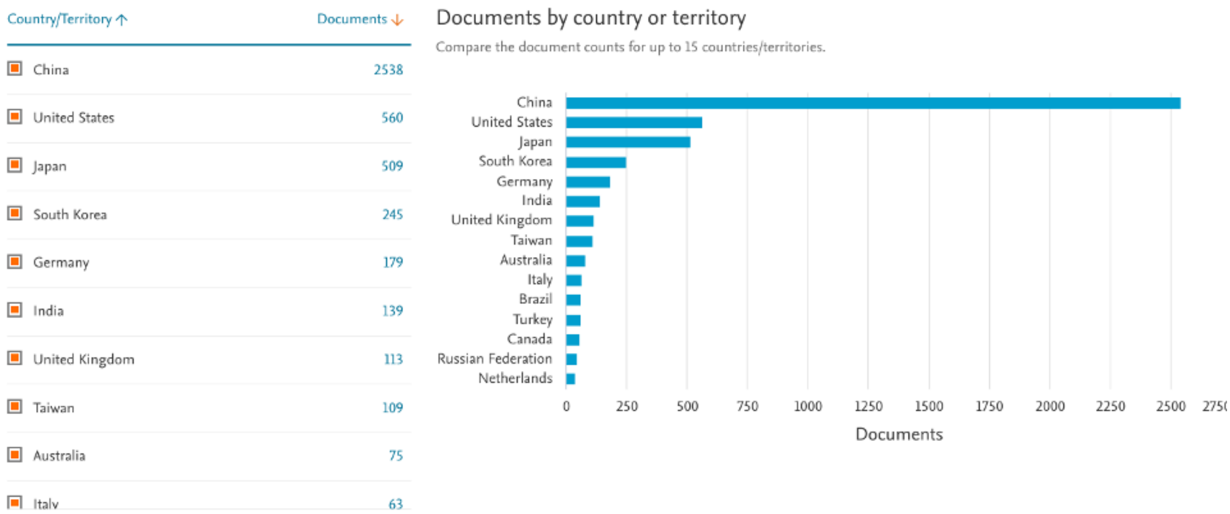


Figure 11.- Documents by country or territory (source Scopus).

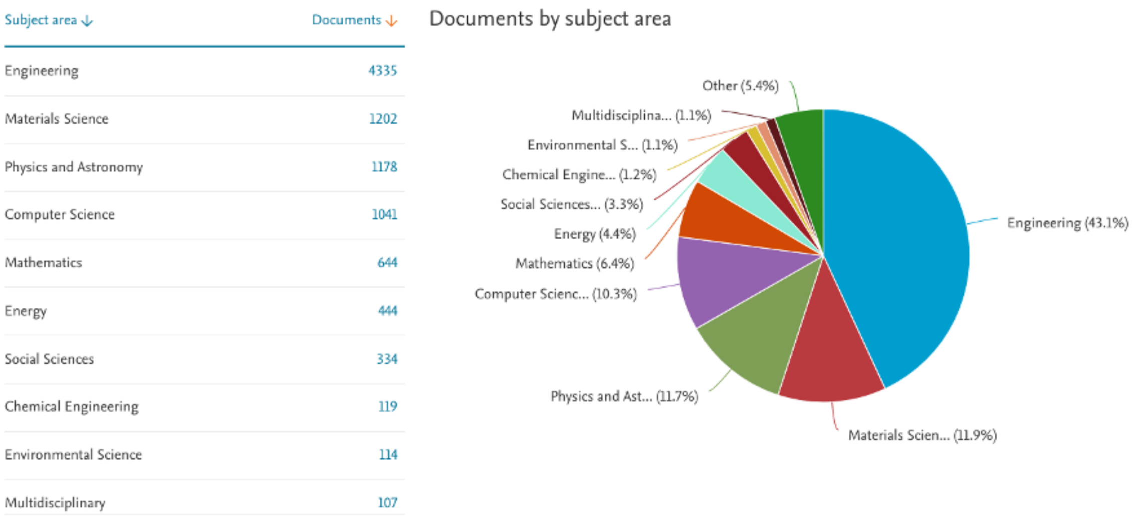


Figure 12.- Documents by source area (source Scopus).

Document type	Documents
Article	3009
Conference Paper	1959
Review	97
Conference Review	75
Book Chapter	59
Letter	18
Book	12
Note	12
Report	10
Short Survey	7

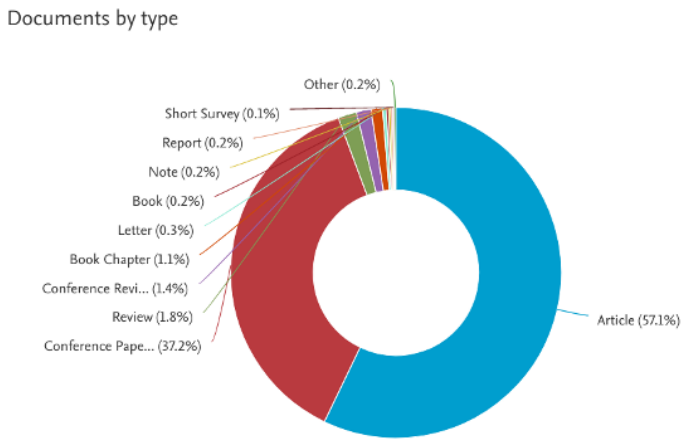


Figure 13.- Documents by type (source Scopus).

Funding sponsor	Documents
National Natural Science Foundation of China	652
National Key Research and Development Program of China	185
Fundamental Research Funds for the Central Universities	176
State Key Laboratory of Traction Power	118
Sichuan Province Science and Technology Support Program	74
China Postdoctoral Science Foundation	43
National High-tech Research and Development Program	40

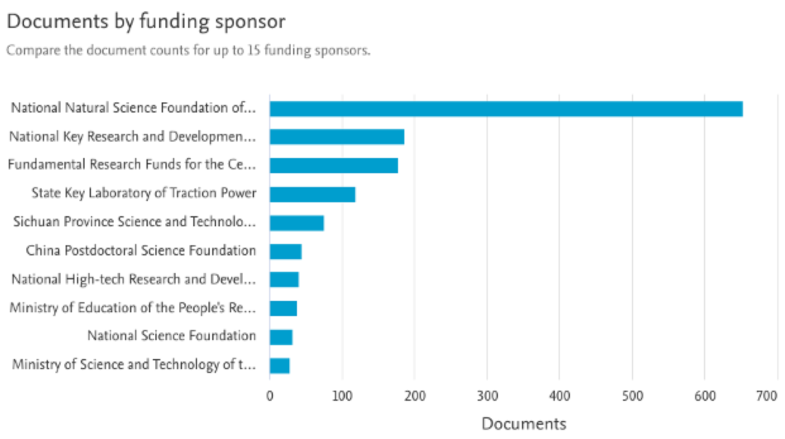


Figure 14.- Documents by funding sponsor (source Scopus).

To conclude this section, the construction of bibliometric networks may be of great interest. These networks may for instance include journals, researchers, or individual publications, and they can be constructed based on citation, bibliographic coupling, co-citation, or co-authorship relations. These networks are very useful to identify concepts. Using the WOS and Scopus data, the VOSviewer application was used to analyse the relevant author and co-author groups, as well as the most relevant and frequently used keywords (Figure 15).

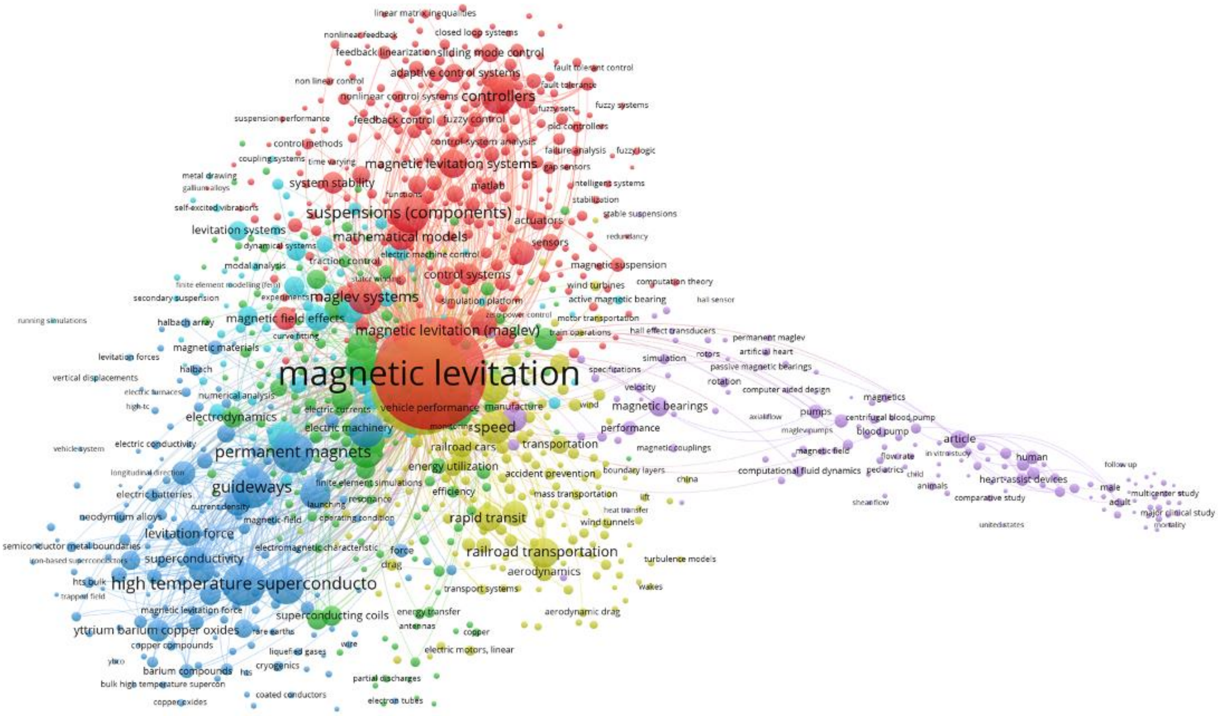


Figure 15.- Clusters of keywords (source Scopus).

A more refined search was then carried out by analysing the main review articles, the top 50 most cited papers and the top 50 most recent papers. The results can be summarised in the following sections.

5.2.3Main Review papers

The purpose of a review paper is to summarise the current state of knowledge on a particular topic, explaining it in summary form to the reader, putting the topic in a historical perspective, and discussing the findings presented in the most recent research papers. In this way, a review paper synthesises the results of several primary literature documents to produce a coherent argument on a topic and in which the author writes with authority because he or she is assumed to have mastered the topic, in its broadest sense. Reviews are often the basis for future research in virtually all areas of knowledge and a good review is likely to be a highly cited article.

A systematic search of the main review papers under study has been carried out. The aim of this study is to obtain a general overview of the main topics that have been dealt with in the literature. The main results, ranked in order of publication, from least recent to most recent, are shown in the Table 9, included in Appendix 1.

There are some early references with review papers presenting the first results of these technologies, published prior to 2006, but, undoubtedly, the key reference on which the rest of the work is based on the paper "Review of Maglev train technologies" (Hyung-Woo Lee et al., 2006). This paper reviews and summarizes maglev train technologies from an electrical engineering point of view and assimilates the results of works over the past three decades carried out all over the world. The purpose of this paper is to make the Maglev train technologies clear at a glance. Such paper covers general understandings, technologies, and worldwide practical projects. Further research needs are also addressed. In this paper, state-of-the-art maglev train technologies are investigated: Levitation including Electromagnetic Suspension (EMS), Electrodynamic Suspension (EDS) and Hybrid Electromagnetic Suspension (HEMS); Propulsion including Linear Induction Motor (LIM) and Linear Synchronous Motor (LSM); Guidance, using Magnetic Repulsive Force and Magnetic Attraction Force; and Transfer of Energy to Vehicle for Low-Medium Speed Operation and for High-Speed Operation. Finally, the paper shows and analyses the types and characteristics of maglev trains in operation: HSST (Japan), Transrapid (Germany) and MLU, MLX (Japan), and "ready for use": UTM (Korea), Swissmetro (Switzerland) and Inductrack (USA), at the time of publication in 2006.

Moreover, different review papers analysed the state-of-the-art of various technologies used in MDS.

In (Zhou et al., 2010), the coupled vehicle-guideway vibration problem, especially for the EMS system, is presented and divided into three main areas: the stationary vehicle-guideway, self-excited vibration; the moving vehicle-bridge coupled vibration; and the vehicle-guideway interaction caused by track irregularity. The available literature relevant to all three coupled vibration problems is reviewed, and the methodologies and main conclusions corresponding to each coupled vibration problem are compared and generalised as a reference for future work. The solutions proposed in the literature for the solution of the coupled vibration problems are also enumerated and their feasibility is discussed.

Reference (Nishijima et al., 2013) provides a roadmap of how superconducting technologies could address these major challenges confronting humanity. In this reference, the authors identify that Superconducting Maglev trains and motors for international shipping have the potential to considerably reduce the emissions that contribute to greenhouse gases while improving their economic viability by reducing losses and improving efficiencies. International shipping, alone, contributes 3% of the greenhouse gas emissions. Three sections of the roadmap identify how high-speed rail can be a major solution to providing fast, low energy, environmentally friendly transport enabling reduction in automobile and aircraft travel by offering an alternative that is very competitive.

More recently, the paper (Wang and Li, 2019) discusses the history and research progress of wireless power transfer (WPT) for railway transportation. In the field of railway transportation traction power supply, the problems caused by the traditional contact-type power supply method have become increasingly prominent: the overhead contact network prone to breakages, scraping and wearing the pantograph, etc. WPT technology, which avoids direct contact with the power supply sources and loads, effectively solves these problems. This paper focuses on the application of WPT technology for railway transit and introduces the research status in China and abroad. Moreover, the main technologies and primary problems of WPT, including magnetic coupler, segmented power supply, design of high-frequency inverter, system optimization and control and practical applications for trams, maglev vehicles, and high-speed trains, are reviewed. A detailed analysis and summary on the technologies is also provided.

In the paper (Li et al., 2023), the technical characteristics of the levitation control systems are described according to the basic principles of levitation systems, model building, mathematical derivation, and control objectives. Three kinds of typical levitation control methods are reviewed as well, namely: linear state feedback methods, nonlinear control methods, and intelligent control methods, according to their improvements and applications. Lastly, the paper summarizes and evaluates the advantages and disadvantages of the three methods, and future developments of levitation control are suggested.

This paper stated that future research on EMS levitation control algorithms should be based on traditional state feedback, with more emphasis on nonlinear control and intelligent control, especially regarding the improvement of the ability of nonlinear control methods to deal with complexity and timely degeneration, and the improvement of the interpretability and online computing efficiency of intelligent control algorithms. In addition, controlled objects should be transferred from the strategies of decentralized and independent levitation control and modular ideas of magnets to complex models, such as multi-electromagnet coupled systems and electromagnet-rail beam coupled systems, while considering issues such as time delay, network transmission, fault tolerance, and fault diagnosis to enhance the comprehensiveness and realism of theoretical research. Lastly, the designed levitation control methods should be evaluated on testbeds or real vehicles to verify their practicality by combining theory and practical application.

Finally, the paper (Beauloye and Dehez, 2023) reviews permanent magnet electrodynamic suspensions (PM-EDSs) used in ground transportation systems, such as magnetic levitation (maglev) trains. The different suspension topologies are first presented, considering separately their two main components, namely the track and the magnetic field source.

Beyond that, a phenomenological explanation of the evolution with the speed of the drag and levitation forces is provided, depending on the track topology. The models aimed at predicting the behaviour and performance of the suspension are then detailed, classifying them according to whether they are global or local. As seen in this review, a lot of interest has been given to PM-EDSs through the years but there is still no real integration of this type of suspension in maglev transportation systems. However, most of the research efforts have been limited to studying specific PM-EDS topologies, sometimes comparing their performance with another one. There is therefore a need for a global comparison between the existing topologies, which could help select a specific type of PM-EDS for a given application.

5.2.4Top 50 most cited papers

Table 10 in Appendix 1 includes the most cited papers. The topics covered in the most cited papers in the bibliography are:

- General (18%),
- Aerodynamics (12%),
- Control, (12%),
- Propulsion (12%),
- Modelling and simulation (8%),
- High temperature superconductors (6%),
- Magnet, magnetic bearings (6%),
- Infrastructure (6%),
- Design (4%),
- Guidance (4%),
- Structural performance (4%).

The most cited articles dating from the last 20 years focus on propulsion, guidance, and general operational aspects. In particular, the behaviour of superconducting materials, fuel consumption and emissions are addressed.

However, to analyse the most recent topics currently being addressed, it is necessary to look at the most recently published articles in the following section. Although they are not the most cited, they do provide an overview of the latest technological developments being made.

5.2.5Top 50 most recent papers

Table 11in Appendix 1 includes the most recent papers. The topics addressed most frequently in the literature in recent years are:

- Modelling and simulation (38%),
- Control, operation (22%),
- Suspension (20%),
- High temperature superconductors, HTS Maglev (18%),
- Vibrations (14%),
- Propulsion (12%),
- Low and Medium Speed Maglev trains, LMS Maglev (10%),
- Infrastructure (10%),
- Aerodynamics (10%),
- Tunnels (8%),
- General (8%),
- Energy, emissions (6%),
- Electromagnetic radiation (2%).

More recent papers focus more on performance and operation, in relation to vibrations caused by irregularities in the guidance system. Computer modelling and simulation methodologies are used to study these phenomena.

Secondly, there is growing concern about energy consumption and emissions. Among the latter, electromagnetic emissions are of concern. There is also a high percentage of publications showing concern about aerodynamic effects caused by pressure waves in tunnels, especially in high-speed trains.

Finally, the literature already distinguishes between two types of maglev trains: high-speed trains, using high-temperature superconductors, called HTS Maglev; and low- and medium-speed trains, called LMS Maglev, operating over short and medium distances and in urban areas.

5.2.6Patent analysis

Similarly, a patent analysis has been carried out. Several tools are available for this purpose. One of the most powerful is Lens, which has been used in this study. The Lens serves integrated scholarly and patent knowledge as a public good to inform science and technology enabled problem solving.

By using the keywords "magnetic levitation railway", the following patent search can be done:

https://www.lens.org/lens/search/patent/analysis?q=magnetic%20levitation%20railway

With this scope, the following patents have been found:

Patent Records	Simple Families	Extended Families	Cites Patents	Cited By Patents	Patent Citations
1,804	878	824	1,029	1,220	17,942

Figure 16.- Patent search (source Lens).

Thus, it can be noted that there are slightly more than 1,800 patents related to magnetic levitation in railways, which are catalogued in about 900 simple families (priority documents), slightly more than 800 extended families (similar technical content) and cite about 18,000 publications. In these terms, a great division can be observed when it comes to grouping the different existing inventions, with a great multitude of families to group them in (one for every two patents) and a 1:10 ratio between the number of patents and the number of publications. Figures 17-20 show the main collected data.

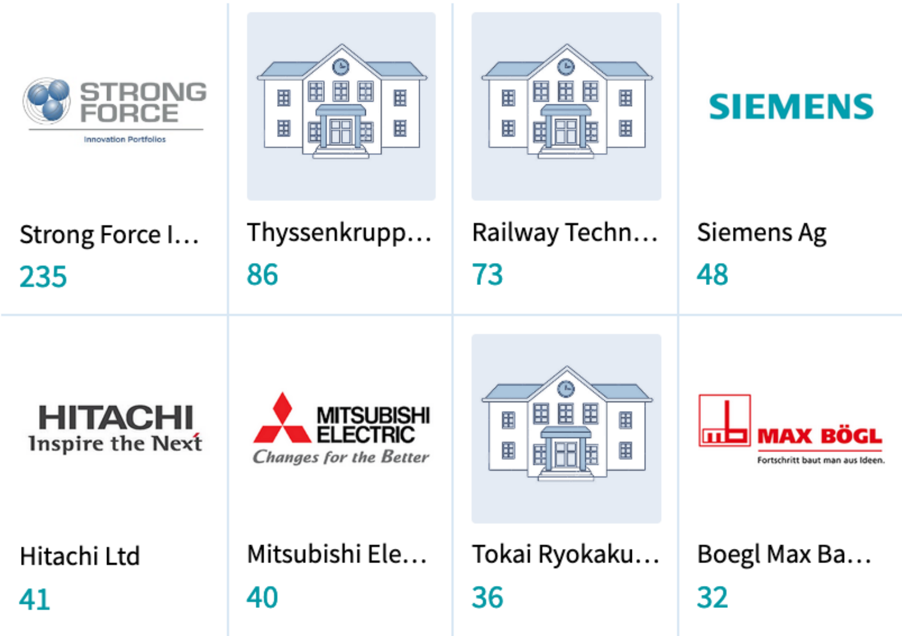


Figure 17.- Applicant name (source Lens).

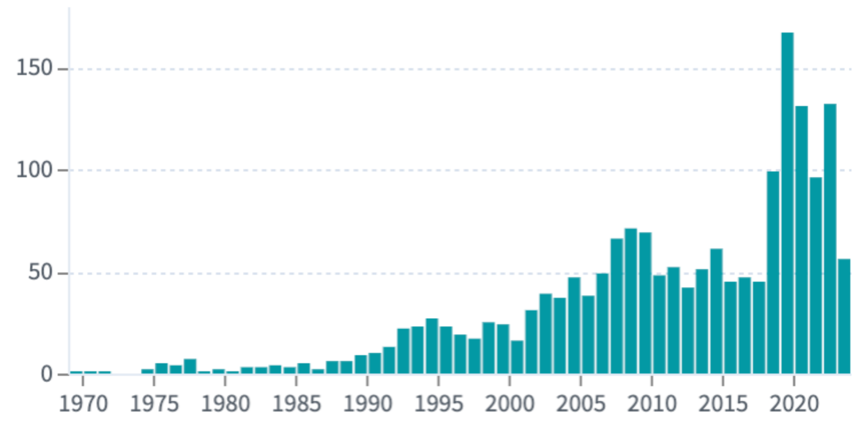


Figure 18.- Publication over time (source Lens).

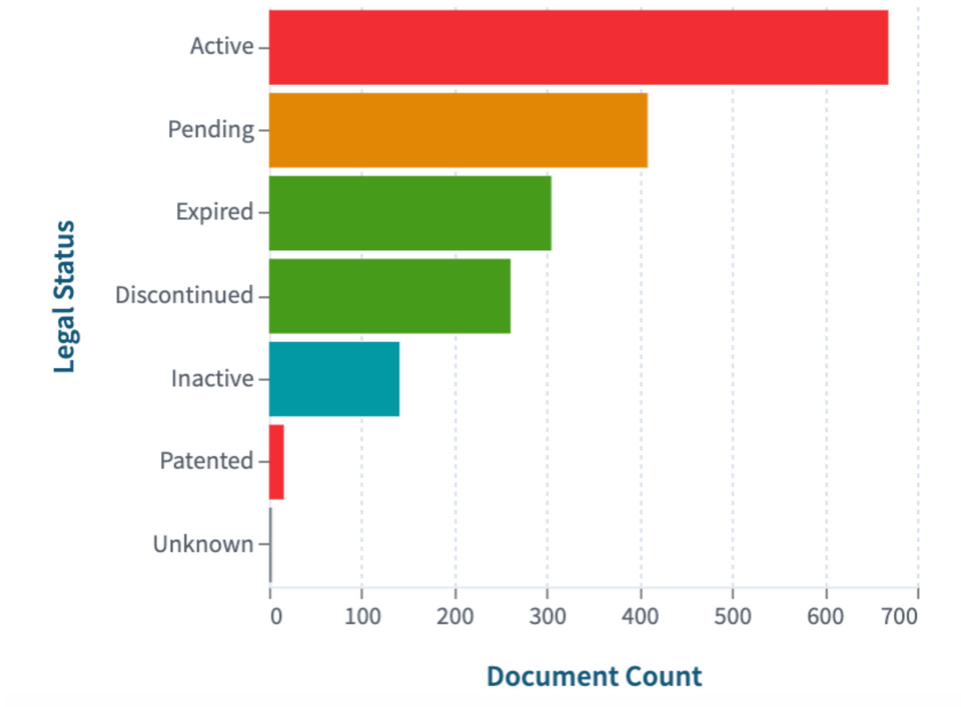


Figure 19.- Legal status (source Lens).

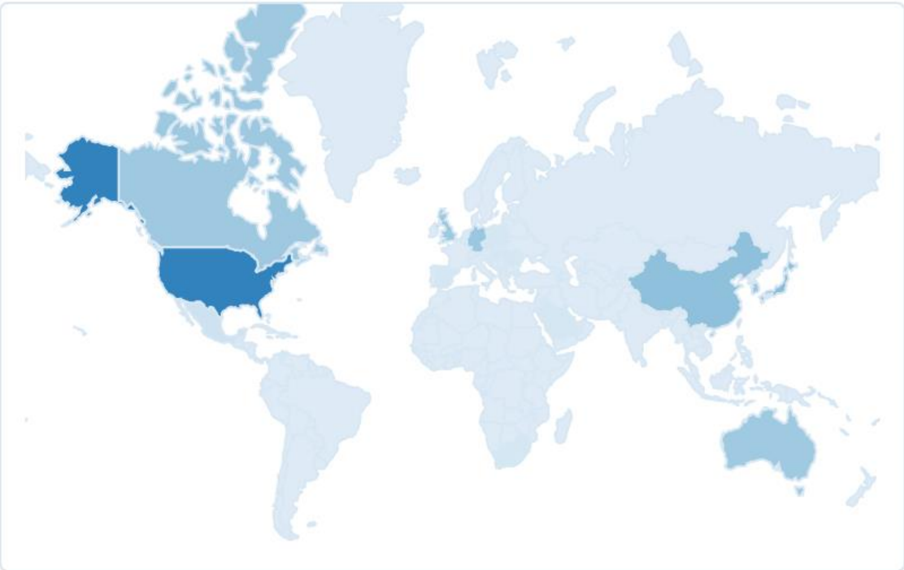


Figure 20.- Jurisdictions (source Lens).

Using the analytical tools of Lens, a more refined patent search can be performed. References (Axel and Siegbert, 2008; Choi et al., 2007; Friedrich et al., 2013; Friedric and Luitpold, 2009; Friedrich and Qinghua, 2018; Helmut, 1992; Hiroshi et al., 1981; Junji, 1993; Junji and Hisamitsu, 1994; Kyung et al., 2006; Lingqun, 2008, 2007; Luitpold et al., 2010; Luitpold and Friedrich 2013; Luitpold and Qinghua, 2010; Mielczarek et al., 2021; Markus and Harald, 2018; Masao, 1993; Radziszewski and Kublin, 2022; Robert, 2012; Sakae and Hitoshi, 1987; Shunsuke and Junji, 1988; Siegbert, 2012; Siegbert and Axel, 2013; Stefan, 2008; Taku, 2011; Taku and Yasuaki, 2011; Tomomi et al., 2019; Walter, 2007) include the patents listed as most relevant by Lens, being the relevance based on the query match score used in Elasticsearch. As described in the Lens documentation, the match score increases on the one hand the more concise the match field is (e.g., title vs. abstract) and the more times the term matches the document. Also, the score of a search term decreases if the term is common to all documents and is therefore less specific than other terms.

From this analysis, the 50 most relevant patents have been obtained, showing that there is a range between 2008 and 2014, and a second, somewhat less relevant range, around 2020-2021 (Figure 21).

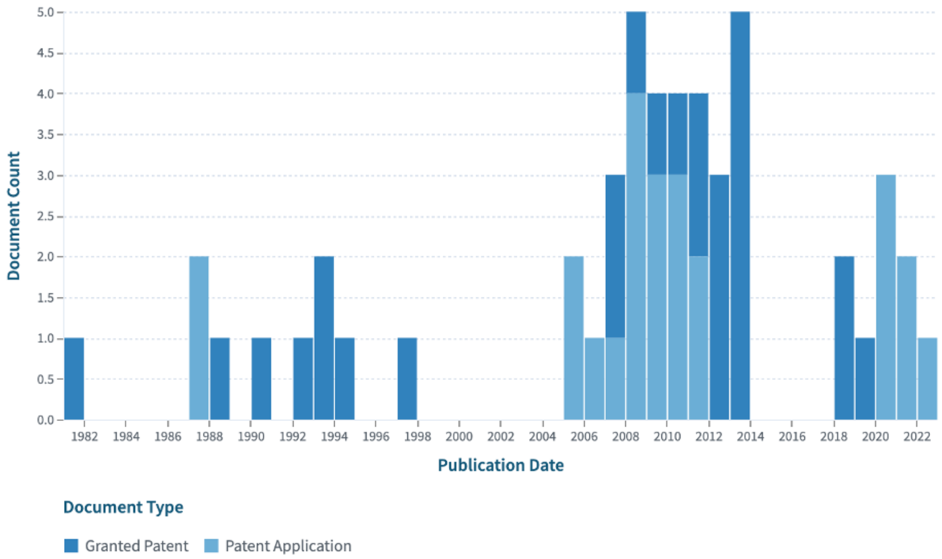


Figure 21.- Patent documents over time (source Lens).

Focusing on the first band with the highest percentage of the most relevant patents (2004-2014), they are basically linked to the US jurisdiction and around half of them to a single owner (Figure 22 and Figure 23). These patents are mainly related to improvements in the magnetic system of the track and the vehicle, including its guidance and propulsion, in some cases the design of the section of the vehicle itself and the rail itself, methods for its operation, the inclusion of compressed air, and in some cases the use of suspended rails.

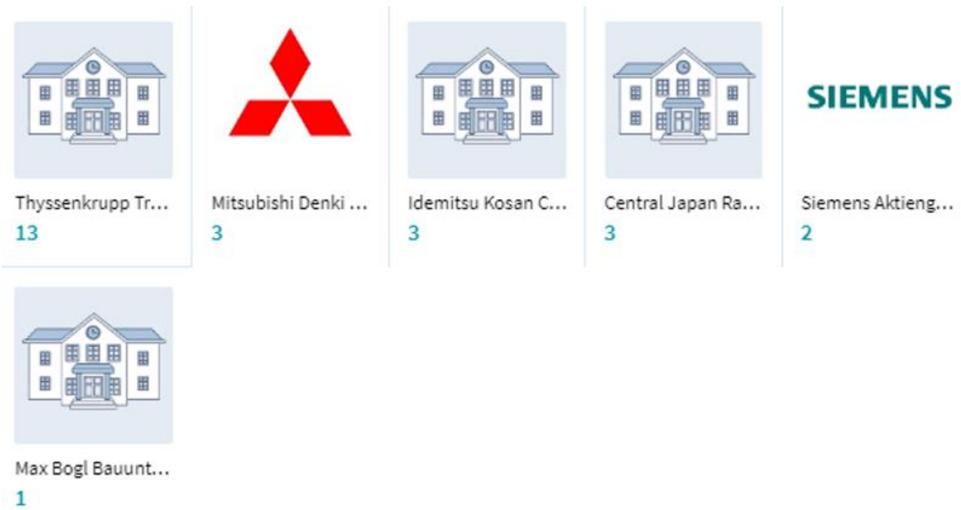


Figure 22.- Main owners of most relevant patent documents in 2004-2014 period (source Lens).

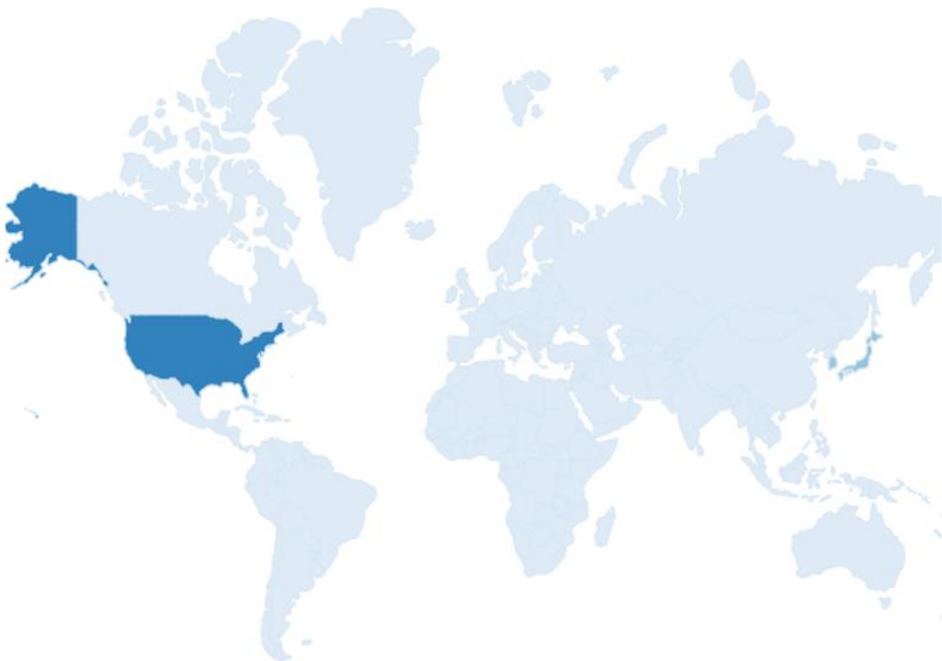


Figure 23.- Jurisdictions more relevant in 2004-2014 period (source Lens).

In relation to the range between 2018 and 2022, both the jurisdiction and the ownership of the most relevant patents are distributed among different areas, not concentrating only in one region (Figure 24). In this sense, the patents are mainly focused on the levitation systems themselves, specifically on the electrical part or on the methods to perform the control thereof.

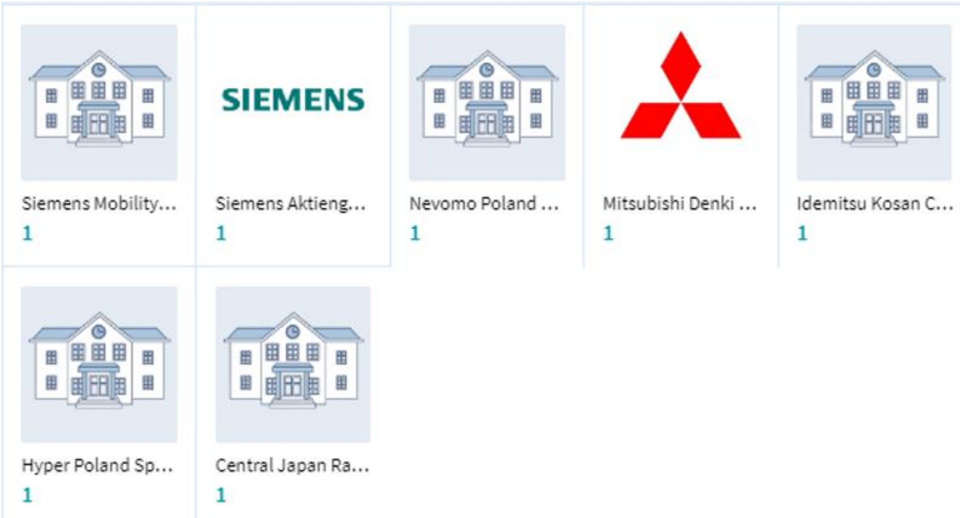


Figure 24.- Main owners of most relevant patent documents in 2018-2022 period (source Lens).

Likewise, concerning the 50 most relevant patents, only 38% are active, i.e., the granted patents are in force, including all published documents associated with the application. In the 24% of the cases, the granted patents are not in force due to expiration, non-payment of the fee, etc. although the patent has not reached its expiration date and can be reactivated. By last, 24% have expired or have discontinuities and have not yet been granted, and 14% are pending patents (Figure 25).

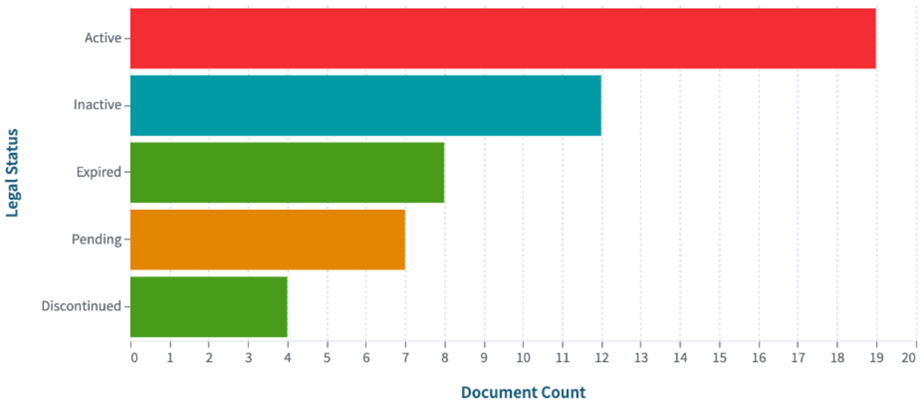


Figure 25.- Relevant Patent documents by Legal Status (source Lens).

5.3 Types of maglev-derived systems

Based on the methodology and the MDS categories shown in 5.1, four groups of MDS have been distinguished: maglevs, air-cushion transport systems, MDS operating on wheels and hyperloop systems.

5.3.1 Maglev systems

5.3.1.1 Introduction

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

There are different methods to generate the electromagnetic forces needed to adopt the technology in the transportation domain, the most common differentiation includes:

- **Electromagnetic suspension (EMS)**: the electromagnetic forces are generated by means of electromagnets on a magnetically conductive track;
- **Electrodynamic suspension (EDS)**: the electromagnetic forces are generated as an effect of relative motion between the conductive element and a source of electromagnetic field (e.g., permanent magnets with aluminium track, or permanent magnets' track and superconductive electromagnets);
- **Passive suspension**: there are other methods of force generation based on forces generated by passive elements, like permanent magnets, not based on dynamic effects, e.g., ferromagnetic levitation (5.4.1.5)

5.3.1.2 Electromagnetic systems (EMS)

Transrapid (Germany)

The Transrapid is a German-developed high-speed monorail train system based on Electromagnetic Suspension (EMS) technology as a joint venture of ThyssenKrupp and Siemens. Its development began in 1969, with the construction of a test facility in Emsland, Germany, completed in 1987. However, despite its technological advancements, the Transrapid has not been deployed on a long-distance intercity line. The system is developed and marketed by Transrapid International, a joint venture between Siemens and ThyssenKrupp.

The development of the Transrapid system was driven by the advantages of maglev technology for high-speed operation compared to low and moderate-speed systems. The evolution of the Transrapid vehicles is notable (Figure 26):

In 1969, the TR01 vehicle was developed for demonstration purposes,

- The TR02, introduced in 1971, featured a linear motor with a short primary winding for propulsion,
- The TR03, developed in 1974, incorporated an active control system for guidance,
- The TR04, developed in 1974 by Krauss-Maffei, was 15 m long, weighed 20 t, and had 20 seats. It utilized electro-dynamic suspension (EDS) and achieved a top speed of 253 km/h in 1977,
- The TR05, built in 1977 by Thyssen Henschel and Siemens, was 26 m long and utilized a long primary linear motor in the guideway; It reached a top speed of 75 km/h,
- The TR08, developed in 1983 for operational speeds of 400 km/h, was 54 m long and weighed 120 t.

Figure 26.- The evolution of the Transrapid vehicles. (Source: [maglev])

In 1987, a 30-km long oval test loop was constructed in Emsland, Germany, furthering the testing of Transrapid technology. The TR06 set a new speed record in 1988, reaching 412 km/h, ranking as the second fastest maglev train globally at the time. In 1989, the TR07 achieved a top speed of 436 km/h. After a series of inspections and evaluations in 1991, Transrapid maglev technology was deemed ready for commercialization.

In 1992, a proposal was made to utilize the Transrapid maglev system on the Berlin-Hamburg line (292 km-long). For commercial operation, the TR08 vehicle was developed with improved structure and reliability, achieving a maximum speed of 436 km/h in 1999. However, in 2000, the German government decided to cancel the maglev project due to financial concerns, opting for conventional high-speed rail instead.

In December 2000, Shanghai initiated the construction of the world's first commercial high-speed maglev line, spanning 30 km and commencing commercial operation in 2003, with a top speed of 430 km/h. In test runs, it reached a remarkable speed of 501 km/h.

The last Transrapid maglev train, TR09 (Figure 27 and Table 1), was completed in 2005. Unfortunately, a tragic incident occurred on September 22, 2006, when the Transrapid collided with a maintenance vehicle, resulting in the loss of 22 lives. Subsequently, the Emsland test track was closed in 2011, and the last TR09 train was preserved in a museum.

Today, the Transrapid technology is active only on Shanghai maglev and without further implementation/improvements. In 2013, the 10-year service contract with Transrapid expired and the Chinese partners took over all the technology and maintenance tasks.

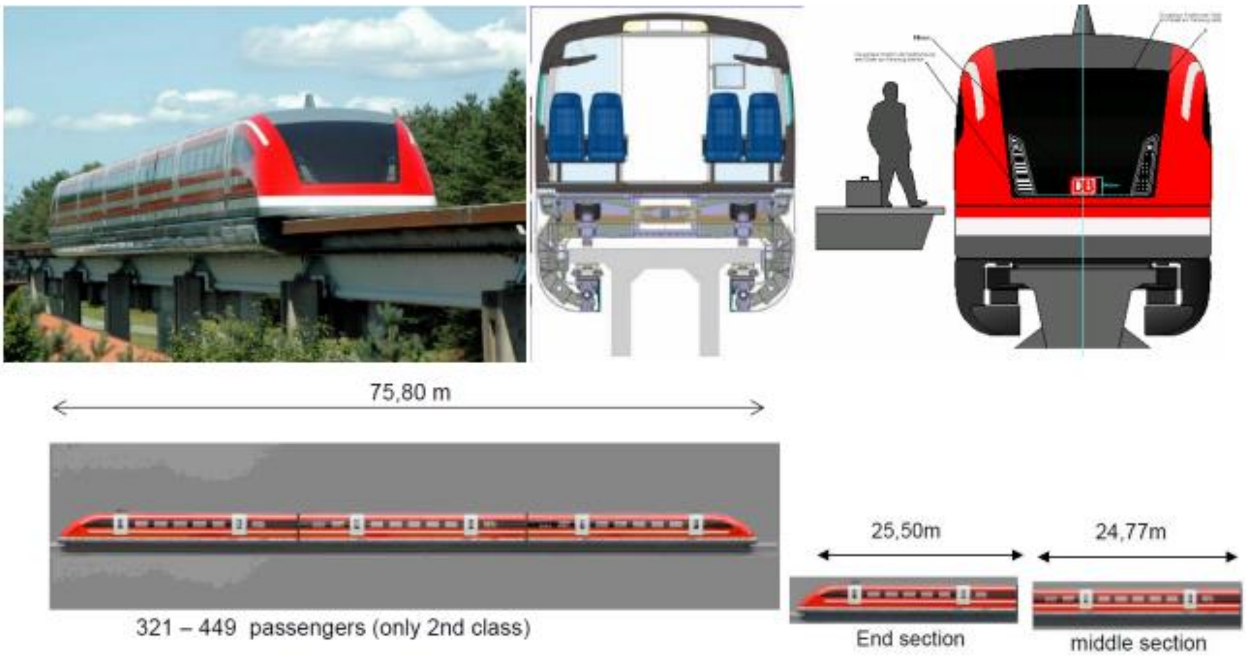


Figure 27.- Features of the Transrapid TR09. (Source: [maglev])

Table 1.- Transrapid system description

Sections	3
Total length	75.8 m
Vehicle width	3.7 m
Vehicle height	4.25 m 3.35 m (from guideway gradient)
Inner width of carriage body	3.43 m
Inner height of carriage body	2.1 m 2.05 m (entrance door area)
Tare weight	169.6 tons
Gross weight	210 tons
Design speed	505 km/h
Passenger capacity	449 seats

<u>Levitation and guidance</u>: electronically controlled support magnets located on both sides along the entire length of the vehicle pull the vehicle up to the ferromagnetic stator packs mounted to the underside of the guideway. Guidance magnets located on both sides along the entire length of the vehicle keep the vehicle laterally on the track. Electronic systems guarantee that the air gap remains constant (nominally 10 mm).

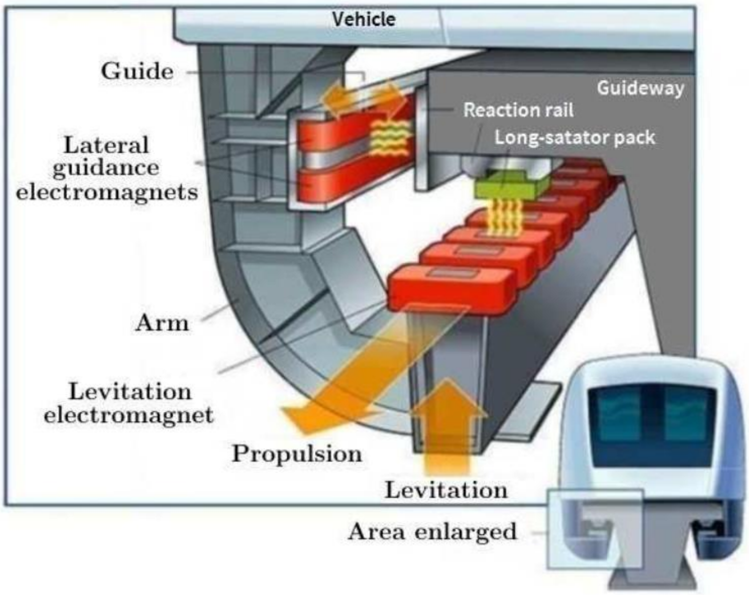


Figure 28.- Levitation and guidance system of the Transrapid vehicle. [Eu, 2015]

Propulsion: the synchronous long-stator linear motor of the Transrapid maglev system is used both for propulsion and braking (Figure 29). It functions like a rotating electric motor whose stator is cut open and stretched along under the guideway. Inside the motor windings, alternating current generates a magnetic traveling field which moves the vehicle without contact. The support magnets in the vehicle function as the excitation portion (rotor). The propulsion system in the guideway is activated only in the section where the vehicle runs. The speed can be continuously regulated by varying the frequency of the alternating current. If the direction of the traveling field is reversed, the motor becomes a generator which stops the vehicle without any contact. The braking energy can be re-used and fed back into the electrical network.

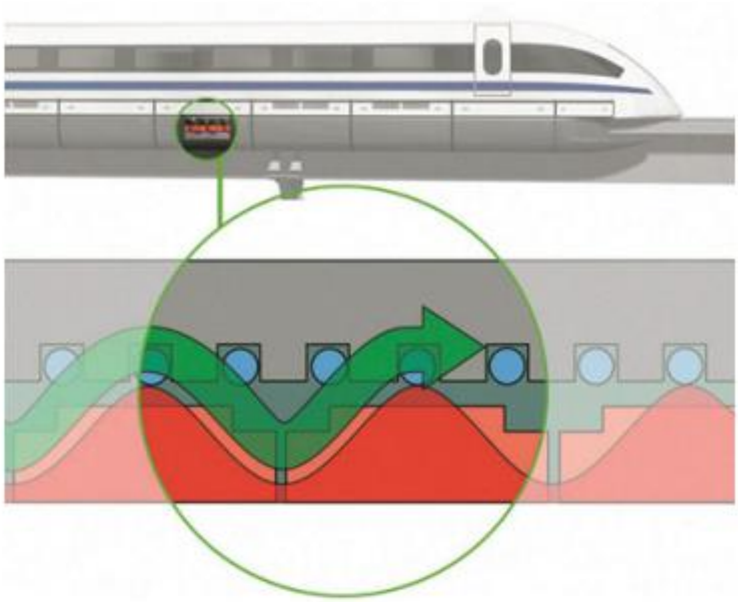


Figure 29.- Propulsion system of the Transrapid vehicle. Source: [maglev2]

Linimo (Japan)

The urban transit system known as Linimo, utilising electromagnetic technology and Linear Induction Motors (LIM), has been in successful operation along the Tobu Kyuryo Line in Nagoya since 2005. Impressively, Linimo accommodates a daily ridership of 20,000 passengers and has demonstrated profitability, surpassing its operational expenditures.

The line is 8.9 km long with maximum inclines of 6% and minimum curve radii of 75 m. The vehicle run with maximum velocity of 100 km/h. System operates using ATC and ATO subsystems.

The genesis of the Linimo system can be traced back to the mid-1970s when Japan Airlines (JAL) embarked on a development initiative. This endeavour was instigated by the pressing necessity for a novel transportation system to connect the newly established Narita international airport with the city of Tokyo. This protracted developmental history ultimately culminated in the realization of the Linimo system and its successful deployment on the Tobu Kyuryo Line.

The structural configuration of the Linimo system is best exemplified by the HSST-100L prototype. The guideway infrastructure is composed of several essential components, including a U-shaped rail for levitation, a reaction plate tailored for the operation of the Linear Induction Motor (LIM), sleepers, girders, power rails, and signalling cables. The Linimo vehicle (Figure 30, Figure 31) comprises five bogies, each of which integrates a levitation/propulsion module, air springs, and associated components.

Figure 30.- The Linimo Maglev Train. ***.*** *Source: [linimo]*

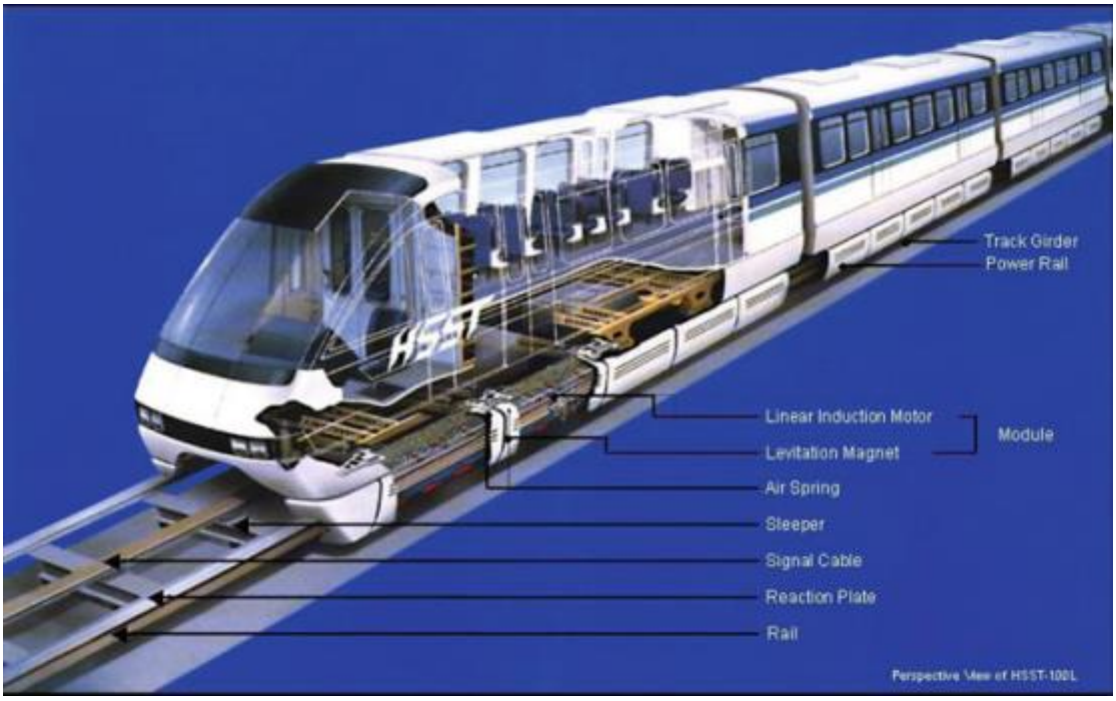


Figure 31.- The structural configuration of the Linimo system. [Han, 2016]

Levitation and guidance: the suspension and guidance forces are provided by a typical U-core electromagnet. The nominal and landed airgaps are 8 and 14 mm (Figure 32). The input voltage to the magnet driver is 275 V DC. The capacity of the levitation magnet is 10.2 kN/m.

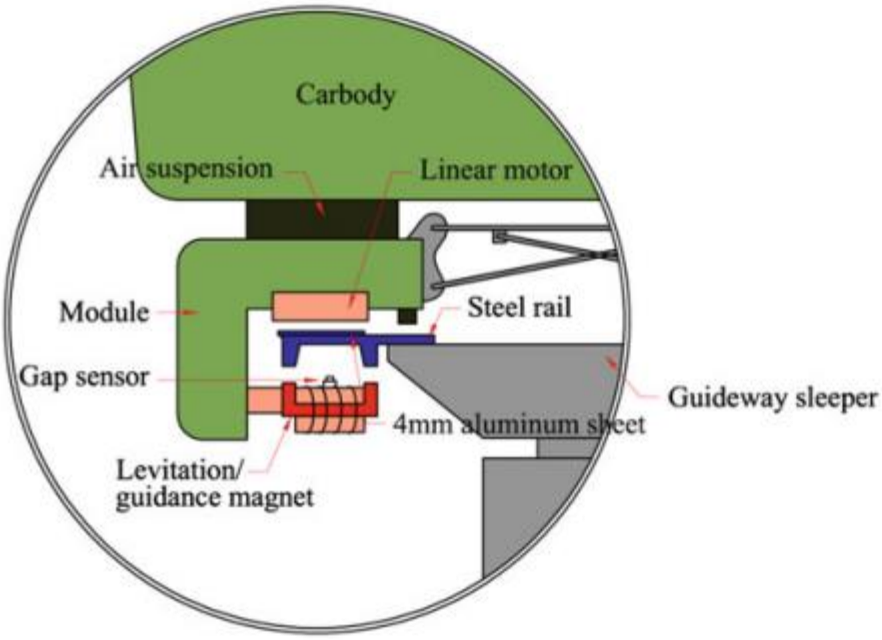


Figure 32.- Levitation and guidance system of the Linimo vehicle. [linimo2]

Propulsion: the thrust needed for propulsion is generated by 10 LIM per car. The rated thrust per car is 39.8 kW/car. One Variable Voltage Variable Frequency (VVVF) with IGBT and PWM is used per car. Although the current control is essentially achieved by the thrust command calculated using ATO notch signal or manual notch signals, the thrust command is compensated by the vehicle weight data, which is picked up by air suspension pressure transducers. In the range of high speed, the thrust is limited due to the limitations of the output voltage of the inverter. The output frequency is also an important factor determining the speed of the vehicle. Non-contact speed detection devices are used as a source of speed data for the inverter system.

Figure 33.- Propulsion system of the Linimo vehicle.

Incheon Airport Maglev (Ecobee) and Daejon Maglev (Korea)

The development of low-speed maglev systems in Korea began in the 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, with an annual ridership of approximately one million passengers. The maglev train consists of two cars (Figure 34) and can reach a top speed of 100 km/h, with a maximum acceleration of 3.6 m/s². Additionally, in 2016, a 6.1 km-long urban maglev line was inaugurated at Incheon airport, called ECOBEE.

a) b)

Figure 34.- The Daejeon Maglev: a) vehicle and infrastructure b) interior structure. [utm-02]

Incheon International Airport and its surrounding area were selected by the Korean government as a maglev demonstration line for ECOBEE in 2007 (Figure 35, Figure 36). The Incheon International Airport is a hub airport in the East Asia region that was opened in 2001 and was used by 46 million passengers in 2014, and the number of passengers that use the airport has long been rapidly increasing. Considering the increasing number of airport passengers and visitors to nearby tourist attractions, this route was chosen due to its competitiveness. The final planned route of 57 km in length is a circular line traveling along the coastline of Yeongjongdo Island, where the Incheon International Airport is located.

ECOBEE is an EMS-based system, with U-shaped magnets and LIMs for levitation and propulsion. The guidance forces are provided by the lift magnets, which are proportional to lateral displacement. The thrust for acceleration and deceleration is achieved by the LIMs, with the on-board primary windings and the secondary reaction plate in the guideway. The mechanical brakes are also used with the LIMs. The operation scheme is almost the same as that of Linimo. In addition, the vehicle has landing skids for emergency landing and landing rollers for rescue operation by other vehicles. The maximum design speed is 110 km/h, and the speed was attained by the running tests.

a)

b)

Figure 35.- The Ecobee Maglev Train: a) vehicle and infrastructure b) interior structure. [ecobee]

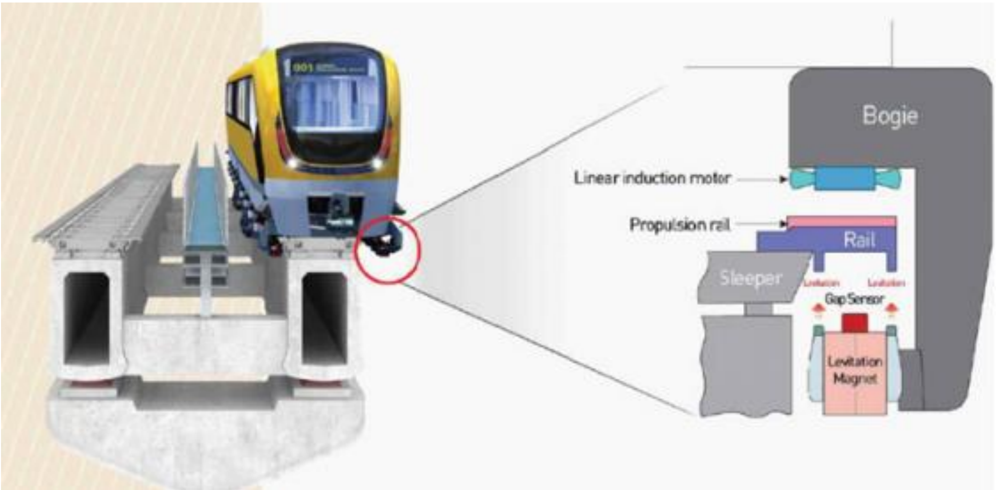


Figure 36.- The structural configuration of the Ecobee system. [ecobee2]

ECOBEE system details

- Levitation: the electromagnet for ECOBEE is composed of two poles, 4 yokes and 8 windings. The F-shaped rail facing the magnet has the profile shown in figure. Long-pole design is employed to reduce the magnetic drag forces. The nominal current for empty load is measured to be about 30 A, while it is 35 A for full load, with nominal airgap of 8 mm. The levitation control is based on the 5 states feedback scheme. The measurement of airgap and acceleration is available through an external sensor module containing two gap sensors, and an accelerometer is placed in between two poles. Two inductive gap sensors are used to output a smoother signal from two measured signals by switching them, avoiding discontinuity in measured signals at rail joints.
- Propulsion: ECOBEE system utilises short stator linear induction motor whereas the vehicle primary is equipped with the 3-phase winding and the infrastructure part is a propulsion rail.
- Operating costs: a relative comparison to wheel-on-rail light railway vehicles was performed based on the energy consumption of ECOBEE measured when station spacing is assumed to be 1 km. The energy consumption was measured to be 20% higher than that of wheel vehicles. Allowing for the lower frequency of replacement of components and the human effort involved, the total operating cost was estimated to

be 60-70% that of wheeled vehicles [Gieras, 2019]. The actual operating cost will be available after the operation of ECOBEE some years in the future.

- Construction costs: The construction cost for the elevated guideway is 39 million USD/km (2009) and included countermeasures that were necessary due to region-specific conditions (poor subsoil, salt damage) and the characteristics of the route. However, in ordinary cities, the cost should not exceed 36 MUSD/km [Gieras, 2019].

Chinese EMS Maglev in Beijing line S1 and Changsha (China)

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. This three-car maglev train has an operational speed ranging from 39 to 140 km/h and can accommodate 363 passengers, with a maximum daily ridership exceeding 12,000.

A second urban maglev system in China, integrated into the Beijing Metro network, opened in 2017, spanning 10.2 km. This system features a six-car maglev train with a top operational speed of 100 km/h and a capacity of 1032 passengers. Both Changsha and Beijing maglev trains) are manufactured by CRRC and employ short-stator asynchronous traction technology.

The system is based on normal conducting EMS guiding technology and SLIM short-stator linear induction motor (SLIM) traction technology.

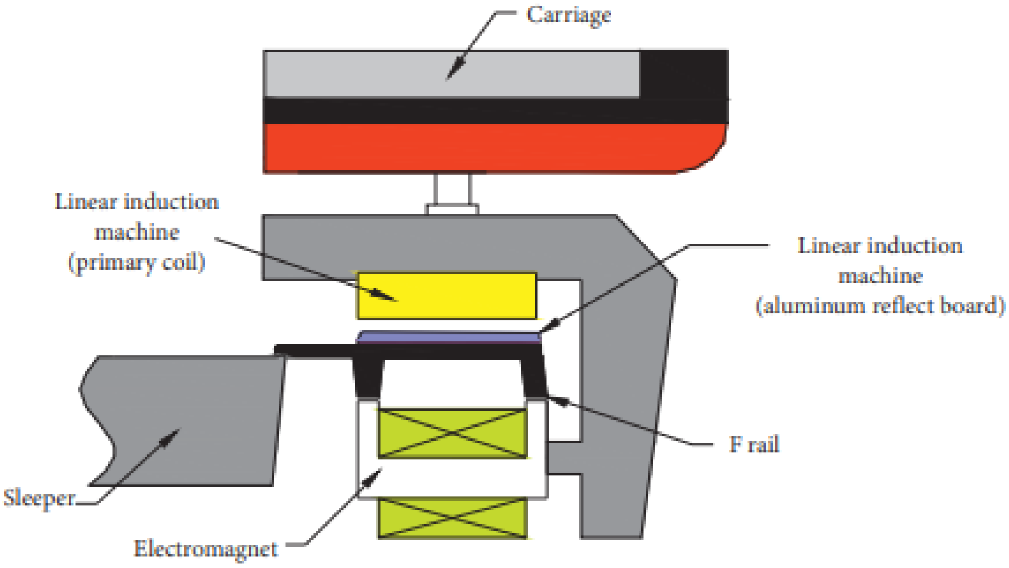


Figure 37.- The structural configuration of the Changsha and Beijing Maglev trains. [Xiao,2020]

a) b)

Figure 38.- The Changsha Maglev: a) vehicle and infrastructure b) interior structure. [Changsha]

First, the Changsha maglev project connects the airport and the south station of the high-speed railway, spanning a total length of 18.5 km, with the entire track being elevated and featuring three stations. Initially, five trains with a 3-section configuration were introduced into operation. The project officially commenced public operation on May 6, 2016.

From May 2018, the maglev train operating on the Changsha line had accumulated an impressive mileage of 2 million km and transported approximately 6.2 million passengers.

Statistical data from the past two years indicates an average operation punctuality rate of 99.85%, and an impressive 99.95% of the operation schedules consistently met.

Lastly, the Beijing maglev application line is called S1 line. The whole length of the line is 10.2 km with 8 stations. 10 trains with 6-sections configuration entered public operation in the early phase of the project. This project has been started in October 2013 and entered public operation at end of 2017.

a) b)

Figure 39.- The Beijing Line S1: a) vehicle and infrastructure b) interior structure. [s1line]

Tongji University Maglev (China)

China imported the German Transrapid maglev system to Shanghai in 1999, meanwhile own research on high-speed maglev systems started in the same year. Based on the Transrapid maglev system, the first prototype train, manufactured by CRRC, was unveiled in Qingdao in 2019. It uses electromagnetic suspension and is designed for a top speed of 600 km/h. The train has a flexible configuration from 2 to 10 cars to meet different needs and each car can accommodate about 100 seated passengers (Figure 40). The prototype train was tested on a test line at Tongji University in Shanghai in 2020. It still needs some time to validate the performance of this maglev system before it can be tested at the designed speed. Although China has the largest high-speed railway network in the world, the maglev system is developed to fill the gap between the current high-speed trains (350 km/h) and aeroplanes (800 km/h) to support the national comprehensive transport network plan for 2035.

Figure 40.- The Tongji University Maglev - vehicle and infrastructure. [tongji]

Fenghuang Maglev (China)

The Fenghuang Maglev is a 9.1-km maglev line, designed with a maximum speed of 100 km/h and featuring four stops, serves as a crucial link connecting the high-speed railway station with an ancient town and nearby scenic areas. This new transportation system (Figure 41) is anticipated to enhance Fenghuang's appeal as a tourist destination by providing convenient, noise-free, cost-effective, and environmentally friendly transportation options for visitors.

Figure 41.- The Fenghuang Maglev. [fenghuang]

Sengenthal (Germany)

Max Bögl Company has developed a new urban maglev people mover system known as the Transport System Bögl (TSB). This automated guided vehicle system is designed for urban traffic applications spanning distances of 5 to 30 km and is adaptable for use worldwide. The trains for this system consist of two or more wagons, each powered by a system of short stator linear motors (Figure 42). The vehicles utilise electromagnetic levitation for propulsion while resting on skids when stationary.

The TSB encompasses a specialized guideway, equipment, operations control technology, and facilities, such as stations and maintenance buildings. Its high reliability is attributed to the redundant and independently functioning core systems, including the drive, levitation, and control mechanisms.

To evaluate the Transport System Bögl, a dedicated test track has been established at Max Bögl's headquarters in Sengenthal, Germany. This test track serves as a platform for assessing the maglev system, monitoring improvements during its development, and conducting realistic tests related to its operation and maintenance.

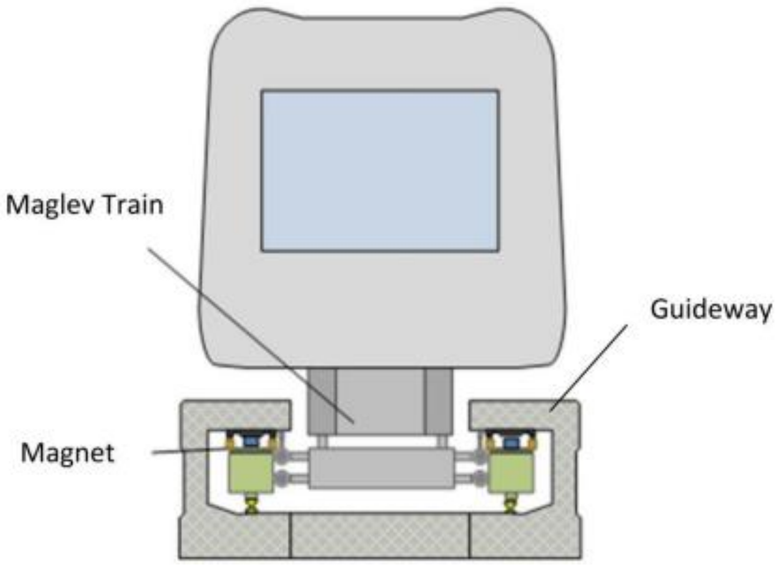


Figure 42.- The structural configuration of the Transport System Bögl trains. [TSB]

At this moment, the test track is round 800 m long, wherein the maglev train can drive at the maximum speed of 100 km/h. The guideway is elevated and consists mostly of concrete prefabricated compounds. A piece of the guideway is made of steel.

Birmingham maglev (England)

The Birmingham maglev in England, which commenced operations in 1984, holds the distinction of being the world's first commercial maglev transport system. This fully automated system utilised an elevated concrete guideway. Feasibility studies for a connection with the airport, railway station, and exhibition centre began in 1979 under the ownership of West Midlands County Council, which was the airport's owner at the time.

The maglev system covered a track length of 600 m, with EMS technology characterized by 15 mm gap (Figure 43). Although it operated successfully for almost eleven years, issues related to the obsolescence of electronic components and a lack of available spare parts led to its unreliability in its later years. Consequently, the Birmingham maglev ceased operation on June 18, 1995, following an investigation that deemed the cost of reinstating and maintaining the system to be prohibitively high.

Figure 43.- The Birmingham Maglev. [Birmingham]

5.3.1.3 Electrodynamic systems (EDS) based on superconductors

Chuo Shinkansen (Japan)

Japan started its research and development on the maglev system after the opening of the first high-speed railway between Tokyo and Osaka 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 (Figure 44).

The 0-Series was developed after the maglev system was proved to be commercially viable. On April 22, 2015, the Japanese superconducting maglev system L0 achieved a running speed of 603 km/h – a record for any guided vehicle. The L0 is also planned by the Central Japan Railway Company to be in service over the route between Tokyo and Nagoya in 2027, as the first phase of its entry into public service.

The Japanese MLX models used superconductivity and the vehicle-guideway design is based on repulsive magnetic forces. The repulsive force for suspension is weak at low speed so the trains run on rubber tires up to the speed of 100 km/h before becoming magnetically levitated. This dual suspension makes the vehicles more complex, but the tests of high-speed running have proven the technical feasibility of the system.

Since 1997, the superconducting maglev system (including the L0 mentioned earlier) has been undergoing test runs on the Yamanashi maglev test line with the aim at achieving its commercialisation. Ultimately, the system is planned to be applied to Chuo Shinkansen, connecting three major metropolitan areas in Japan: Tokyo, Nagoya, and Osaka.

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. The propulsion method is the iron-cored long-stator LSM, wherein the superconducting magnets are also used as the field for LSM. This concept is a representative electrodynamic levitation system, with the prime advantage of having no active control requirement. The guideway has a U-shape made of concrete (Figure 45). Each bogie has 8 magnets, which make 2 magnetic poles on either side. The three-phase primary windings of LSM are installed in between inner and outer layers of the side wall.

Figure 44.- The evolution of the MLX vehicles. [maglev]

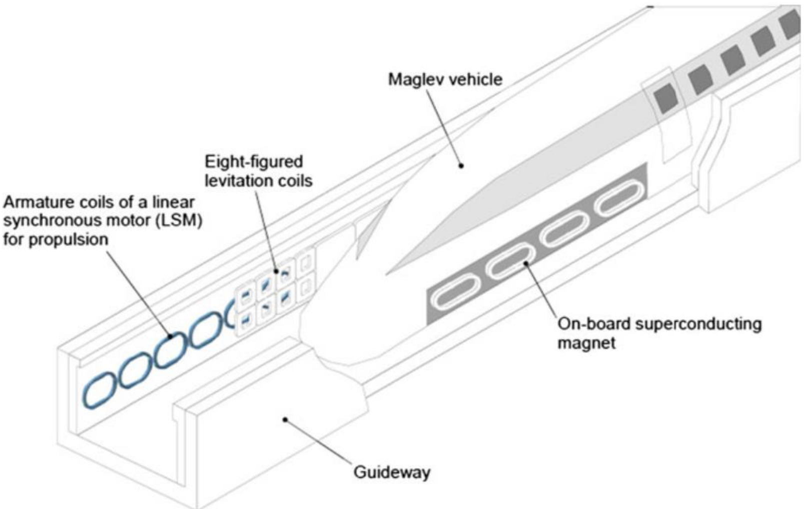


Figure 45.- The structural configuration of the Chuo Shinkansen. [maglev]

HTS Maglev–ETT (China)

On December 31, 2000, the first crewed high-temperature superconducting maglev wagon was tested successfully at Southwest Jiaotong University in Chengdu, China – capital of southwest China's Sichuan Province. This system is based on the principle that bulk high-temperature superconductors can be levitated or suspended stably above or below a permanent magnet. The YBCO bulks (77K) constructed by Domestic manufacturer were utilised.

In March 2013, a group of scholars at Southwest Jiaotong University made significant strides in the development of test facilities for the high-temperature superconducting maglev train, known as ETT (Evacuated Tube Transport). When ETT was put into operation, it functioned within a vacuum environment, maintaining a pressure level just one-tenth of normal atmospheric pressure. As a result, air resistance was dramatically reduced, enabling the train to achieve higher speeds. However, due to the limitations of the test facilities (Figure 46), which featured a 6-meter diameter tube, the prototype train was only tested at a speed of 50 km/h.

Figure 46.- Prototype of the HTS Maglev–ETT. [Li,2016]

In 2021, the world's first locomotive prototype using high-temperature superconducting magnetic levitation technology (Figure 47) has been unveiled in Chengdu City.

The system, jointly developed and built by Southwest Jiaotong University, the China Railway

Group and CRRC Corporation, has been designed to run at a speed of 620 km/h.

Figure 47.- The HTS Maglev. [maglev]

Maglev-Cobra

The Maglev Cobra is a Brazilian maglev train, which was developed at Federal University of Rio de Janeiro (UFRJ) by Instituto Alberto Luiz Coimbra for Graduate Studies and Research in Engineering (Coppe) and by the Polytechnic School through the Laboratory of Applications of Superconductors (LASUP).

Maglev-Cobra is based on the interaction between superconductive YBCO bulk blocks with NdFeB magnets.

The prototype was presented in 2009, which consisted of a module (wagon) with capacity for 28 persons that would travel at 30 km/h (Figure 48). In 2018, the test line was being operated in the testing phase in a 200-meter stretch, on the premises of the University City of UFRJ, connecting two buildings of the Technological Centre and transporting more than 1000 students every day. Having successfully completed the testing phase, the University has issued an application for international certification and is awaiting the result of its approval to begin with its industrial production.

In 2020, the COVID-19 activity and mobility restrictions ended up, making it difficult for UFRJ to search for partners to enable the expansion of maglev. The project is currently abandoned in Rio de Janeiro, due to lack of investments.

In Maglev-Cobra (Figure 49), levitation repulsive forces are generated due to the flux pinning effect between the superconducting material within the vehicle cryostat and NdFeB permanent magnets Halbach arrays installed on the guideway. Each cryostat contains 24 YBCO bulks of 32×64×12 mm in 2 rows. The bulks are placed within the copper block, which is filled with liquid nitrogen (LN2) in cavity. The main advantage of this system is that it is passively stable, providing both levitation and guidance.

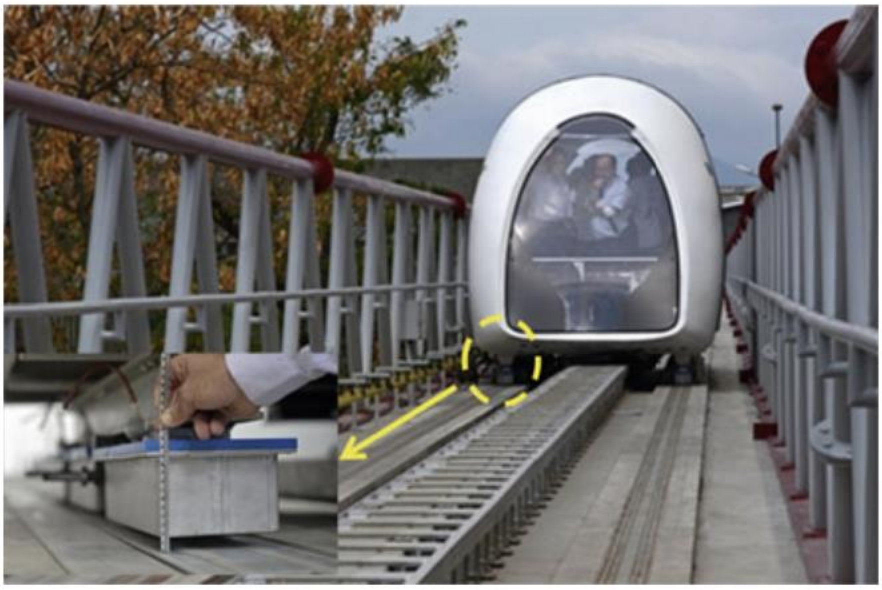


Figure 48.- The Maglev-Cobra. (source: Maglev Cobra)

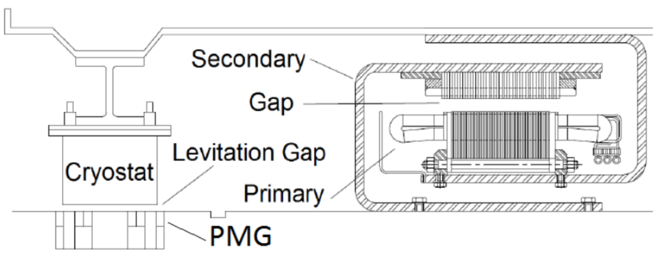


Figure 49.- The structural configuration of the Maglev-Cobra. (source: Maglev Cobra)

5.3.1.4 Electrodynamic systems (EDS) based on permanent magnets

Indutrack Urban Maglev (United States of America)

Indutrack was invented by a team of scientists at Lawrence Livermore National Laboratory in California, headed by physicist Richard F. Post. A passive induced-current system employing permanent magnets on the moving vehicle, in the Indutrack system repelling magnetic forces are produced by the interaction of a flux-concentrated magnetic field, produced by permanent magnets arranged in a Halbach array electromagnets, with an inductively loaded closed electric circuit.

On the topic of the Indutrack system study, General Atomics started the Low-Speed Urban Maglev Technology Development Program, with the aim of developing an alternative Maglev system for a public transport system.

In the Indutrack Urban Maglev, the levitation system uses vehicle mounted permanent magnet double Halbach arrays (Figures 50-51). The orientation of the magnetization of the magnets in the Halbach array is arranged such as to concentrate the field lines below the array while nearly cancelling the field above the array. This results in a system which requires no active magnetic shielding of the passenger compartment.

Figure 50.- Visualisation of the Inductrack Urban Maglev. [maglev]

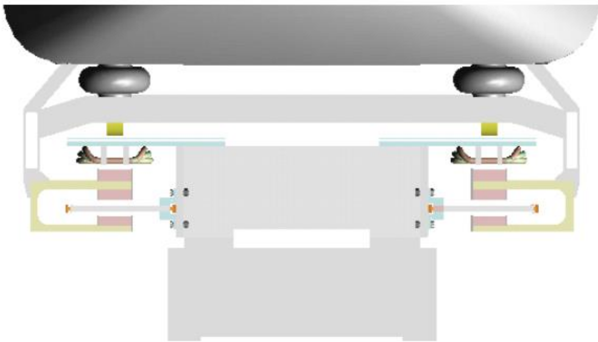


Figure 51.- Structural configuration of the Indutrack Urban Maglev. [maglev]

Xingguo maglev (China)

In 2022, the construction of a test track for China's first permanent magnetic levitation train known as "Xingguo" was completed in Xingguo County, East China's Jiangxi Province (Figure 52). The test line, jointly developed by the Jiangxi University of Science and Technology, China Railway Liuyuan Group (CRL Group), China Railway Hi-Tech Industry Co., Ltd. and China National Rare Earth Functional Material Innovation Center, can be applied to bear suspended trains with medium and low speed and volume.

The main part of the test track is an 800-meter elevated single track, with a double track reserved for operations. The train can carry 88 passengers and is designed to run at a speed of 80 km/h.

The highlight of the test train is that instead of relying on rubber wheels for load-bearing driving, it uses the principle of repulsion between permanent magnetic materials and rails, which can maintain a suspended state in the centreline.

Figure 52.- Xingguo Maglev. [xingguo]

5.3.1.5 Passive levitation systems

Ironlev

Ironlev is the commercial name of a magnetic levitation technology developed and commercialised by Ironbox Srl and based on Ironbox patents.

Ironlev technology is based on the principle of magnetic induction between materials with different permeability through the interaction of a U-shaped slider with a ferromagnetic rail. The slider is the movable part and it is realized with appropriately arranged permanent magnets in a U-shaped ferromagnetic profile. The other part, the rail, is made of high magnetic permeability material, such as iron. The interaction between slider and rail generates the vertical force that suspends the load. The levitation principle is called “ferromagnetic levitation” (Figure 53).

Figure 53.- Ironlev first demonstrator. (Source: Ironbox)

Lateral guiding and propulsion can be based on different technologies according to the specific application requirements and infrastructure design. Just to mention a few examples, lateral guidance can be provided by lateral wheels or EMS guiding system; traction systems can be based on linear motors, lateral traction wheels, ropeways.

Here are described three system categories based on the use of different rail infrastructures:

A. Standard railway track,
B. Custom rail,
C. Hybrid configuration of standard track coupled with custom rail portions.

A. Ironlev system applied to standard railway tracks

Ironlev technology can be applied to standard railway track shape thanks to the ferromagnetic properties of the iron rail itself. The magnetic slider interacts with the head of the rail creating the suspension force.

The system is conceived for fast adoption in urban scenario thanks to the possibility to repurpose existing infrastructure (e.g., urban metro systems) by exploiting the wide availability of standard railway tracks and allowing full interoperability with existing trains (Figure 54).

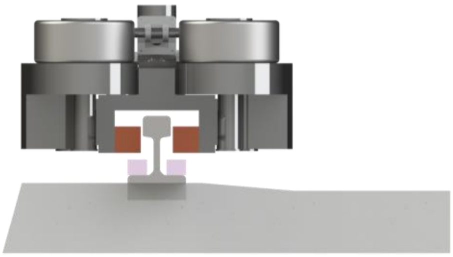


Figure 54.- Ironlev standard rail interaction - section view. (Source: Ironbox)

A first system was tested in 2018 with a first full scale prototype consisting of a levitating platform for a total of 7 tons load capacity applied to a standard railway track. Performed tests showed a static friction coefficient of 0.001 and validated the magnetic levitation principle in a full-scale railway track (railway standard 60E1). The system was based on lateral guiding idle wheels and does not comprise traction. (Figure 55, Figure 56). The test was performed to validate the applicability of Ironlev to a standard railway track. The designed system can reach a maximum load capacity of 3.5 ton/m.

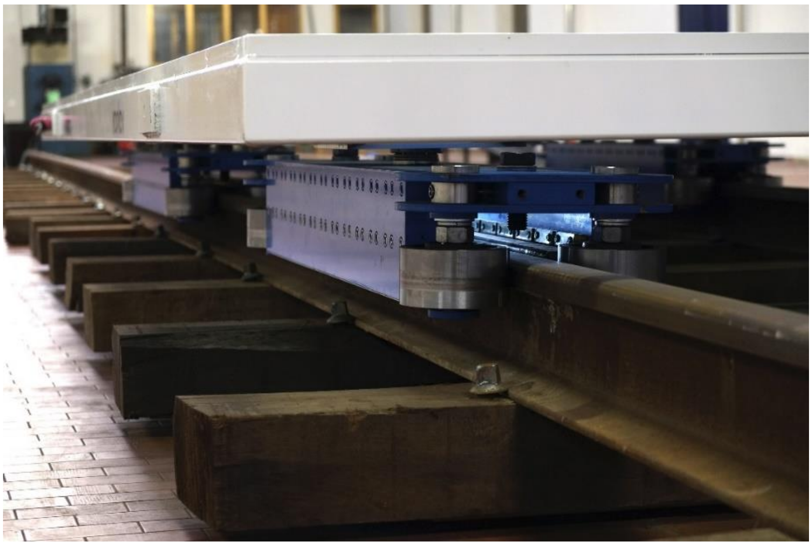


Figure 55.- Ironlev full scale platform on standard rail – side view. (Source: Ironbox)

Figure 56.- Ironlev full scale platform on standard rail – loaded configuration. (Source: Ironbox)

According to lateral guiding and traction, two main variants can be identified.

A1 Ironlev bogie with lateral traction wheels

In the developed design, lateral wheels guiding the system are used in order to provide propulsion and operational braking. Ironlev bogie system is composed by two sliders connected by kinematic elements that allow to adapt to railway gauge changes. The system can include secondary suspension to maximize comfort for passenger transport.

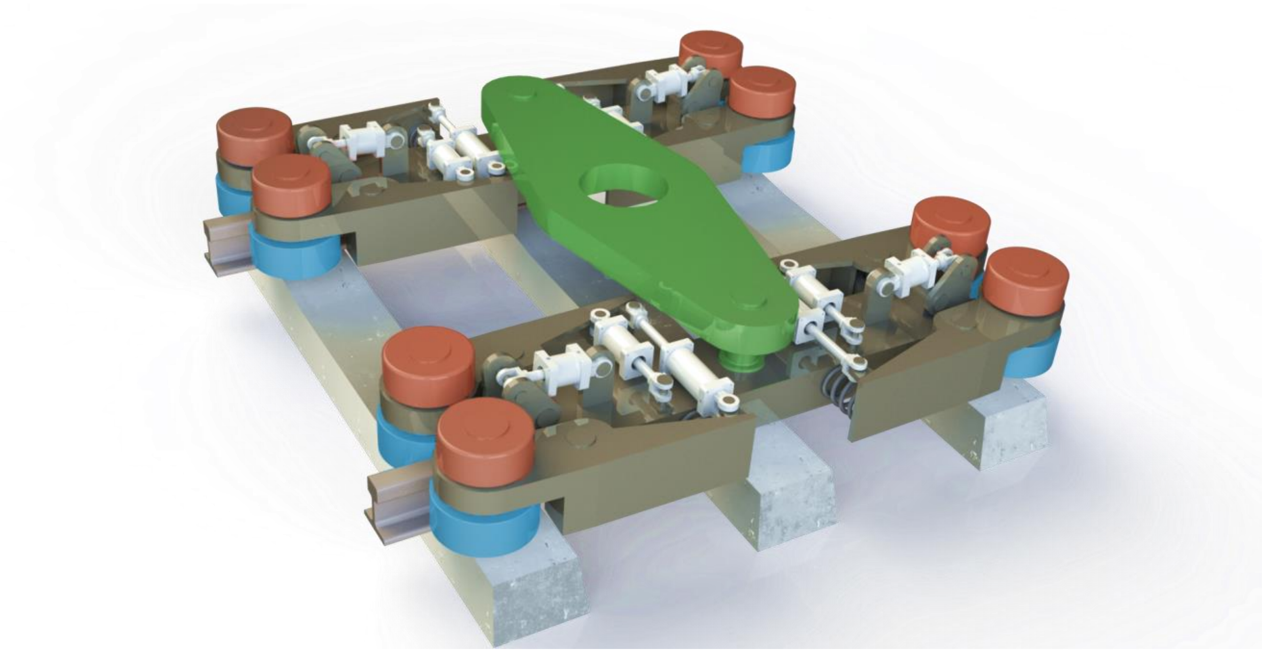


Figure 57.- Ironlev bogie design with lateral traction wheels. (Source: Ironbox)

Propulsion and regenerative braking can be obtained by electric motors connected to lateral centring wheels. Distributed traction and active contact force control allow to use small size motors.

Existing standards in industrial and electric drivetrain systems enable easy integration and control.

Slider centring and magnetic gap control is obtained by using electric actuators. By using dedicated load cells on wheels, the mechatronic system controls the contact force on wheels allowing to manage traction, braking and cruise phase. When required during acceleration and braking phases, contact force can be adjusted to reach the desired traction; instead during cruise phase the contact force is minimised to the value required to win aerodynamic drag, by optimising the overall efficiency of the system.

The lateral balancing system enables to manage curves by misaligning the slider and generating a lateral magnetic force that counteracts centrifugal force, thus maintaining low contact forces on the centring wheels to reduce friction.

This solution requires dedicated track switches or a closed loop track. The switch can be of bending type system that enables to manage the wrapping shape of the Ironlev slider.

A prototype system applied to standard 50E5 track is currently under development (Figure 58) and a speed test is scheduled by the end of 2023. The system is designed to perform a speed test of max 100 km/h in an existing operating railway route of 2 km without any modifications applied.

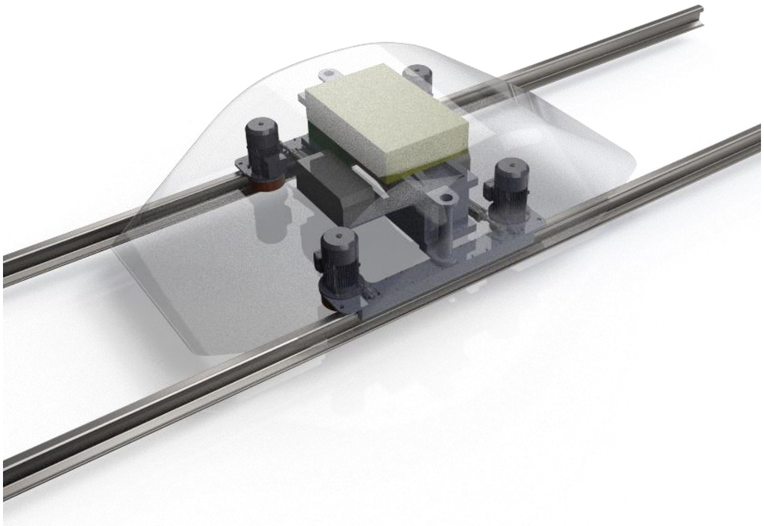


Figure 58.- Ironlev prototype vehicle. (Source: Ironbox)

A2 Ironlev bogie with centring wheels coupled with standard bogie

The system is based on the coupling of a standard wheel-based bogie with a series of Ironlev bogie systems distributed along the length of the wagon (Figure 59). On the infrastructure side, the system is applied in a standard track with traditional switching systems.

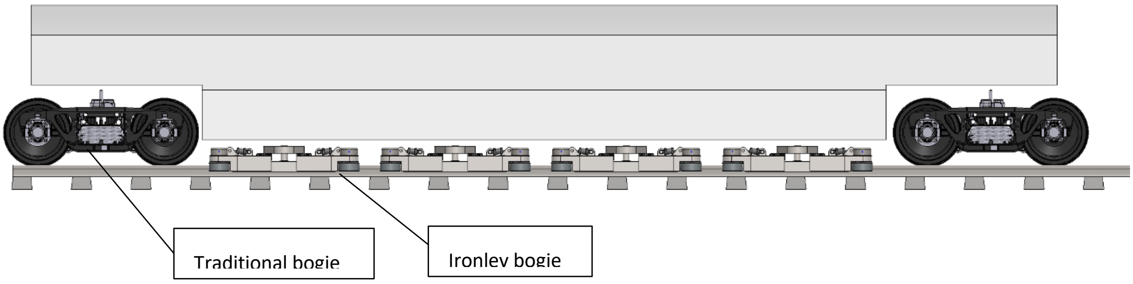


Figure 59.- Ironlev bogie coupled with standard bogie – lateral view. (Source: Ironbox)

Ironlev bogie system is designed to be anchored and disconnected to the rail based on the operating phase of the vehicle: during low-speed switch crossing the Ironlev system is magnetically removed from the rail and the vehicle operates on wheels; instead, during speed cruise phase, the Ironlev system is engaged and partially bears the load of the wagon and the system operates in a hybrid load configuration.

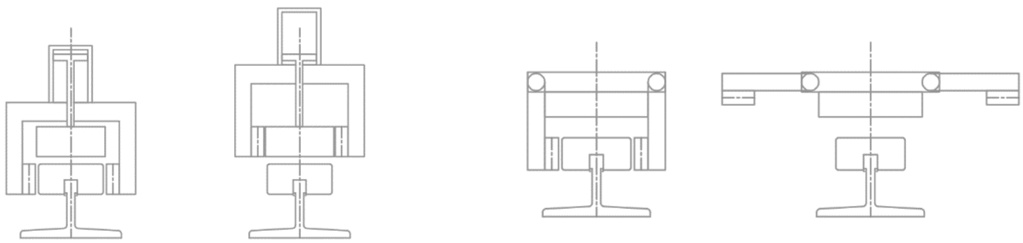


Figure 60.- Possible Ironlev engaging mechanisms. (Source: Ironbox)

The Figure 60 depicts two possible configurations of the Ironlev engaging mechanism. The two cross-sections in the left are with linear actuator and the two in the right are with rotary mechanism. The advantage of this hybrid configuration is the reduction of the load applied on the wheels which increases the overall efficiency of the system and reduces the wear on the infrastructure. The design allows a gradual implementation of MDS systems with a fully interoperable solution. Traction can be provided by wheeled bogie (Figure 61), by distributed traction between vertical wheels and lateral wheels or by linear motors.

Figure 61.- Ironlev bogie coupled with standard bogie - overview. (Source: Ironbox)

B. Ironlev with custom rail

For high efficiency and high-speed applications, Ironlev slider is coupled with a custom rail designed to minimize eddy currents. The custom rail is composed of a laminated head connected to a T-shape steel drawn profile (Figure 62).

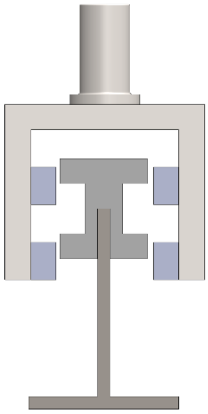


Figure 62.- Ironlev custom rail and slider interaction. (Source: Ironbox)

The laminated top head of the rail is made by using commercially available electrical steel laminations widely adopted in motors and transformers. Steel laminations are available in preassembled bars that can be easily installed in the profile and are flexible to adapt to curves.

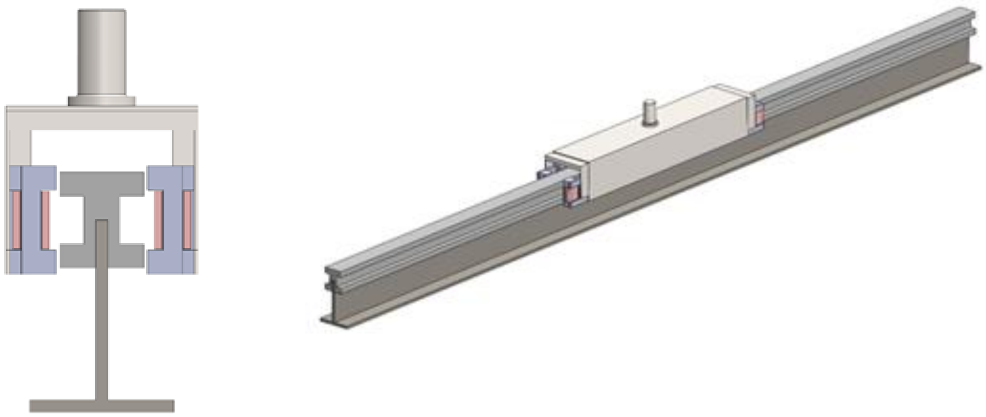
The use of standard components makes the system scalable and a low-cost solution for railway.

Ironlev rail can be scaled for heavy freight application or light rail transport applications like people mover. Linear load capacity affects section dimension and costs.

According to the application, guidance and traction are based on lateral wheels or electromagnetic systems.

B1 Ironlev custom rail with EMS guidance

The system is a complete maglev contactless vehicle that couples Ironlev levitation support for vertical load (wagon weight) with EMS guidance, obtained by using electromagnets coil pairs positioned at the end of the slider that interact with the ferromagnetic rail head (Figure 63). EMS system is equipped with a control system that maintains the slider centred on the lateral equilibrium position. By maintaining the equilibrium position, the lateral force is around zero and the coils current is limited. When a lateral load occurs (e.g., turning phases), the EMS system misaligns the magnetic part to counteract the load, minimising EMS lateral force. This architecture is designed to increase the overall efficiency of the system by eliminating the contact friction.



a) b)

Figure 63.- Ironlev custom rail with EMS lateral guidance. a) Section view b) overview. (Source: Ironbox)

This layout enables complete integration with linear motors or ropeways. In this design option, the lateral centring means (guidance) are constituted by electromagnetic active systems, while there is no need for traction wheels and rubber belt tracks, resulting in a simplified slider and rail architecture.

B2 Ironlev custom rail with lateral wheels

The system layout integrates lateral centring and traction wheels on a custom rail. The lateral wheels are made of steel and coupled with rubber belts to increase maximum achievable speed.

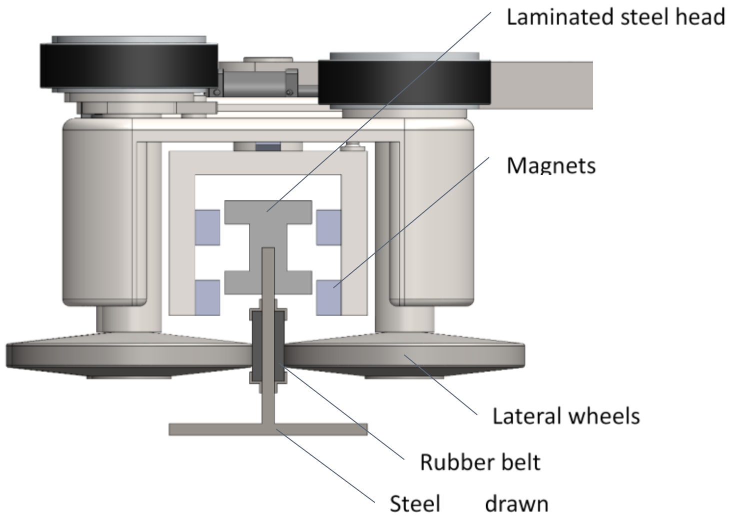


Figure 64.- Ironlev custom rail and slider with lateral wheels. (Source: Ironbox)

This solution reduces noise and vibration. High durability vulcanized rubber is adopted to increase system lifetime, by using steel wheels and avoiding rubber stress-cycling of standard rubber wheels. Compared to standard rubber wheels subjected to centrifugal force, this architecture enables to reach high-speed applications up to 1,000 km/h.

Table 2 includes dimensioning and costs for different applications.

Table 2.- Dimensioning and cost table for Ironlev system.

	Freight transport	LRT – People mover
Linear load capacity	3.3 ton/m	1 ton/m
Section Dimensions	W x H (mm)	W x H (mm)
Laminated steel head	120x200	60x60
Drawn steel support	15x250	10x100
Rubber Belt	60x13	35x5
Total estimated costs	**710 k€/km**	**195 k€/km**

A design of Ironlev system with custom rail is based on traction and braking provided by electric motors in Figure 65. Lateral contact force is controlled by electric actuators. Active lateral centring is obtained with dedicated actuators and kinematics.

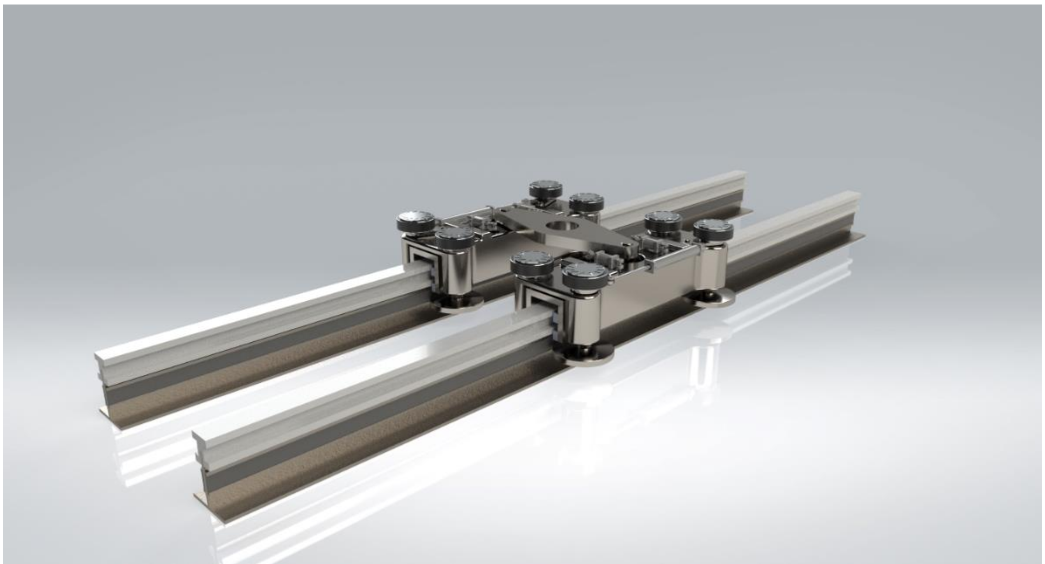


Figure 65.- Ironlev bogie with custom rail and lateral wheels - overview. (Source: Ironbox)

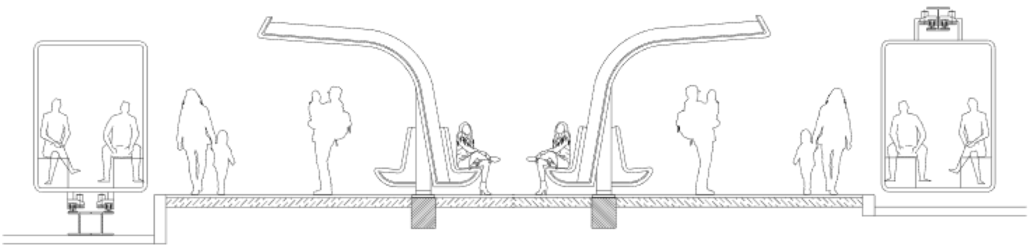


Figure 66.- Ironlev multimodal transport concept. (Source: Ironbox)

C. Ironlev hybrid systemThe Ironlev system with custom rails can be adopted in combination with traditional wheeled systems to obtain a hybrid system architecture where traditional wheels are used at low speed and over track switches, while there are dedicated Maglev corridors in between for high speed and high efficiency ride. The details of the Ironlev system comprising sliders and custom rails are described in the previous section.

There are two alternative solutions:

- C1 Ironlev Hybrid system with EMS guidance,
- C2 Ironlev Hybrid system with lateral centring wheels.

Here are possible conceptual configurations with the advantages of:

- Standard tracks with improved Maglev corridors,
- Possible interoperability and gradual adoption,
- Ready for standard switches,
- Suitable for interurban High-speed trains,
- Low infrastructural costs for the upgrade,
- Low energy costs during operation thanks to high efficiency levitation systems.

Regarding propulsion, for C2 can be made by lateral traction wheels with electric traction motors; instead for C1 linear motors are adopted (Figure 67).

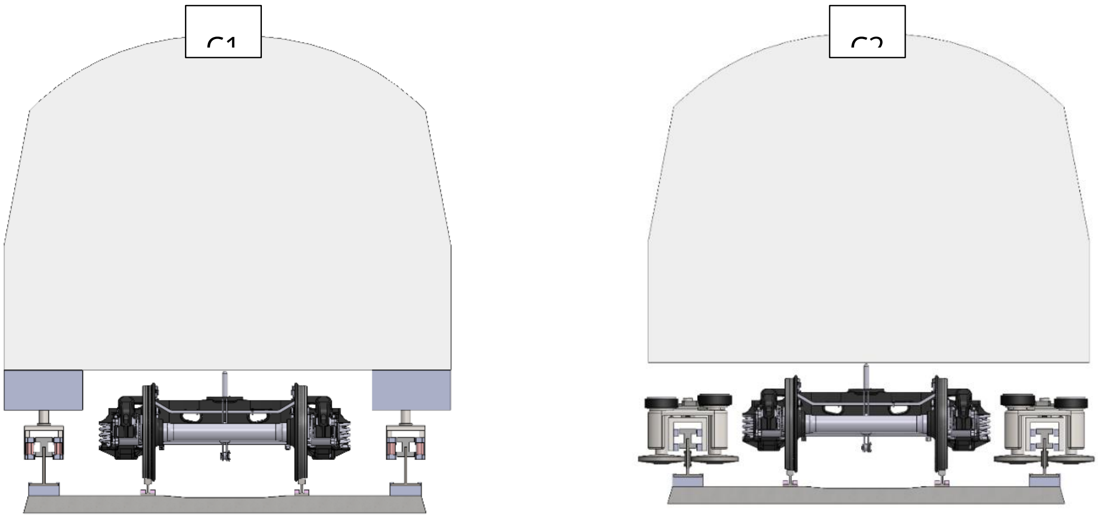


Figure 67.- Ironlev hybrid system c1) with Ironlev EMS lateral guidance c2) with Ironlev lateral wheels. (Source: Ironbox)

D. MagRail

MagRail is a high-speed transport system (v > 250 km/h) developed by Nevomo, whose vehicles are propelled by a linear electric motor and equipped with an electrodynamic suspension system (EDS). The unique feature of MagRail is that its vehicles will move along the existing railway corridors and use the conventional railway infrastructure (Figure 68). What is needed to operate is a magnetic infrastructure for propulsion and for suspension mounted within the track.

Figure 68.- Artistic vision of MagRail system. (Source: Nevomo)

MagRail infrastructure elements included the linear motor, which is a permanent magnet synchronous motor with a long stator, where the copper windings are mounted within the infrastructure. The windings are sectioned and their power supply is controlled by stationary inverters. The electrodynamic suspension system infrastructure needs a track made of aluminium plates mounted outside the railway track.

In 2022, a 700-meter test track of the MagRail infrastructure was established, located in Nowa Sarzyna, Poland. (Figure 69).

Figure 69.- MagRail infrastructure test track (Source: Nevomo)

The main components of the test vehicle included the linear motor mover, the supporting structure, the levitation and stabilization system and the low-speed propulsion system. For safety reasons, the vehicle was equipped with 4 safety rollers and 4 emergency rail brakes. The test vehicle of the MagRail system is shown in Figure 70.

Figure 70. - MagRail system test vehicle (Source: Nevomo)

The system is currently being developed by Nevomo. The tests in 2023 in test track proved the operation of the system at a speed of 130 km/h (magnetic levitation at a height of 20 mm was achieved).

5.3.2Air-cushion transport systems

5.3.2.1 Introduction

The demand for high-speed rail transportation arose in the 1950s, stimulated by rapid economic growth, which was characterized by population shifts from rural areas to major cities, and the necessity for efficient goods transportation. In response to these needs, three innovative solutions were developed for enhanced speed guided transportation: maglev (magnetic levitation), speed-enhanced wheel-rail systems, and air-cushion suspension (Pelle, F. H., & Magdalena, S. R., 2019).

For rail transportation, Japan led the way by introducing the first high-speed railway line, Tokaido Shinkansen, coinciding with the 1964 Summer Olympics in Tokyo. This significant line established a connection between the capital, Tokyo, and Osaka. Concurrently, European countries undertook enhancements in their rail network infrastructure with a focus on both passenger and freight transportation and initiated research for their high-speed lines, such as the TGV. In 1981, France's TGV service commenced, establishing a 2.5-hour connection between Paris and Lyon. This success inspired other European countries to follow: Italy's “Direttissima” partially opened in 1988, Germany's ICE began operation in 1991, Spain's AVE was inaugurated in 1992, and Eurostar, providing a connection through the Channel Tunnel between France and England, started service in 1994. Furthermore, the Acela Express, first high-speed rail (HSR) train in North America, began its service in December 2000.

However, to achieve a higher train speed of more than 400 km/h, replacing the traditional wheel-rail contact is a challenging but very efficient and green solution. In the last century, the progress in railway vehicle technology has moved towards reducing friction, a major limiting factor in the speed and efficiency of traditional trains.

The technology to conquer this limitation came in the form of maglev trains. By leveraging magnetic fields, maglev trains float above the track, eliminating rolling resistance and allowing for speeds that were previously thought unattainable. However, while maglev technology was a significant advance, it also faced challenges such as high costs of construction and operation.

In parallel with maglev technologies and solutions, air cushioned technology for railways (or track way in general) has been studied since 1950s. Recently, air levitation for railway vehicles becomes worthy to study, since the air multiplier technology has enabled enough air levitation forces to train. This brings us to the threshold of the next potential leap in railway technology, the air levitation train, in short, the Airlev train. This technology will utilize a cushion of air to lift the vehicle, which was envisioned to further eliminate friction, reduce energy consumption, and enable even higher speeds similar to maglev trains but with much lower costs.

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

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

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

However, as with any innovative technology, air levitation for railway vehicles faces its own unique set of challenges. This 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.

5.3.2.2 Air-cushion principle

The principle behind air cushion suspension is rooted in creating a pressure differential between the air inside and outside an air chamber. This generates enough mechanical force to lift an object, such as a vehicle, a few millimetres off the ground. In Figure 71, a simplified depiction of this mechanism as used in British Hovertrain is shown. A fan draws in air to inflate the air chambers within the vehicle, creating pressure areas. This inflation continues up to the chambers' maximum capacity, thereby creating an upward force that raises the vehicle off the surface, maintaining a small air gap beneath it. The skirt is constructed from a flexible material that allows a minimal amount of air to escape.

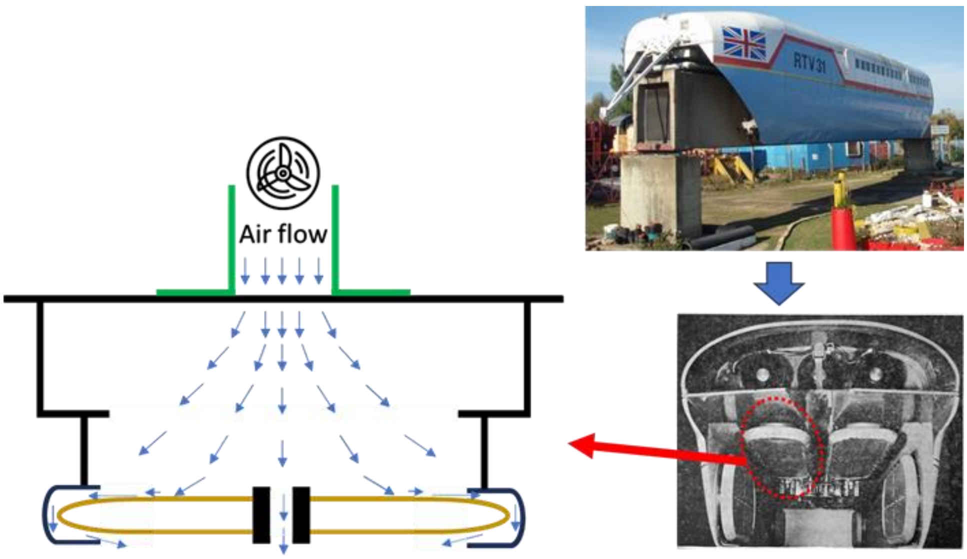


Figure 71.- Air cushion principle for British tracked hovercraft, RTV 31 (also named as Hovertrain or tracked air cushion vehicle) (figure modified after Pelle, F. H., & Magdalena, S. R., 2019; Bailey, M. R., 1993).

5.3.2.3 Prototypes and applications

The success of maritime hovercrafts using air-cushion technology, along with advancements in Linear Electric Machines (LEM) and the quest for innovative mass transportation solutions, has led to the application of this suspension principle in ground transportation systems. This is particularly true for guided systems like trains, resulting in the development of hovertrains or Tracked Air Cushion Vehicles (TACV). Figure 71 illustrates a typical hovertrain setup.

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.

The vehicle's propulsion is facilitated by the interaction between the primary and secondary windings of the linear motor. The extensive knowledge gained from hovercraft development positioned the United Kingdom as a leader in hovertrain research. Initiated in 1962, the Tracked Hovercraft project explored the interactions between track surfaces and cushioning principles, whether air or gas-based, and established the technical viability of this approach with a prototype in 1963, as shown in Figure 72. In 1966, a small-scale model was constructed and showcased on a closed loop, demonstrating propulsion through a Linear Inductor Motor (LIM).

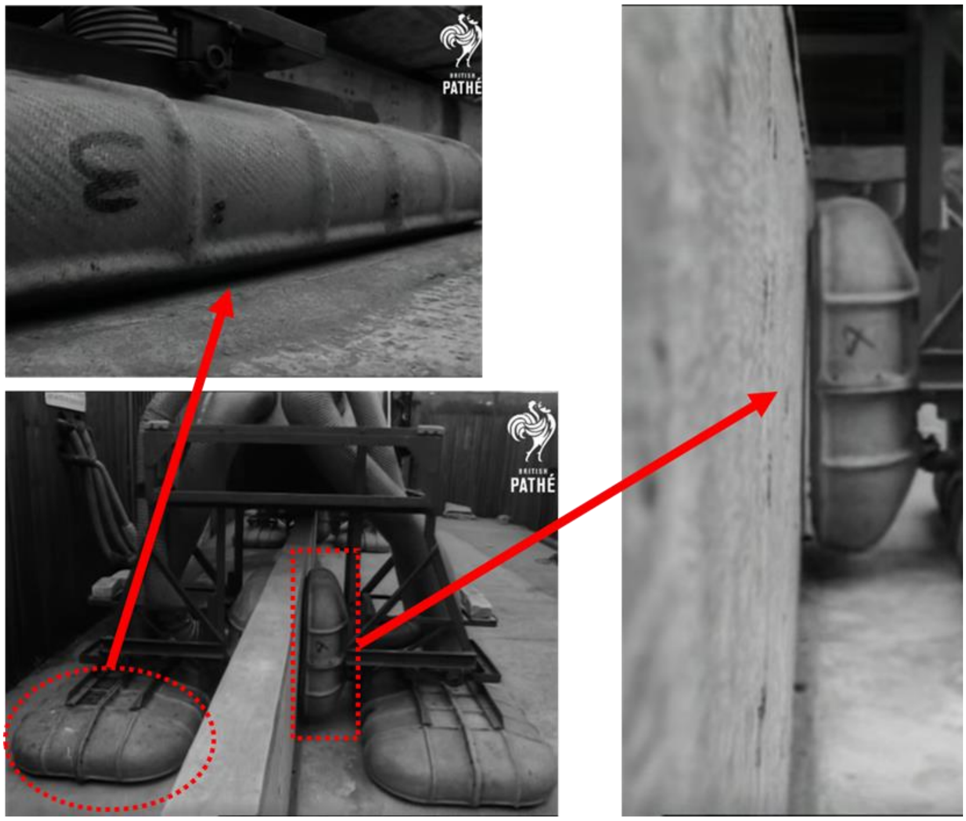


Figure 72.- Testing on air-cushion system of Hovertrain in 1963 (Source: https://www.youtube.com/watch?v=YdDVLRaB8sk).

Between 1971 and 1973, a 1.6-km segment of a planned 32-km test track featuring an inverted T-shape was constructed. A full-scale model, dubbed RTV 31 (Figure 71), was developed, employing a one-sided Linear Inductor Motor (LIM). The vehicle achieved a top speed of 170 km/h before the project was halted in 1973 due to insufficient funding.

France's engagement with TACV started in 1956 with research into air-cushion technology. After successfully demonstrating the viability of small-scale models, half-scale prototypes known as Aérotrain 01 and 02 were trailed on a 6.7-km inverted T-shaped track in 1965 (Figure 73 a). Various propulsion techniques, such as propellers, turbofans, jet fans, and rockets, were evaluated. The prototypes reached top speeds of 345 km/h with rocket propulsion and 422 km/h with turbofans, as shown in Figure 73 b). In 1969, the full-scale Aérotrain S44 was developed for inter-city travel and featured a double-sided LIM propulsion system. It achieved a top speed of 200 km/h on a 3-km test track. In the same year, an 18-km test track was constructed for the Aérotrain I80 and I80-HV models, both designed to accommodate 80 passengers. These models, propelled by turbofans, reached a peak speed of 430 km/h. In 1974, the president of the French Republic chose the rail solution for the future Paris-Lyon high-speed project and decided to stop the Aerotrain project. Due to this decision, the lack of financial backing, the Aérotrain research project came to an end in 1977. However, part of the funding was allocated to research and development of the linear induction motor until 1986, which allowed testing at 300 km/h of an original full-size motor prototype (in the Grenoble Wheel test bench laboratory today owns by TACV Lab).

This linear induction motor is characterized by U-shaped armature, it showed highest efficiency and power factor performance for these machines, which are now developed by TACV Lab company. The Aerotrain prototype i80 was authorized to transport passengers during validation tests from 1973 to 1976, 100,000 km were covered with 26,000 passengers without any incidents (2900 passengers at 350km/h).

a)

b)

Figure 73.- Aérotrain and test track in France: a) Aérotrain 02; b) Aérotrain I80 (Source: https://en.wikipedia.org/wiki/A%C3%A9rotrain)

In 1967, the Aeronautics Engineering Institute at Palermo University initiated research on

TACV with a small-scale prototype named Aerotreno IAP-1 to validate the technology's feasibility. The IAP-2 model was designed to carry three passengers and utilized turbo-propeller propulsion; it was tested on a 200-meter track on the university campus. In 1972, the IAP-3 model, designed to seat 20 passengers and featuring LIM propulsion, underwent testing on a 600-meter U-shaped track at Trapani-Milo Airport, as shown in Figure 74. The vehicle's target speed was 250 km/h. By 1973, the university shifted its research focus to magnetic levitation trains.

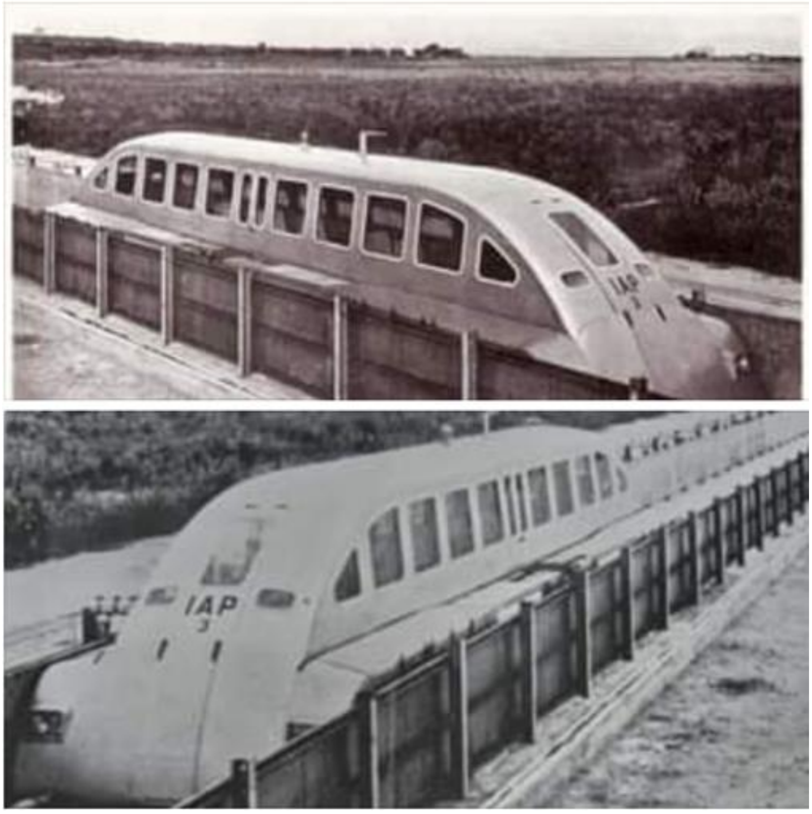


Figure 74.- Tracked air-cushion vehicle, IAP-3 in Italy [air-cushion].

In the early stages of magnetic levitation train research, West Germany created the Transrapid 03 (TR-03) prototype, which utilized air cushion levitation technology, in 1972, as shown in Figure 75. The aim was to directly compare the performance of a Tracked Air Cushion Vehicle (TACV) with a maglev Electro-Magnetic Levitation (EML) vehicle, specifically the Transrapid 02 (TR-02), under the same conditions and on the same 930-meter track. Both vehicles employed double-sided Linear Induction Motor (LIM) propulsion. While TR-02 achieved a top speed of 164 km/h, TR-03 reached only 140 km/h and was deemed to be less efficient. Testing continued until 1974, after which research efforts shifted exclusively to maglev trains.

Figure 75.- Tracked air-cushion vehicle, Transrapid 03 (TR-03) in Germany [maglev].

In the United States, research into Tracked Air Cushion Vehicles (TACVs) gained momentum in 1965, thanks in part to government incentives aimed at advancing high-speed transportation systems. In 1969, the U.S. Department of Transportation's Office of High-Speed Ground Transportation (OHSGT) initiated the construction of the Transportation Technology Centre (TTC) in Pueblo, Colorado. This centre was dedicated to the study of urban trains and high-speed transport, and it launched a program focused on TACVs. The initial prototype called LIMRV, developed by the Garrett Corporation's Air Research Manufacturing Division, centred solely on propulsion via Linear Induction Motors (LIM) or jet engines. It operated on a 10-km inverted-T-shaped test track with a wheel-rail system. Concurrently, in California, a vehicle named TLRV, equipped with an Air Cushion Vehicle (ACV) suspension system and created by the same company, was developed to explore power delivery to the LIM primary winding at speeds up to 480 km/h. By 1972, another prototype, TACRV, engineered by Grumman Aerospace Corporation, underwent testing on a 35-km track and achieved speeds of 150 km/h using jet engine propulsion. In 1974, Rohr Industries initiated the PTACV program, which designed the UTACV, a vehicle with a 60-passenger capacity and double-sided LIM propulsion, as shown in Figure 76. This was quite similar to France's Aérotrain technology and was aimed at inter-city transport. The UTACV hit speeds of 240 km/h on a 5-km test track.

However, by 1975, the U.S. TACV program was discontinued due to a reallocation of funds toward magnetic levitation train research and the development of Automatic People Movers (APMs) for urban transit.

Figure 76.- Tracked Air Cushion Vehicle in USA [Wikipedia CC]

In 1970, Centro Universitário FEI in São Bernardo do Campo, São Paulo, initiated a high-speed tracked air cushion program called TALAV. Leveraging the institution's extensive expertise in the automotive industry, the program utilized exclusively Brazilian technology and materials. The research initially focused on a small-scale prototype to validate the technical viability of the air cushion vehicle (ACV) suspension and various propulsion systems, such as propellers and jet engines. By 1972, a full-scale vehicle was developed, featuring seating for 20 passengers and dual jet engine propulsion capable of achieving cruising speeds of up to 200 km/h, as shown in Figure 77. This vehicle was showcased at the Brazil Export Exposition in São Paulo the same year. Some of the TALAV vehicle's notable features included its lightweight construction using fiberglass and aluminium sheets, a specialized mechanism for guideway switching, telescopic doors designed to reduce station size and facilitate emergency exits, and modular cabins that could easily switch between freight and passenger transport. Additionally, the vehicle was designed to link multiple wagons, much like building blocks, to adapt to varying demand. Despite garnering attention and receiving proposals from several Brazilian cities after its exhibition, the test track was never constructed due to government budget constraints. As a result, the TALAV research program was concluded in 1973.

Figure 77.- Tracked Air Cushion Vehicle, TALAV in Brazil [Pelle, 2019]

The Duke University Medical Centre operated a Personnel Rapid Transit (PRT) system, also referred to as the Patient Rapid Transit system, from 1979 to 2009 in North Carolina, USA (Figure 78). Known for its cutting-edge design, this automated people mover was equipped with linear induction motors for propulsion and used a compressed air bed for suspension like hovercraft technology. A standout feature was the cars' ability to move not just forward and backward, but also laterally. Designed by the Otis Elevator Company in the 1970s, construction began in 1977, culminating in its inauguration on December 8th, 1979. The system consisted of three driverless Otis Hovair vehicles, each equipped with hinged windows at both ends to serve as emergency exits. The infrastructure included a dual-track concrete guideway, linking three stations: Duke South, Duke North, and Parking Garage II. The route included a tunnel passage beneath Erwin Road.

In Japan, between 1992 and 2013, a 280-meter track connected two terminals at Narita International Airport, as shown in Figure 79. The system was engineered by Nippon Otis Elevator, a firm specializing in elevators and escalators. Although it resembled a railway, it was technically, and by legal definition, a horizontal elevator. Cars were tethered to a moving cable in a manner akin to a funicular. Instead of using wheels, the cars hovered above the track on a thin layer of compressed air, just 0.2 mm thick. This marked the first implementation of such a technology in an airport and was also a pioneering effort in Japan.

Figure 78.- Otis Hovair PRT at Duke University Medical Centre (figure reproduced from Wikipedia: https://en.wikipedia.org/wiki/Otis_Hovair).

Figure 79.- Horizontal elevator using air-cushion technology in Japan (Source: https://en.wikipedia.org/wiki/Otis_Hovair).

Between 1985 and 1999, the Otis Hovair® system transported passengers on a 760-meter track connecting Harbour Island to Downtown Tampa, Florida. Currently operational Automated People Mover (APM) systems employing Otis Hovair® technology are found in multiple countries, each with its unique features. The APM installations in Austria and Switzerland are subterranean, while others are built on elevated tracks. These systems have been produced by Otis, POMA, and more recently, by the Leitner Ropeways group. POMA and Leitner collaborated to create MiniMetro®, combining their expertise in cable driven and APM technologies. The most recent Tracked Air Cushion Vehicle (TACV) system was launched at Cairo International Airport in 2013, as depicted in Figure 80.

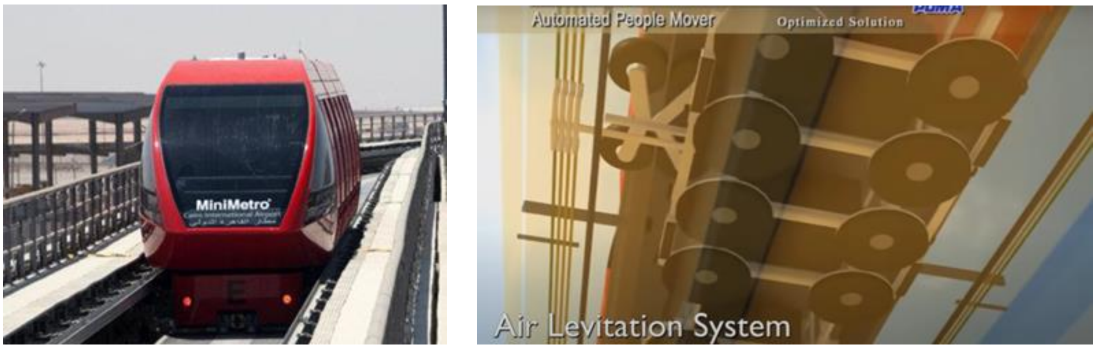


Figure 80.- Cairo International Airport MiniMetro® using air-cushion technology (Source: https://www.youtube.com/watch?v=0O92BxcFw2s).

5.3.2.4 Patents/Concepts

Some patents presented some ideas of using air levitation for vehicle. For example, in Figure 81, the idea of the air levitated train components is shown. Some main points are given as follows:

- Levitation:
  - Air levitation to the vehicle is done by two tubes containing high-pressure air,
- Propulsion:
  - 215A and 215B are thrust nozzles,
  - 208A and 208B are opposing impulse vanes.

Another patent using air cushion technology is produced in Netherlands with the key improvements at the new propulsion means, i.e., electro-dynamic wheels (EDW, rotating magnet), as shown in Figure 84 a). The principle of this TACV is given in Figure 84 b). Another interesting thing about the idea of using EDW propulsion were shown in Figure 84 c), which is laboratory tests to check the propulsion force. In addition, numerical simulations were also performed in these studies.

U-TRACE (Tracked Air Cushion Equipment propelled by U shaped linear induction motor) by TACV Lab

Ultralight passenger transport system, contactless and powered by a U-shaped linear induction motor. The air cushion system is issued from the Bertin technology, Aérotrain project, and propelled by an on-board U-LIM linear induction motor, with high efficiency/power factor.

Depending on the operational speed, the guidance system can be assumed either by Air cushion or electromagnetic.

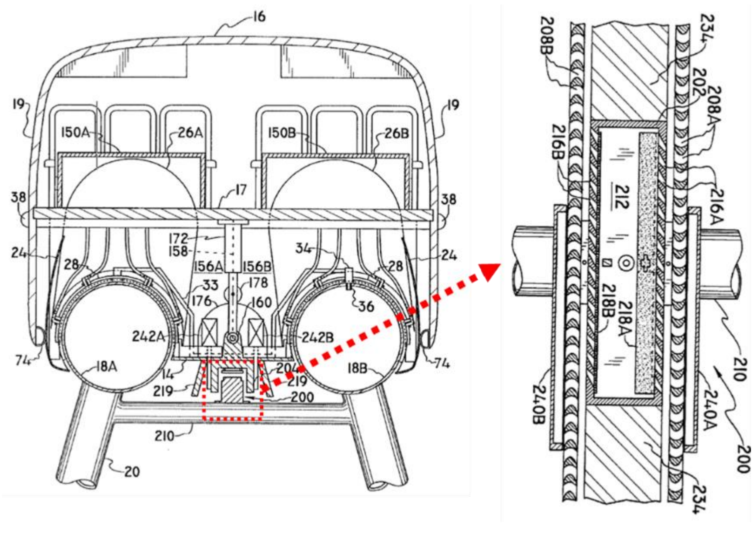
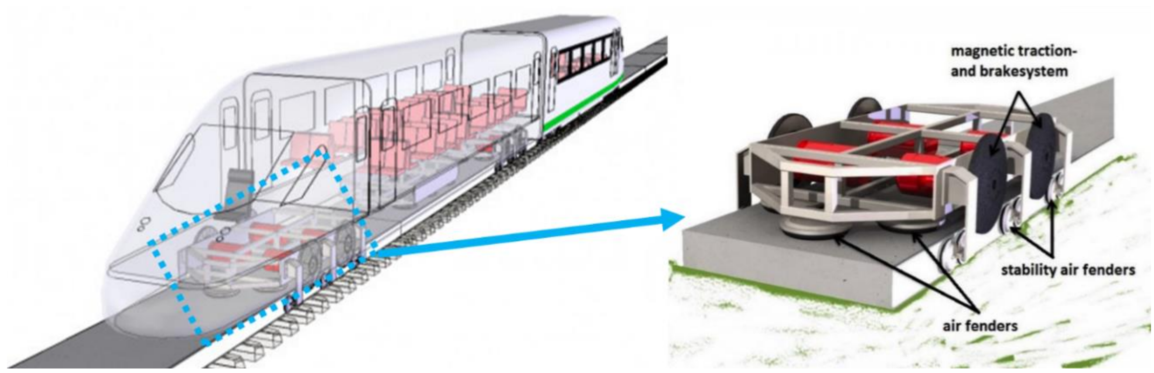
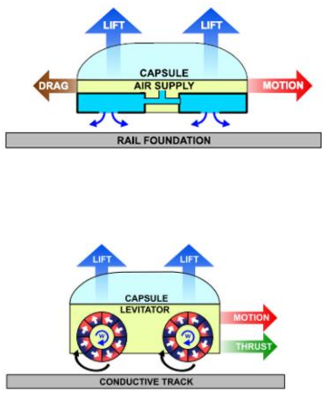


Figure 81.- United States Patent USOO5909710A – Air-levitated train, granted in 1999.

a)



b)



c)

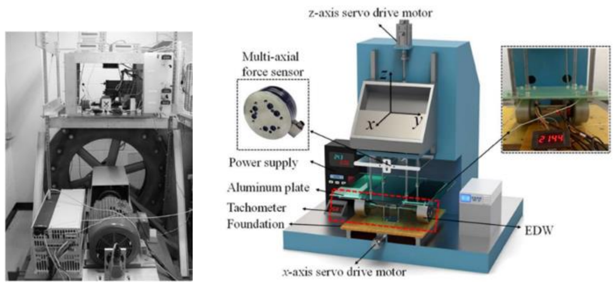


Figure 82.- New propulsion technology for air cushion vehicle: a) United States Patent US 10293803B2 and European Patent EP 2701960 – Levitation system for a train, granted in 2019; b) TACV with Rolling magnet propulsion principle; c) Laboratory tests performed in literature. (figure reproduced from website: https://www.technologie.nu/tag/atrain/; Nøland, J. K. 2021; Shi, H., Ke, Z., Zheng, J., Xiang, Y., Ren, K., Lin, P., ... & Deng, Z. 2023; Bird, J., & Lipo, T. A. 2006)

A major objective is to reach an ultra-light vehicle, which allow to design a lightweight and compact elevated track thanks to ultra-high performance fibre concrete.

With a Capacity of 80 seats per vehicle, in convoy of 2 to 5 vehicles, the U-TRACE is designed for Commercial speed of 150 km/h (300 km/h for the FULTRACE version, with Fast Ultra-light Air Cushion Equipment) (Figure 83).

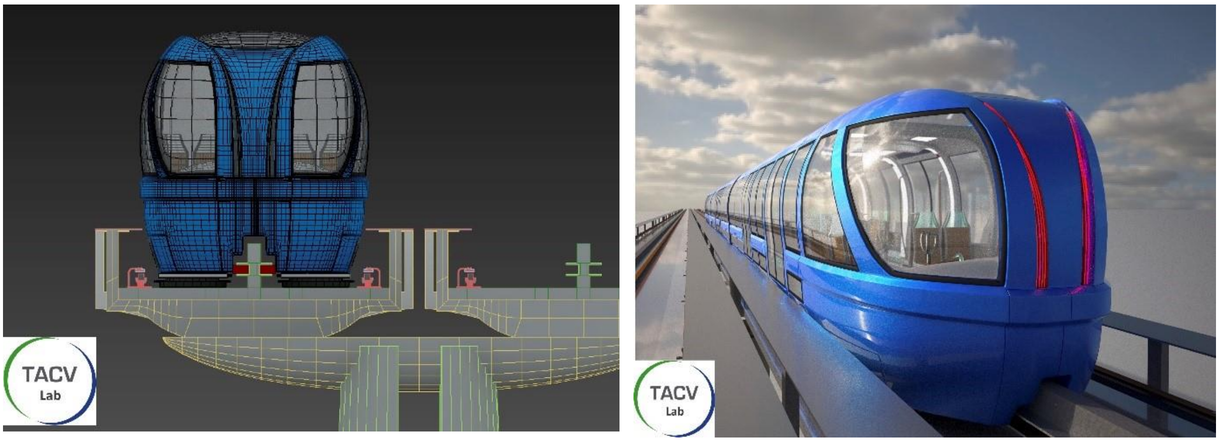


Figure 83.- Design view of U-TRACE concept system (Source: TACV Lab)

By using autonomous driving technology, the lane signalling system is significantly reduced, the operating system offers a fully automatic and flexible mode of transport, mixing programmed synchronization with high and low traffic periods, depending on the transport demand.

U-TRACE is a zero-CO_2 contribution system in its operational mode, which can also be combined with a track-integrated solar power generation concept, to achieve an elevated energy autonomy.

The challenge of the U-TRACE system is to provide an elevated track at the most competitive cost possible compared to conventional ground transport solutions. To achieve this goal, 3 major technologies must be combined:

- Very light vehicle concept using aeronautical technologies (car shell material, ultralight saddle, etc.),
- Air cushion sustenance allows the mass of the vehicle to be evenly distributed along the track with very low pressure, greatly reducing mechanical stress,
- Contactless traction and braking system by high-efficiency linear induction motor.

5.3.2.5 Summary air cushion vehicle

In Table 3, the information of different air-cushion vehicle is summarised.

Table 3.- Information of air-cushion vehicle prototypes.

Country	UK	France	Italy	Germany	USA	Brazil
Vehicle length (m)	22	10	13	12	28.6	15.6
Seat capacity	-	6	20	4	60	20
Weight (t)	23	2.5	10	8	21	3
Max speed (km/h)	173	345	N/A	140	240	-
Designed speed (km/h)	480	N/A	250	N/A	274	200
Fan power (kW)	630	75	N/A	160	520	44.7
Propulsion	Single side LIM	Jet engine	Double side LIM	Double side LIM	Double side LIM	Jet engine
Motor power (kW) **Thrust (kN)**	3730	185 11.8	450	24.5	2000	9.4
Guideway track length (m)	1.6	6.7	0.6	0.96	5	-

The historical analysis of air-cushion vehicle underscores that all the projects, aimed at intercity and long-distance transport, did not come to fruition. The attempts to leverage air cushion technology for ground transportation were overly optimistic, expecting a short development time frame, like hovercrafts, before becoming operationally feasible.

Many national railway operators, including those in the United Kingdom and France, were not convinced of the viability of air-cushion vehicle technologies and continued to invest in the more established wheel-rail High-Speed Trains (HST), which were at a higher level of readiness. It is noteworthy that all national air-cushion vehicle projects were performed between 1973 and 1977, and the economic aspect is one of the explanations for this coincidental termination of the projects.

Technical factors also played a significant role in making high-speed maglev trains more appealing than the corresponding TACV. The power consumption needed for the suspension system in TACV was significantly higher than in an electromagnetic maglev. The Tracked Hovercraft estimated a power requirement of 2200 kW to levitate a 40-ton vehicle, while the

Transrapid Maglev would only need 40 kW. The mean power density for the suspension system of air-cushion vehicle is around 25 kW/ton, while an equivalent electromagnetic maglev train only requires 1-2 kW/ton. The fans and blowers required by an air cushion system also contribute to the increased vehicle weight and reduce the available space for passengers, accounting for approximately 15% of the weight. Therefore, economic and technical constraints, including power consumption and space efficiency, were pivotal in halting the progress of TACV projects in favour of other emerging technologies.

With advancements in fan technology, the Otis Hovair® notably diminished both the power consumption and noise levels of the ACV suspension system, compared to high-speed TACV. The power density of its ACV suspension stands at approximately 1 kW/ton, mirroring that of electromagnetic maglev.

Examining this from a control systems standpoint, it is crucial to highlight that air-cushion vehicle inherently possesses stability and only necessitates a singular control loop to enhance both vehicle suspension and passenger comfort, showing resilience to external disruptions. In contrast, electromagnetic maglev systems inherently lack stability and mandate intricate control loops and backup systems to maintain the vehicle's levitation at the predetermined position.

Urban air-cushion vehicles, specifically Hovair® and MiniMetro®, have successfully established their market presence in settings requiring straight and concise routes such as resorts, museums, hospitals, and airports. At present, they offer a competitive Automated People Mover (APM) solution in comparison to other conventional transit modes, solidifying their role in specific transportation niches.

5.3.3 Maglev-derived systems operating on wheels

5.3.3.1 Introduction

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

- Increase in the allowable track slope,
- No limitation of traction due to adhesion between the wheel and the rail,
- Absence of rotating components,

- Compact wagon design, with smaller cars and smaller tunnels.

Of course, there are also disadvantages like e.g., the need to adapt the system to the railway regulations.

5.3.3.2 Systems with linear motors

MagRail Booster

MagRail Booster is part of the MagRail product portfolio and allows for a quick retrofit of existing rail cars and existing infrastructure with linear motor propulsion. Unlike MagRail technology, MagRail Booster does not use a magnetic levitation system, but uses wheels for rolling and guidance, not for transmitting traction forces. The MagRail Booster vehicle will be able to achieve a speed of 120 km/h.

The linear motor used is a permanent magnet synchronous linear motor with a long stator, with copper windings embedded within the infrastructure. These windings are segmented, and their power supply is controlled by stationary inverters. The linear motor mover was installed on conventional freight wagons supplied by GATX Rail Europe (Figure 84 - Figure 86).

Figure 84.- Artistic vision of the MagRail Booster platform. (Source: Nevomo)

Figure 85.- The structural configuration of the MagRail Booster. (Source: Nevomo)

Figure 86.- The MagRail Booster with GATX platform. (Source: Nevomo)

One key advantage of this system is that single Booster wagons can operate independently without being connected to the locomotive. This opens possibilities for new applications in which wagons can be organized into small groups instead of full trainsets. This feature is particularly useful in "last mile" areas, such as cargo terminals and industrial facilities, where a high degree of flexibility and movement automation is highly desirable.

The system is currently being developed by Nevomo. The first tests took place in the second half of 2023 on a test track in Nowa Sarzyna. MagRail Booster technology is also applicable to passenger trains. It helps improve the technical parameters of the existing vehicles, allowing them to accelerate and brake faster.

Freight transportation system on rail track boosted by linear motor: U-CARS (U-LIM Containers Autonomous Railway Shuttle) by TACV Lab

U-CARS is a rail shuttle designed from a standard articulated container wagon (Sggmrss 90'), with 3 bogies, that offers (Figure 87):

- Transport capacity: 4 20' containers (TEU) or 2 40' containers (FEU), considering a total payload of 105 tons on track at 22.5 t/axle, equivalent to 3 semi-trailers of 44 tons,
- 2 electric traction systems with energy autonomy thanks to the on-board battery pack,
- Integrated axle traction by wheel/rail contact, on each of the 6 axles of a U-CARS unit,
- A linear U-shaped induction booster to overcome slopes greater than 2.5% up to 10%,
- Ground contact based electrical energy system for dynamic battery charging, to increase traction power with the linear motor on high slopes,
- Concept of electric funicular for steep links, with potential energy recovery associated with a ground-based electricity storage system (case of the São Paulo-Santos rail link*),
- Autonomous driving system based on the autonomous mobility technologies of road shuttles (obstacle detection by camera day/night, lidar-sonar, GPS location, traffic control, 4G/5G communication), with integration of online remote-control system,
- Circulation in "Platooning" mode or automatic mechanical coupling to form a convoy of 2, 3, 4 or more U-CARS units, depending on the capacity response to be achieved,
- Autonomous commercial speed: 50 km/h,

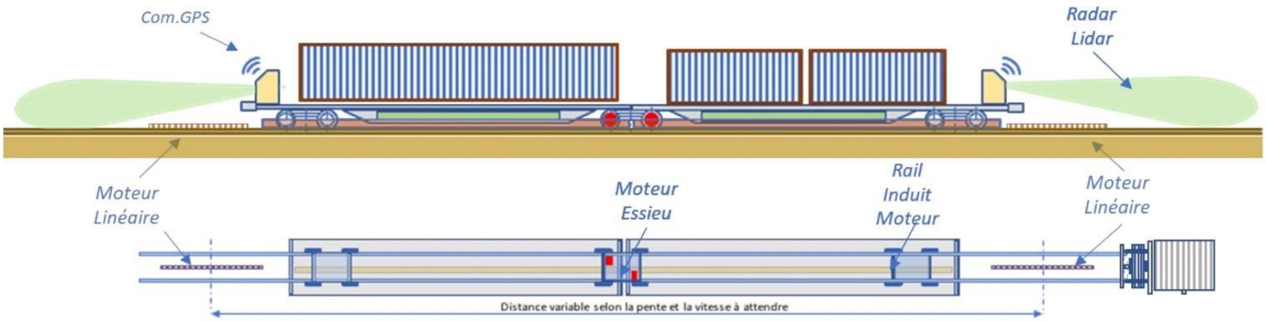


Figure 87.- Schematic diagram of the U-CARS system. (Source: TACV Lab)

The U-CARS system is boosted by U-shaped Linear Induction Motors (U-LIMs), which can either be carried by the vehicle or installed in the track depending on the length and degree of the slopes to be overcome.

The basic version of U-CARS uses rails for lateral guidance. A new version of the U-CARS is designed to reduce the empty weight of the vehicle by removing the bogie with independent wheels, the U of the U-LIM is then used as a reference for central guidance of the vehicle. The payload is then increased for the same load constraint on the track.

Yokohama Municipal Subway 10000 series

It is a linear motor-powered electric multiple unit (EMU) operated by the Yokohama Municipal Subway on the Yokohama Municipal Subway Green Line since March 2008. It is based on Mitsubishi Electric MAP-144-15V154 IGBT–VVVF traction system (Figure 88).

Figure 88.- The Yokohama Municipal Subway Green Line. (Source: https://en.wikipedia.org/wiki/Yokohama_Municipal_Subway_10000_series)

Osaka Municipal Subway 70 series

The Osaka Municipal Subway 70 series is a rapid transit electric multiple unit (EMU) train type operated by Osaka Municipal Subway on the Nagahori Tsurumi-Ryokuchi Line in Japan.

The 70 series was among the earliest trains in Japan to use linear motors and is capable of driverless operation. The traction is based on a variable frequency linear motor (Figure 89).

Figure 89.- The Osaka Municipal Subway 70 series. (Source: https://commons.wikimedia.org/wiki/Category:Nagahori_Tsurumi-ryokuchi_Line)

Sendai Subway Tozai Line

The Sendai Subway Tozai Line is one of the two lines of the Sendai Subway system operated by the Sendai City Transportation Bureau in the city of Sendai, Japan. It opened on 6th December 2015. The Tozai Line uses Mitsubishi MB-7012-A 135 kW (181 hp) 3-phase AC linear induction motors. The fleet of 15 four-car linear motor-powered EMUs was manufactured by Kinki Sharyo (Figure 90).

Figure 90.- The Sendai Subway Tozai Line. (Source: https://commons.wikimedia.org/wiki/File:Sendai-Tozai-Line_Series2000-2513.jpg)

SkyTrain rolling stock

The SkyTrain is a rapid transit system located in the Metro Vancouver region of the Canadian province of British Columbia (Figure 91).

The Expo Line and Millennium Line Bombardier Advanced Rapid Transit (ART) technology is a system of automated trains driven by linear induction motors, formerly known as the Intermediate Capacity Transit System (ICTS). The system uses the following linear traction systems:

- UTDC ICTS Mark I: UTDC GTO–VVVF,
- Bombardier ART Mark II,
- Batch 1: Toshiba linear IGBT–VVVF,
- Batches 2-3: Bombardier MITRAC IGBT–VVVF,
- Bombardier Innovia Metro Mark III: Bombardier MITRAC IGBT-VVVF,
- Hyundai Rotem EMU: Mitsubishi IGBT-VVVF.

Figure 91.- The SkyTrain rolling stock. (Source: Bombardier)

Toei Ōedo Line

The Toei Ōedo Line is a subway line in Tokyo, Japan, operated by the Tokyo Metropolitan Bureau of Transportation (Toei) (Figure 92). It commenced full operations on December 12th, 2000.

Figure 92.- The Toei Ōedo Line. (Source: https://eo.wikipedia.org/wiki/Linio_%C5%8Cedo_(Metroo_Toei)

The Ōedo Line is the first Tokyo subway line to use linear motor propulsion (and the second in Japan after the Osaka Metro Nagahori Tsurumi-Ryokuchi Line).

The system uses and Toei 12-000 and Toei 12-600 series rolling stocks equipped respectively with GTO–VVVF and IGBT–VVVF and IGBT–VVVF and hybrid-SiC/IGBT–VVVF traction systems.

5.3.4Hyperloop systems

Hyperloop is an ultra-high speed transport system, wherein in most configurations, the system promises a maximum speed of over 800 km/h. This system's main distinguishing feature is that the Hyperloop capsules will move in a dedicated tubular artery with a very low-pressure environment inside (depending on the project up to 0,001 atm). Vehicles can travel at ultra-high speeds with low energy expenditure due to a significant reduction in aerodynamic drag.

Several commercial companies and research centres are currently developing Hyperloop. There are several proposed solutions for the propulsion and suspension systems. In most cases, the electric linear motor drive is considered for propulsion. Depending on the design, the powered part of the motor is either in the vehicle or on the track. There is also contemplated a propulsion system based on a fan and an air compressor. Suspension systems, in most cases, are magnetic and they can be Electrodynamic Suspension (EDS) or Electromagnetic Suspension (EMS).

The companies developing hyperloop technologies are listed below.

Hyperloop One

The company has developed a hyperloop system (Figure 93) with propulsion based on long stator permanent magnet linear synchronous motor and its guidance system based on electrodynamic suspension (EDS). They have built an about 500-m long test track in Nevada (USA) with a vacuum pipe. The highest velocity achieved is about 310 km/h. On the same vacuum test track, the Hyperloop One company have conducted operational test with passengers on board. Since then, the company has changed its direction of development, and changed the propulsion and suspension systems. Now they claim that they plan to use linear homopolar motor for propulsion (with active windings on board) and active electromagnetic systems for levitation and guidance.

Hyperloop Transportation Technologies

The company is developing a hyperloop system which propulsion is based on linear induction motor and suspension is using Inductrack systems. At low speeds, the vehicle will be moving on wheels, and after reaching a certain designed velocity, the EDS levitation system will take over the vehicle weight and will start to levitate. The company developed a full scale hyperloop shell (Figure 95), made of material which they've called Vibranium. The company states that their hyperloop systems will speed up to 1200 km/h [Hyperloop Transportation Technologies].

Figure 93.- Prototype of the Hyperloop One. [Branson, 2017]

Figure 94.- Artistic vision of the new Hyperloop One vehicle. [Hyperloop One]

Figure 95.- The HTT vehicle mock-up [Hyperloop Transportation Technologies]

Zeleros

The Spanish company Zeleros is developing hyperloop system, whose propulsion is based on switched reluctance motor for acceleration and an electric compressor for maintaining the velocity in the vacuum pipe (Figure 96, Figure 94) or guidance their system is planned to be using active electromagnetic levitation and stabilization systems. In 2023 Zeleros developed a test rig for the propulsion motor in full scale. The company states that their hyperloop systems will speed up to 1000 km/h [Zeleros].

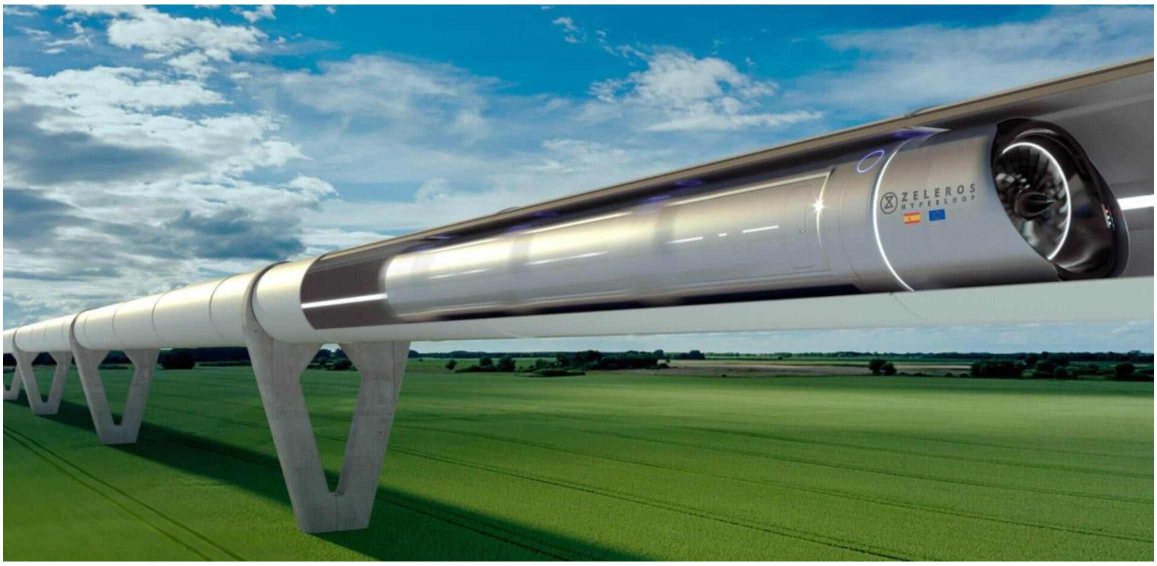


Figure 96.- Artistic vision of the Zeleros hyperloop system [Zeleros]

European Hyperloop Centre

The European Hyperloop Centre (Figure 97) is a project led by the Dutch company Hardt Hyperloop, in which several technology companies are collaborating. The project will include a centre to allow research into hyperloop technology including a test track with vacuum pipe. The chosen propulsion system is a homopolar linear electric motor, the suspension system will be based on an active electromagnetic levitation system, and forces from the propulsion motor itself. The project is designed for speeds up to 700 km/h.

Figure 97.- Visualization of the European Hyperloop Centre facility.

TransPod

TransPod is a Canadian hyperloop company which aims to develop both passenger and cargo vehicles. Every vehicle will be able to carry up to 50 passengers or up to 10 tons of payload. The maximum speed is planned to be 1000 km/h. TransPod has developed a unique system (FluxJet) for combined propulsion and suspension (Figure 98). They plan to use the same single infrastructure for both purposes. The propulsion motor will be linear synchronous, and the guidance will be based on electromagnets. Lately, they developed a small-scale project for demonstration and tests propulsion and guidance systems.

Figure 98.- TransPod "FluxJet" vehicle.

TUM Hyperloop

TUM Hyperloop is a German project being developed at the Technical University in Munich. They are planning to develop certified hyperloop system able to reach 900 km/h [TUM Hyperloop]. Lately they have developed a full-scale vehicle and a short test track. In 2023 they have successfully conducted a full vacuum ride with passengers on this test track (speed about 5 km/h). The vehicle was using linear synchronous motor for propulsion and electromagnetic systems pod guidance and suspension.

Swissmetro

The Swissmetro project is a high-speed public transportation system intended to connect Switzerland's major cities, capable of reaching speeds up to 500 km/h. It operates within two vacuum-sealed tubes (tunnels) and deploys linear motor technology, magnetic levitation, and guidance to transport 200 passengers/vehicle every 6 minutes (Figure 99). This system minimizes energy consumption by reducing air resistance. Swissmetro is centred around two tunnels, one for each direction of travel, with an internal diameter of 5.0 meters and an external diameter of 7.7 meters.

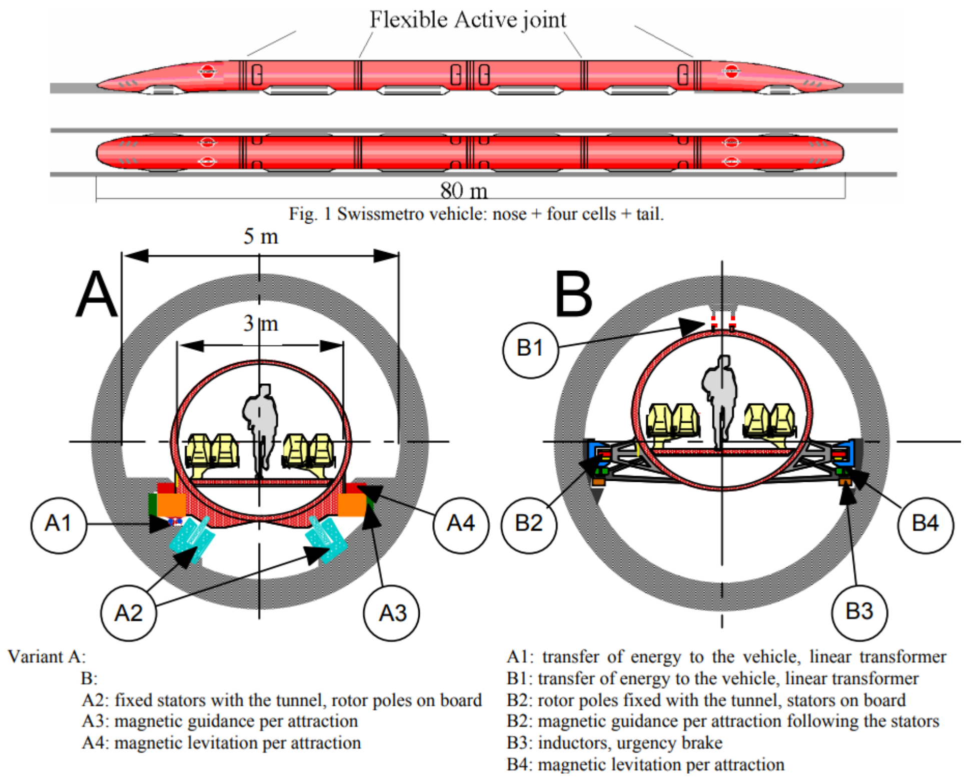


Figure 99.- The Swissmetro system setup and dimensions. (Source: Cassat, Swissmetro)

Combining the propulsion with the levitation and the guidance imposes to give up the homopolar linear motor (as chosen for the actual two variants A and B) and to choose a classical synchronous motor. The favourable tunnel environment permits to consider long stator motor with windings close to industrial motor, thus permitting to avoid the use of high voltage cables for the winding. High voltage cables impose a coil opening of three slots, for a three-phase motor. To decrease the Joule losses created by the levitation and the guidance inductors, a combination of polarized inductors with an additional DC winding is considered. Furthermore, this combination is necessary if the same inductor is considered also as a rotor pole of the linear motor, with its excitation. The combined propulsion with the levitation and the guidance reduces the number of active surfaces of the vehicle where a force is created. This permits a better mechanical integration of the electromechanical components, both fixed with the tunnel and onboard the vehicle.

5.4 Technologies overview

5.4.1Propulsion

5.4.1.1 Linear Motors

Linear motors play a pivotal role in the propulsion system of MDS vehicles, revolutionizing the way we think about high-speed transportation. These motors provide the necessary thrust to propel MDS vehicles along their tracks without the need for traditional wheels or rails. In Figure 100, Figure 101 and Figure 102 there are schemes of different categories of linear motors, each contributing to the efficiency and speed of MDS.

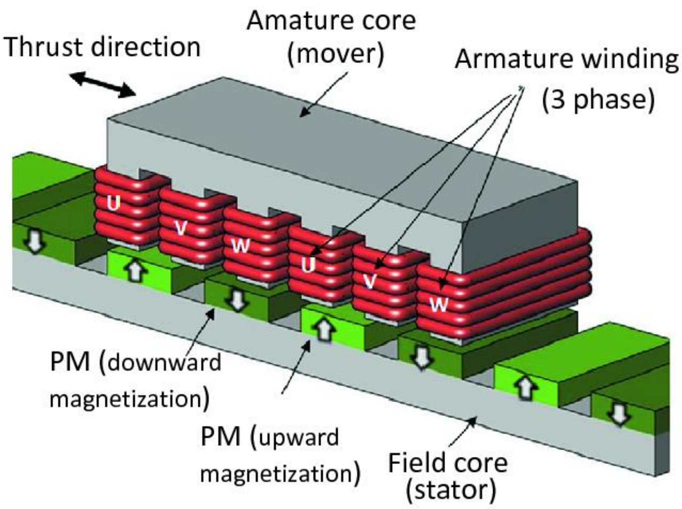


Figure 100.- Permanent magnet linear synchronous motor (PMLSM). [Wakiwaka, 2019]

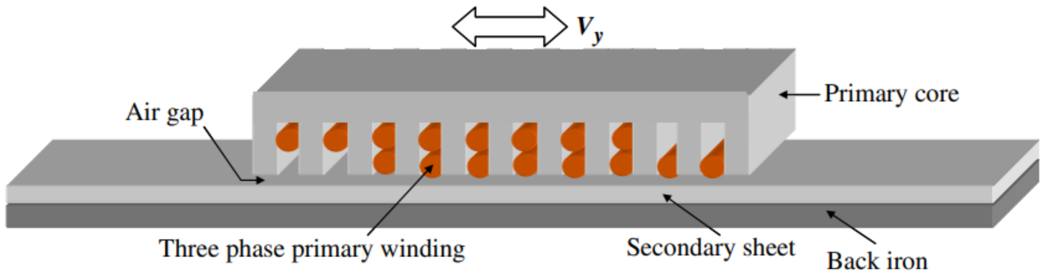


Figure 101.- Linear Induction Motor (LIM). (Source: https://eumhd.com/wp-content/uploads/2021/04/LoPinto.pdf)

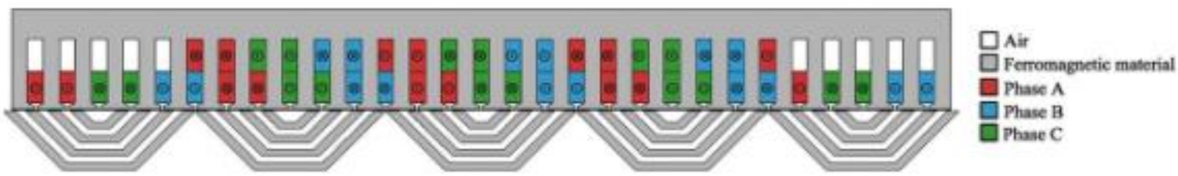


Figure 102.- Linear Synchronous Reluctance Motor (LSRM). (Source: https://www.youtube.com/watch?v=ZdaN8fEEVeM, timeframe 0:24)

Permanent Magnet Linear Synchronous Motor (PMLSM)

It is a linear motor consisting of 2 parts moving relative to each other. The first consists of 3 phase windings, while the second is equipped with permanent magnet systems. When energized, the windings produce a moving magnetic field that interacts with the magnetic field from the permanent magnets. By appropriately controlling the frequency and voltage of the winding supply, the magnetic field starts to travel along the motor, thus producing a synchronous relative motion of the mover with respect to the pole. Depending on the configuration, the winding can be stationary and placed in the track along the entire route (long-primary motor) or it can be moving and placed on the vehicle (short-primary motor).

Linear Induction Motor (LIM)

It is a linear motor consisting of 2 parts moving relative to each other. The first one consists of 3 phase windings, while the second consists of a package of aluminium plates laid on a ferromagnetic plate. When energized, the windings produce a moving magnetic field. By appropriately controlling the frequency and supply voltage of the winding, the magnetic field starts to travel along the motor, thus producing asynchronous relative motion of the mover with respect to the pole. Depending on the configuration, the winding can be stationary and placed in the track along the entire route (long-primary motor) or it can be moving and placed on the vehicle (short-primary motor).

Linear Synchronous Reluctance Motor (LSRM)

It is a linear motor consisting of 2 parts moving relative to each other. The first consists of 3 phase winding. The energized winding produces a magnetic field that penetrates the ferromagnetic secondary. By appropriately controlling the frequency and supply voltage of the windings, the magnetic field begins to travel along the motor thus producing synchronous relative motion of the mover to the pole. Depending on the configuration, the winding can be stationary and placed in the track along the entire route (long-primary motor) or it can be moving and placed on the vehicle (short-primary motor).

Linear induction motor using U shaped armature /TACV Lab (U-LIM)

TACV Lab is developing an original linear induction motor technology called U-LIM, due to the U-shaped armature. As shown in Figure 103 and Figure 104, U-LIM is a very different LIM design compared to the flat LIM used in many metros in Asia. The inductor windings surround the magnetic core of the motor, and the U-shaped armature covers the assembly. The figures show a view of the design of the engine with its cooling system. The U-shaped armature is composed of a first internal part in copper or aluminium for the circulation of the induced currents, intimately associated with a part in magnetic material for channelling the magnetic field.

The topology of the U-LIM offers a significative advantage on efficiency and mainly a high-power factor. On the open side of the U-shaped armature, the inductor is capped with an electromagnetic screen which blocks the leakage electromagnetic field and makes it possible to achieve a power factor of 0.7-0.8, which is the higher value for this type of machine. The consequence is a reduced and optimized sizing of the power converters. In addition, this design drastically reduces the electromagnetic leakage field in the environment close to the engine.

The U-LIM linear motor has been studied, designed, manufactured at full-scale and tested up to 300 km/h several years ago by a French team funded as part of a government research program. This team brought together a public research institute (IRT, now UGE) and a company for the design and the manufacturing of the U-LIM (CELDUC). The U-LIM tests were carried out on a remarkable test bench located in Grenoble (France), specifically designed for the characterization of high-speed linear induction motors. This test bench consists of a 13-m diameter wheel sized for the critical peripheral speed of 400 km/h but limited to 300 km/h in operation. Several U-LIM linear motors are working today from 5kW (500 units for airport baggage handling system) to 500 kW.

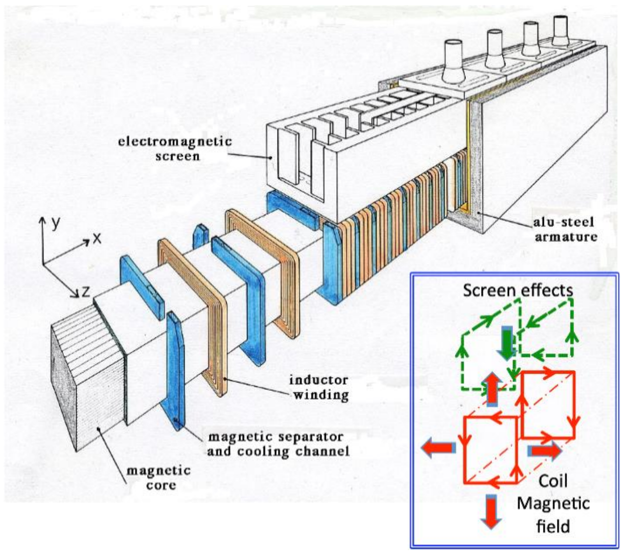
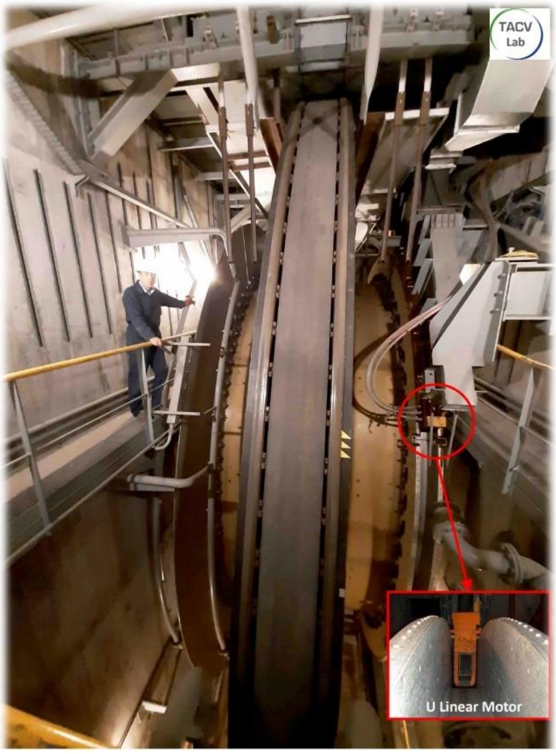


Figure 103.- Final design of the U-LIM including cooling. (Source: TACV Lab)



TACV Lab. Grenoble Wheel Laboratory, 13m diameter, 300km/h

Figure 104.- Grenoble linear motor testing laboratory "Wheel" (Source: TACV Lab. Photography). Guidance

5.4.1.2 Electromagnets

An electromagnet consists simply of a ferromagnetic core, such as steel, and a current-carrying winding wound on the core. While the manufacturing and operation of the magnet is relatively easy, a sophisticated feedback control system needs to be incorporated to maintain a constant separation between the pole face of the magnet and the ferromagnetic reaction surface, as the system is inherently unstable due to the use of attractive forces proportional to its separation.

Under this principle, magnetic levitation means that the magnet that is free to move is suspended continuously at a distance from the fixed track (Figure 105, Figure 106).

The physical arrangement can be also inverted, with the magnet fixed to ground and the ferromagnetic object suspended.

When this concept is applied to a vehicle, generally the vehicle is propelled by a linear motor, while the levitation clearance is obtained by adjusting the current in the magnetic coils.

To reduce eddy current effects, laminated guideways can be adopted instead of solid ones.

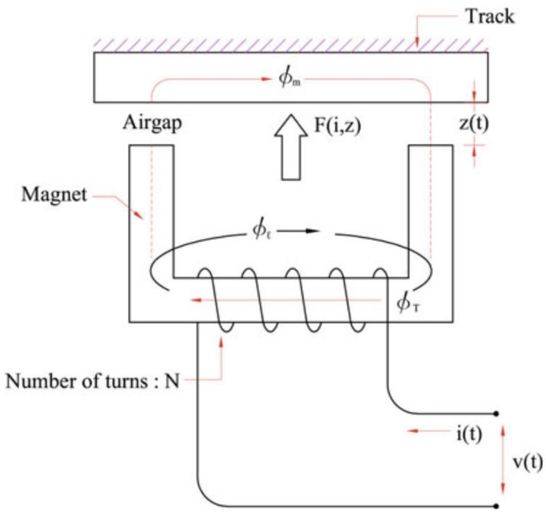


Figure 105.- Electromagnetic Suspension (EMS) system principle. [Han, 2016]

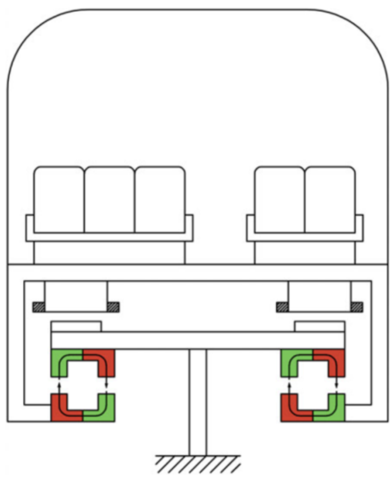


Figure 106.- Electromagnetic Suspension (EMS) system vehicle schematics.

5.4.1.3 Permanent magnets

A permanent magnet creates its own persistent magnetic field once magnetized by any external magnetic field. The main feature of a permanent magnet is that a continuous supply of power is not needed.

Levitation using permanent magnets in static mode is based simply on static repulsive or attractive forces between two magnets. Both these two configurations are conceptually very simple. Although there are no static permanent magnet vehicles in service or under construction, with the development of higher strength magnets, they may have potential for use in applications like conveyor systems for lightweight cargo.

To overcome permanent magnets field limitations, a new configuration was developed and proposed by Klaus Halbach to increase magnetic field strength, called "Halbach array". This array would give a strong field underneath, while the field above would be cancelled (Figure 107).

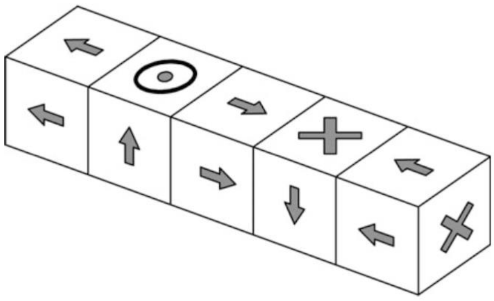


Figure 107.- Halbach array magnets configuration. (Source: https://en.wikipedia.org/wiki/Halbach_array)

Repulsive forces can be generated when a permanent magnet moves over a con-ducting sheet, such as an aluminium sheet. The repulsive force magnitude depends on the relative speed between a moving magnet and the conducting sheet. This kind of levitation that is dependent on speed is called electrodynamic suspension (EDS) (Figure 108). If a permanent magnet moves relative to a conducting sheet, its magnetic field induces currents in the sheet, and the currents in turn produce magnetic fields. The two magnetic fields produce repulsive forces by the interaction between them.

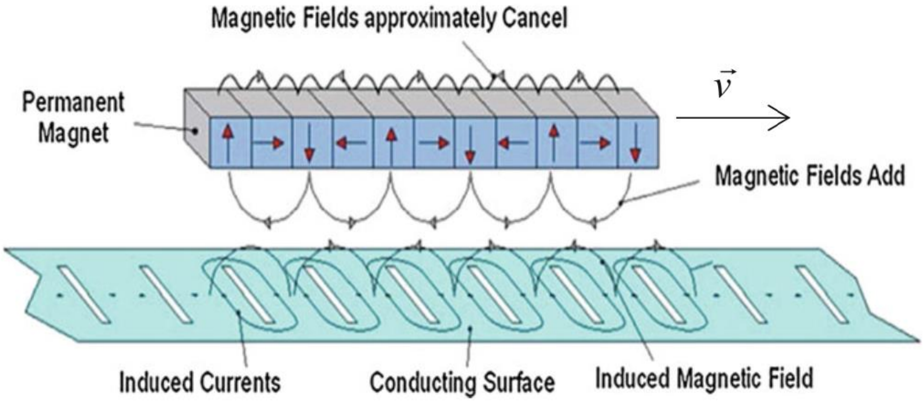


Figure 108.- Electrodynamic Suspension (EDS) system principle. (Source: https://www.edn.com/spacex-hyperloop-pod-competition-design-from-creative-young-minds-part-1/)

These repulsive levitation systems using moving permanent magnets are inherently stable but may require relatively greater thrust to overcome magnetic drag forces that arise due to the induction effect. For this reason, many high-speed magnetic trains that employ a Halbach array have been conceptually proposed, but none are yet in service.

The levitation technology referred to as “Inductrack” uses high NdFeB permanent magnets in one or multiple Halbach rows located on the moving vehicle. The second key element of the Inductrack is the track itself (Figure 109, Figure 110). To optimize both the inductive coupling between the moving Halbach arrays and the track, it consists of a close-packed array of shorted circuits. Such an arrangement maximizes the active area that generates the levitating force.

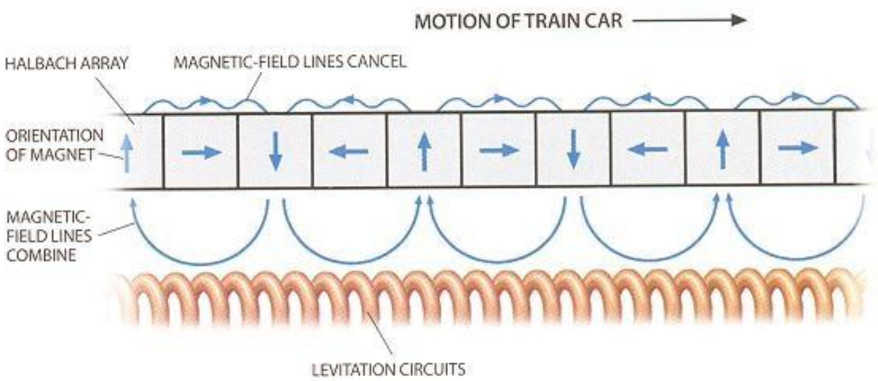


Figure 109.- Indutrack system principle. [Post, 2020]

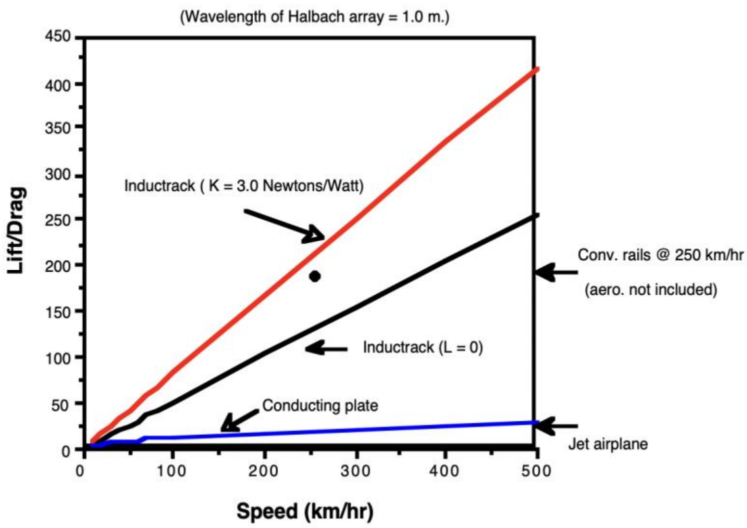


Figure 110.- Inductrack lift to drag ratio. [Post, 2020]

The major limitations of repulsive levitation that involves moving permanent magnets above is the need for translational relative movements and the magnetic drag generated. Figure 110 represents the lift to drag coefficient as function of the speed for different EDS architectures.

There is a way to obtain relative velocity by rotating magnets rather than translational movements. This technique is called magnetic wheel.

One of the approaches to using permanent magnets to support vehicles is the use of the so-called “hybrid magnet” (or “controlled permanent magnet”), which is a combination of iron core and permanent magnet core. The main advantage of this magnet is the considerable improvement in the lift/weight ratio and the reduction in the rated on-board power amplifier and supply.

5.4.1.4 Superconductors

Some conductors lose their electrical resistance completely below a particular temperature, becoming ideal current-carrying conductors. This phenomenon is called superconductivity, and it is influenced by temperature and the ambient magnetic field.

Once an electric current is set up in a superconducting loop, the current flows and induces a magnetic field persistently if the temperature is kept below critical temperature, making the superconducting coil behave like a permanent magnet.

One of the most important effects for the application of superconductors for magnetic levitation is flux pinning, the phenomenon in which a superconductor is pinned in space above a magnet by means of diamagnetism for levitation and magnetic flux tubes entering the superconductors for stabilization, thus avoiding the need for auxiliary systems for stabilization and guidance (Figure 111). One example of application of flux pinning effect is Maglev-cobra system [Sotelo G., 2014].

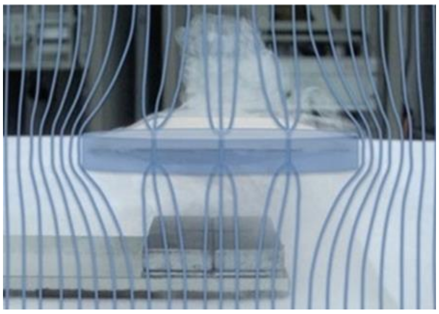


Figure 111.- Superconductor type II behaviour – flux-pinning effect. (Source: Wikipedia)

An electrodynamic system can be obtained also with the use of superconductors instead of permanent magnets. Therefore, excepting for the strength of the magnetic field produced by the superconductor, most of its features may be the same as those of a permanent magnet system.

At lower speeds, the force may be not sufficient for lifting the magnet and its associated gear off the conducting sheet. The speed when net lift force is positive is called critical speed. In this type of electrodynamic levitation system, an auxiliary wheeled suspension is needed for operations at below critical speeds. This critical speed is dependent on vehicle weight and the magnetic field strength in the airgap.

The latest and most advanced version of using superconducting magnets in dynamic mode is the null-flux system of the L0 vehicle [Murai, 2003], employing 8-figure guideways loops to cancel out current flows when in centred configuration; when decentred, current flows and a strong field is generated by the coil, which tends to restore the spacing (Figure 112).

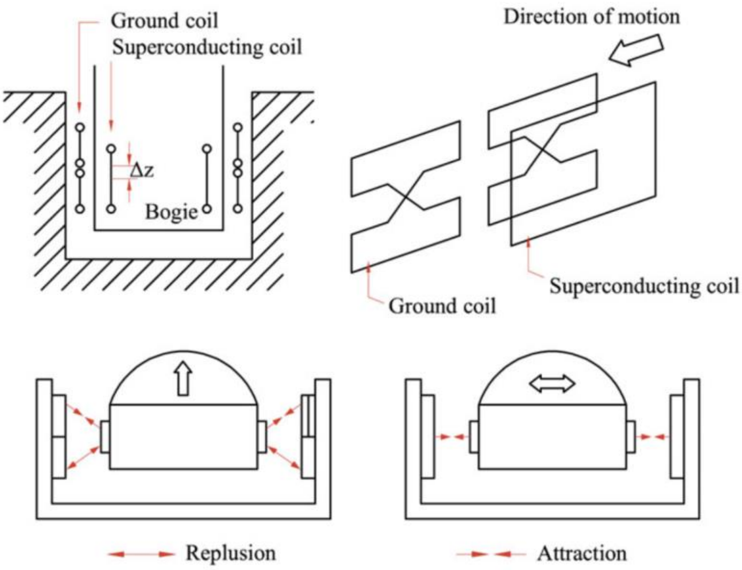


Figure 112.- L0 vehicle guidance system principle.

5.4.1.5 Ferromagnetic levitation

Ferromagnetic levitation principle is obtained by coupling a magnetic slider with a ferromagnetic rail (Figure 113).

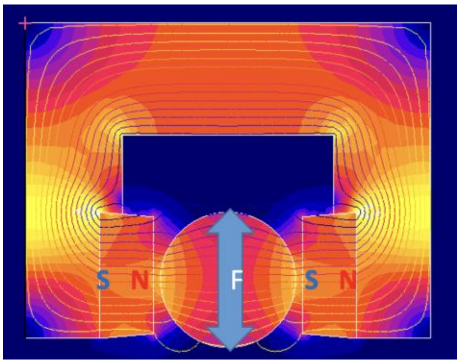


Figure 113.- Ferromagnetic levitation principle. (Source: Ironlev)

The slider is made of a ferromagnetic U-shaped profile with an installed array of permanent magnets and coupled with a ferromagnetic rail.

The magnetic flux crosses the rail in a direction transversal to the first axis and creates a closed-loop magnetic circuit on the U-shaped profile. This configuration generates a stable equilibrium along the first axis that maintains the rail centered on the flux crossing point (minimum magnetic reluctance) and allows to bear a load magnetically.

The permanent magnets are arranged as to generate a magnetic field oriented transversely to the direction of motion. The slider is coupled with the rail positioned inside the U-shape profile and separated by two lateral air gaps. This configuration allows the magnetic flux to cross the volume with different magnetic permeability. Such flux is guided through the conductive material and tends to be channelled into the material with higher magnetic permeability. This phenomenon is able to develop a force on the slider until the equilibrium position is reached.

The following graph shows the lift-to-drag ratio in a standard iron rail track with different slider length (from 1.2 m to 10 m) (Figure 114).

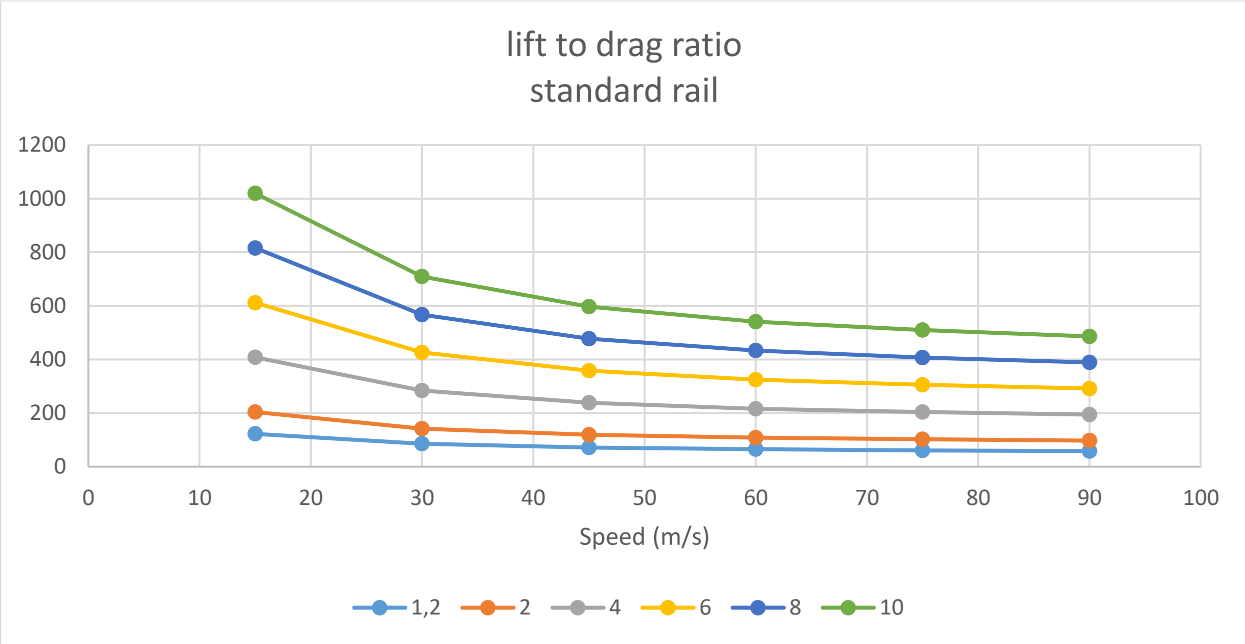


Figure 114.- Ferromagnetic levitation – lift-to-drag ratio – standard rail. (Source: Ironlev)

The eddy current effect can be almost eliminated with a custom iron rail with the addition of a laminated head with which the magnetic slider interacts. In this architecture, the lamination is transversal to the direction of motion. Figure 114 shows the lift to drag ratio of a 3 m long slider of 5-ton load capacity designed for a freight wagon of 40 ton – 12 m length.

5.4.2Suspension

The suspension system reduces the vibrations arising from ride factors and gives ride comfort to the vehicle. Generally, the mechanical suspension is the system that connects the support/guidance system to the vehicle chassis. In the MDS domain, the suspension system can be of different architecture based on the support/guidance system used.

For EMS systems, a fully active electromagnetic configuration is used, and the suspension system can be referred as the system that provides the stabilization of the inherently unstable suspension, and it is integrated with the levitation control system.

The system must usually be designed to meet the suspension stability and ride comfort requirements. Since the suspension stability is closely related to the physical dimensions of the levitation system, a suspension system design derived only from ride comfort considerations may not provide a sufficient margin of stability. Thus, any secondary suspension between the passenger cabin and the levitation magnet may be introduced to the system to achieve the required primary suspension stiffness while allowing an acceptable ride quality. Typical secondary suspension systems consist of a spring and a damper based assembly.

5.4.3Braking

Braking in MDS is typically achieved through a combination of electromagnetic and mechanical methods. The specific type and description of braking in MDS can vary depending on the design and technology used. Here's an overview of common braking methods in MDS.

5.4.3.1 Linear motor braking

Linear motor braking is based on the operation of the same linear motor used for propulsion. It involves reversing the direction of the magnetic field generated by the linear motor to create opposing forces between the stator and mover. The strength of the braking force is controlled by adjusting the electric current supplied to the stator windings. This allows for precise control over deceleration. Linear motor braking has the potential for energy recovery, as the braking action generates electrical energy that can be converted and used within the system or returned to the power grid.

5.4.3.2 Electrodynamic brakes

This braking system relies on the principles of electromagnetic induction to generate braking force without physical contact with the track or guideway. When the vehicle needs to slow down or stop, the electromagnets in the guideway or track generate a magnetic field that opposes the motion of the vehicle.

MDS vehicles can be equipped with magnets, typically permanent magnets, on their undercarriage or vehicle frame. These magnets create a magnetic field as the train moves along the guideway or track. As the train moves, its magnetic field interacts with the guideway's metal conductors, which are often made of aluminium or copper. The induced electric currents, known as eddy currents, circulate within the conductors of the guideway. These circulating currents create their own magnetic fields, which oppose the original magnetic field of the moving train. This opposition generates a braking force known as electromagnetic drag. The electromagnetic drag generated by the interaction of the magnetic fields between the train and the guideway provides the braking force needed to slow down the train. The strength of this braking force can be controlled by adjusting the strength of the magnets on the train or the properties of the conductors in the guideway. Like other forms of electromagnetic braking, electrodynamic braking in MDS can be highly efficient and allow for the recovery of energy. The electrical energy generated by the braking process can be converted and fed back into the system or the power grid, reducing energy consumption.

5.4.3.3 Friction brakes

Mechanical braking, including friction brakes, is an additional method used in some MDS to provide supplemental or emergency braking when needed. In some MDS, especially those designed for safety redundancy or as a backup measure, traditional friction brakes may be incorporated. These are like the brakes found in conventional trains and automobiles. In MDS, friction pads will work only when the vehicle rides on the wheels. Friction brakes typically consist of brake pads (usually made of high-friction material) that are pressed against rotating brake rotors attached to the wheels of the vehicle. When the brake pads encounter the spinning rotors, the friction between them generates heat and resistance. This resistance slows down the rotation of the wheels, which, in turn, decelerates or stops the vehicle. Mechanical brakes are often used as a supplementary or emergency braking system, providing an extra layer of safety in case of system failures or emergencies. They may also be used at lower speeds or during maintenance procedures.

5.4.4Infrastructure

MDS represent a significant advancement in modern transportation technology. There are various types of MDS infrastructures. What they have in common are components facilitating propulsion (e.g., linear motor stator) and suspension (e.g., magnetic suspension track). The existing MDS infrastructure, or the one described in the literature, can primarily be categorized into those utilizing existing conventional railway infrastructure (and conventional railway tracks) and those requiring a separate and new infrastructure on a dedicated track.

MDS utilizing existing railway infrastructure

MDS that utilise existing railway infrastructure have the advantage of being able to exploit the existing railway tracks. This represents a significant step towards expediting the implementation of such systems, as the processes involved in establishing new transportation systems, including land acquisition, typically span several decades. However, these systems must be capable of coexisting on the same route with conventional railways. Therefore, the infrastructure of such a MDS should be designed with specifications that allow for interoperability with traditional railway systems. Examples of such systems include Nevomo's

MagRail and the Ironlev technology-based system (Figure 115).

a)
b)

Figure 115.-Example of an MDS infrastructure integrated within the railway corridor; a) MagRail; b) Ironlev.

MDS with dedicated separate infrastructure

The vast majority of existing and described MDS are designed with a separate and dedicated infrastructure. This approach offers significant optimization possibilities as the design is not constrained by railway requirements. Each of the subsystems being designed (including propulsion, magnetic suspension, power transmission, and communication) can be tailored and located in the optimal manner for the specific system. For this reason, the infrastructure of many MDS projects is supported by concrete pylons (as in i.e., Transrapid, Max Bögl systems), on which the vehicles travel (Figure 116). There are MDS where vehicles move on the pylon-based infrastructure while being suspended beneath it (as exemplified by the Xingguo Maglev presented in Figure 117), although such instances are relatively rare.

Additionally, there are MDS where the dedicated infrastructure is constructed directly on the ground, such as the Japanese Shinkansen Maglev (Figure 118). This approach significantly reduces the construction and maintenance costs of the infrastructure.

Figure 116.- Transrapid infrastructure. [maglev]

Figure 117.- Xingguo infrastructure. [xingguo]

Figure 118.- Shinkansen Maglev infrastructure. [shinkansen]

5.4.5Power supply systems

In the realm of MDS systems, the importance of electrical power supply systems cannot be overstated. Electric power is critical in various aspects of MDS, including propulsion, levitation, and auxiliary systems (like air-co or lightning). Depending on where the powered components are, the power supply methods can be categorized into two primary approaches. When the powered components are situated on the vehicle, it is essential to either utilize onboard energy storage or continuously supply power to the vehicle. Conversely, when the powered components are integrated into the track infrastructure, the entire length of the track must be energized to ensure seamless operations. This dual nature of power supply is a fundamental consideration in the design and operation of MDS.

5.4.5.1 Infrastructure power supply

MDS with large infrastructure-mounted power devices, such as the stator windings of a linear motor, among others, require the provision of power with adequate parameters along the entire length of the route and the linear motor infrastructure (Figure 119).

To reduce energy losses, the propulsion motor is divided into sections. The stator is also divided into sections that are powered independently of each other. Only those sections closest to the moving vehicle are activated. This ensures that sections not involved in the movement of the vehicle are not powered. At its simplest, each stator section has its own dedicated traction substation consisting of a transformer and an inverter (Figure 120). In more advanced solutions, the same traction substation can serve multiple sections (Figure 121), thus reducing the hardware costs of power electronics.

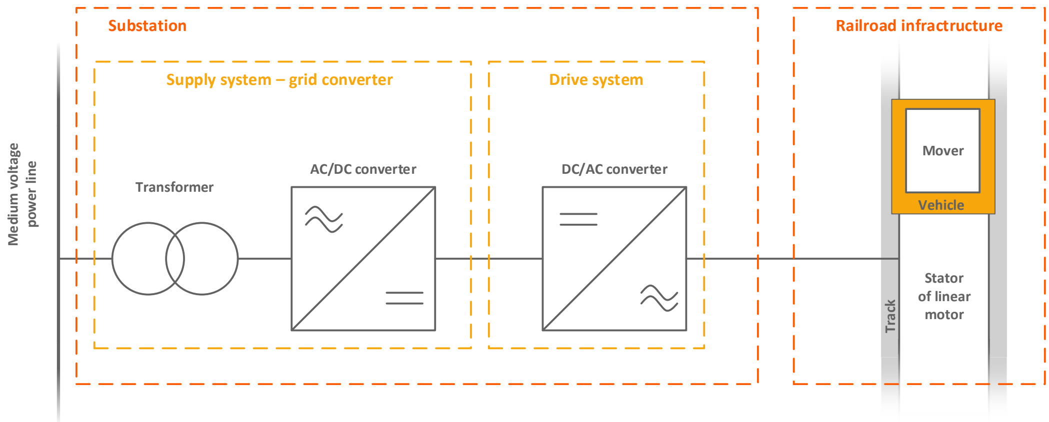


Figure 119.- Infrastructure power supply.

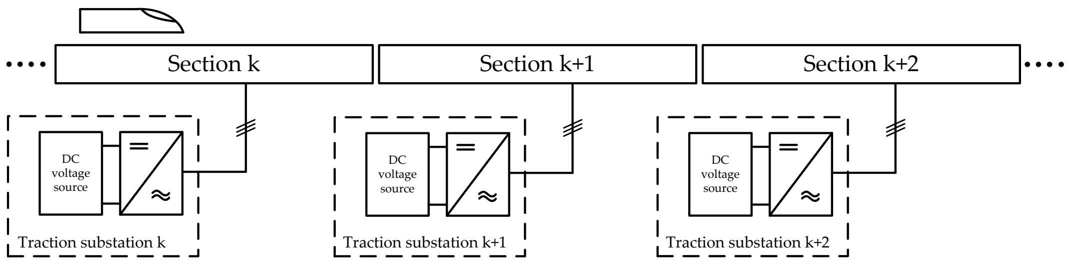


Figure 120.- Infrastructure power supply – own dedicated traction substation for each section.

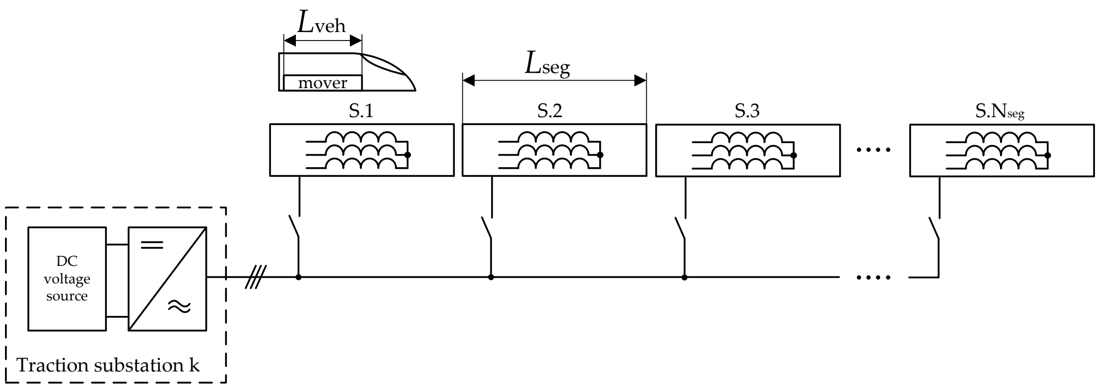


Figure 121.- Infrastructure power supply – same traction substation for multiple sections.

Vehicle power supply

MDS in which propulsion requires power to the active part of the linear motor located on the moving vehicle typically use contact power transmission to the moving vehicle. Power rails are installed in the infrastructure, on which a voltage of the appropriate parameters prevails. The vehicle is equipped with a current collector. The collector touches the power rails and in effect the electrical power is transferred to the vehicle's propulsion system as well as to any other systems requiring electrical power (like levitation system or non-traction related systems). The power rails installed in the infrastructure are also sectioned so that only the sections around the vehicle are powered.

The more advanced power transmission systems use contactless systems (inductive energy transfer) so that the system can travel at higher speeds and transfer more energy. Vehicle systems can also draw power from an on-board energy storage device on the vehicle, which may be an electrochemical battery or a hydrogen system.

5.4.6Communication and localisation systems

5.4.6.1 Communication systems

In the automotive and rail domains, vehicles are entering the era of full automation thanks to wireless sensors and communication systems shifting control functions from the human driver to computers. High data rate, robustness, high reliability, and ultra-low latency are required for wireless communications in the context of autonomous train and safety critical applications. From a general point of view, wireless communications for high-speed systems like maglev or MDS, should support very high speed and very high Doppler shift, particularly during handover between the different radio access points deployed along the line. In addition, the system should also be deployed in harsh environments and tunnels, and it should be resilient to any type of electromagnetic interferences (voluntary or not).

Historically, in Europe, and more generally in the world, each country had its own wireless communication systems deployed for control and command of trains. To optimize European railway travels and cross borders with high-speed trains, a common control and common system, called ETCS (European Train Control System) was developed under international union of railway (UIC) and European Commission support. The system has been deployed widely. Two main components of this system are the radio system GSM-R and the Eurobalise system. GSM-R is a cellular system based on GSM Phase2+ specifications on which specific and mandatory railway functions called Advanced Speech Calls Items (ASCI) have been developed to answer railway specific needs such as group calls, location dependent addressing, priority levels, broadcast group calls, emergency calls, shunting mode and direct mode, etc. GSM-R is deployed today along 150,000 km of railway lines, from which only 23,000 km are high-speed lines.

GSM-R allows secure voice and data transmission with a low data rate. It is based on circuit mode communication available in 2G standard. It carries the signalling information for the ETCS system. GSM-R generally uses dedicated Base Transceiver Stations (BTS) close to the railway line. The distance between two BTSs is 3-4 km. The train maintains a permanent digital modem connection to the train control centre. This connection has a higher priority than other users: Multi-Level Precedence and Pre-emption Service) (eMLPP). If the modem connection is lost, the train stops automatically. Specific frequency bands have been allocated at the European level for deploying GSM-R: 874.4-880 MHz for Uplink (Train-to-ground) and 919.4-925 MHz for downlink (Ground-to-train).

To increase the data rate and migrate toward IP technology, GSM-R networks have been enhanced with GPRS (Global Packet Radio System) deployment, corresponding to the normal evolution of the 2G standard toward the 3G standard.

Today, the Future Railway Mobile Communication System (FRMCS) is under development at the European level within the International Union of Railways (UIC), the Europe's Rail Joint Undertaking (EU-Rail JU), and the European Commission. It will answer all railway's current and future needs and the shift from the vision of "network as an asset" to a more modern vision of "network as a service". It will be IP-based, multi-bearer, and resilient to evolution of technologies and interferences. It is ambitious to bring bearer flexibility to the railway telecommunication essential services using the capabilities of 5G NR new standard. It will be the system that will offer a full migration towards 5G for the railway industry, as GSM-R will become obsolete in 2030. The frequency bands envisaged today for FRMCS are the following:

- 874.4-880 MHz / 919.4-925 MHz FDD,
- 10 MHz in the lower part of 1900-1920 MHz TDD,
- 10 MHz in 2290-2400 MHz TDD as a tuning range.

The two first bands are decided. The last band is still under negotiation.

It must be noted that FRMCS is meant for high-speed railway systems with a maximum velocity limited to 500 km/h. This may be a limiting factor for ultra-high-speed MDS compatibility in the future, however this is still a matter of several years to address this challenge.

The coexistence between GSM-R and FRMCS is being studied, and solutions will be proposed for example in the French-German 5GRACOM project. FRMCS is under evaluation in laboratories and on site in the framework of the 5GRAIL European project. Solutions to solve the question of cross borders are also proposed and evaluated.

The spectrum scarcity for all applications foreseen for FRMCS constitutes an important drawback for high data rate applications. Solutions to solve this bottleneck should be found. In some countries, particularly in China, the LTE system has also been considered as a successor of GSM-R.

Due to spectrum scarcity, 5G standard includes the evolution toward high-frequency bands. Such millimetric bands (mmW). 5G mmW frequencies refer to the frequencies between 10 GHz and 100 GHz. The bands foreseen for 5G NR standard are located at 28-30 GHz, 38-40 GHz, the free-licensed band 57–64 GHz, extended to 71 GHz, with 14 GHz of contiguous band. The band between 40.5 and 43.5 GHz has been mentioned for Railways at CEPT. The 60 GHz band is of great interest for railways in case of very high data rate and very low latency requirements. Developments in this field are very active between 24 GHz and 100 GHz. They are suitable for high-speed mobile applications and other railway safety critical applications identified such as virtual coupling of trains (platoons of trains) from different manufacturers based on Train to Train (T2T) wireless communications.

In the urban domain, the control and command of trains relies on wireless communication systems referred to as Communication Based Train Control (CBTC) and balises, generally for positioning and speed controls. CBTC systems are based on IEEE 802.11 WLAN (Wi-Fi), as the radio technology, mainly due to its cost-effectiveness. CBTC carries mission-critical data. Non-safety-related rail applications are called Closed Circuit Television (CCTV) and referred to data related to on-board Internet, audio and video surveillance, maintenance, etc. The IEEE 1474.1 published in 1999, defines performance and functional requirements for CBTC. An additional standard 1474.3, published in 2008, defines recommended practice for CBTC system design and functional allocations. Contrary to ERTMS standard, IEEE CBTC standard is not strictly respected by CBTC suppliers because generally, it appears that the CBTC systems are proprietary because in general there is no need for interoperability between different metro operators. Urban railway applications operate in a small band in the ITS safety band (around 5.8 GHz).

Moreover, the question of cybersecurity of wireless systems is crucial today [Soderi23] [Soderi23-1].

5.4.6.2 Localisation systems

Train positioning is crucial for safe train operation in general. There are a lot of applications with different service requirements. The positioning techniques can be divided into solutions using track-side devices such as track-circuit, balises and on-board solutions based on Doppler radar, eddy current sensor, wheel sensor, inertial measurement unit and satellite positioning applications, which are generally coupled with other sensors.

To decrease maintenance costs on the infrastructure side, the same trend than for communication systems is observed. Radio-based solutions excluding balises are explored today. Mainly Satellite based solutions also called Global Navigation Satellite Systems (GNSS) are in development today. Satellites are not used alone but in multi-sensors systems. The main bottleneck to be solved is the lack of satellite visibility that creates errors that decrease availability of the positioning system [Zhu20]. Various multi sensors prototypes exist and are being tested in various demonstrators in Europe considering multi constellations approach (GALILEO, GPS, GLONASS, etc.). [Marais17] and [Otegui17] are still updated documents to highlight various projects. A survey of potential interferences is given in [Morales19].

With the deployment of 5G NR networks, localisation solutions can also use 5G NR networks as a complementary solution. Some developments are ongoing on this topic [Ko22].

5.4.7Command, control and signalling systems

5.4.7.1 Introduction

The signalling systems applicable for this type of solution can be various. For system that travel on a fixed location that cannot change in the sense that it is not a set of railway lines, the most suitable solutions are those like the CBTC world, while if we adopt solutions that overlap railway lines then the appropriate solution is to use ETCS, also for interoperability reasons.

In both types of signalling systems there is a general principle that must be followed, namely radio communication between the wayside and on-board systems as described in the Communication System paragraph.

CBTC systems currently used consider both the signalling and automation parts adopted in the most modern metros in the world. It does not have the objective of being interoperable because it is a system confined to the specific line and usually has no interactions with other lines. For this reason, CBTC systems have guidelines but do not identify, for example, which specific radio system to adopt and which transponders (if necessary) to adopt.

These systems are applied to very simple line configurations which are often implemented with autonomous guidance at Grade of Automation 4 (GoA4).

The distance between trains is regulated by a spacing based on radio communication and automation (ATO) is achieved between the cooperation between wayside ATO and On Board ATO.

Since the CBTC system does not require to be interoperable, this aspect has a positive impact for the potential application to innovative MDS.

In fact, as far as possible, the application of CBTC systems allows the adoption of the communication system, the transponders and in general a large part of the sensors. This has a positive impact on the system to be created as it is possible to choose the solution that minimizes the risks linked to aspects of compatibility with the technology adopted both in terms of mechanical aspects and electromagnetic compatibility.

As mentioned before, when considering solutions that operate on railway lines then the system to adopt is ETCS. In this case, specific rules must be applied, and it is not possible to choose other typologies of interfaces between wayside and on-board systems and innovative MDS will have to adopt the TSI requirements specified for railway lines.

At a macroscopic level the systems based on CBTC and those on ETCS (Radio communication) have a very similar architecture. Figure 122 shows a very high-level architecture.

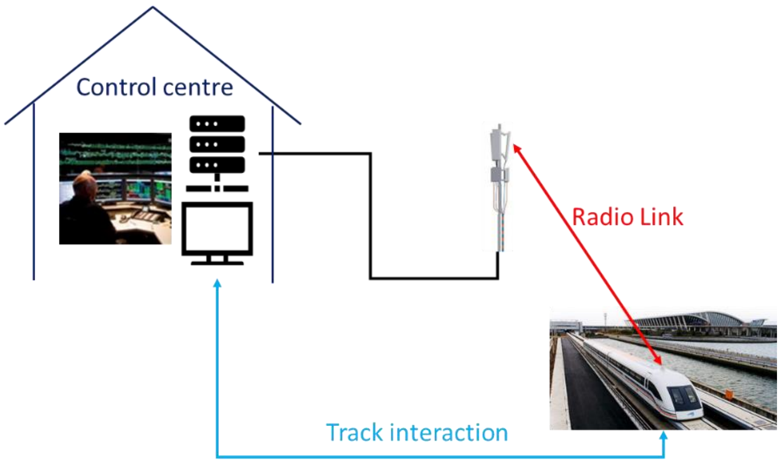


Figure 122.- Control Centre, Radio communication between Wayside and On Board (Radio Link), connection between the control centre and the wayside devices (track interaction) (Source: Uni Eiffel)

5.4.7.2 CBTC

Communications Based Train Control (CBTC) uses telecommunications between the train and equipment for traffic management and infrastructure control. By means of CBTC systems, the exact position of a train is known more accurately than with traditional legacy signalling systems. This results in a more efficient and safe way to manage rail traffic and improved outcomes while maintaining or even improving safety.

A CBTC system is a "continuous automatic train control system that uses high-resolution train position determination, independent of track circuits; Continuous, high-capacity, bidirectional train-to-wayside data communications; and transformers Trainborne and Wayside capable of implementing Automatic Train Protection (ATP), as well as optional Automatic Train Operation (ATO) and Automatic Train Supervision (ATS) functions".

The main objective of CBTC is to increase capacity by safely reducing the time interval (stepping time) between trains traveling along the line.

Unlike traditional fixed block systems, in moving block CBTC systems, the protected section for each train is not statically defined by the infrastructure (except for virtual block technology, with the operational aspect of a moving block but still limited by physical blocks). Furthermore, the trains themselves continuously communicate their exact position to the equipment on the track by means of a two-way link, inductive loop or radio communication. This technology, which operates in the 30-60 kHz frequency range to communicate trains and roadside equipment, has been widely adopted by subway operators despite EMC compatibility issues, as well as other concerns, installation, and maintenance, potentially compatible with innovative MDS.

As with the new application of any technology, problems could arise in the beginning. However, the improved reliability of radio-based communication systems will help to solve these problems.

5.4.7.3 ETCS

ERTMS was introduced to replace the various national systems of EU countries, ERTMS has become the main international standard for control systems and train control, and became a reference worldwide used in several countries such as Brazil, Mexico, Australia, and China. A main component of the ERTMS system is the European Train Control System (ETCS), a signalling system (the signal is presented in the driver cabin) and speed control. Due to the nature of the functions required, the system ERTMS/ETCS is partly on the track (managed by infrastructure holders) and partly onboard trains (managed by railway undertakers). This defines two systems, the “Trackside system” and the “Onboard system”.

The “Trackside system” includes:

- Transmission devices (beacons), also called “Eurobalise”, are used to send telegrams from the track to the onboard system,
- ERTMS Lineside Electronic Unit (LEU) encoder generates telegrams through beacons, based on information received from external ground systems (interlockings, control centres, etc.),
- Radio Block Centre (RBC) is a computerised system that develops messages to send to the train based on information received from external ground systems and exchanged with onboard systems itself,
- GSM-R is an international standard for mobile telephone communication dedicated to railways, which is used for the bidirectional exchange of messages between ground systems and RBCs,

The “on-board system” includes:

- a computerized system which supervises the movement of the train to which it belongs, based on the information exchanged with the Trackside system,
- GSM-R, same as above,
- European Vital computer (EVC), it is the core of the on-board systems and it interacts with the other equipment; it also communicates with the Radio Block Centre (RBC). The EVC communicates also to the driver via the ETCS Displays.

ERTMS can operate in three levels, plus optional Level 0 and Specific Transmission Module Levels (STM).

5.4.7.3.1 ETCS Level 1

ERTMS Level 1 (Figure 123) is designed as an overlay of a conventional line, already equipped with track signals and train sensors. Communication between the trackside system and the train is ensured by beacons located on the edge of the track adjacent to the track signals at regular intervals and connected to the RBC. By receiving the information about the state of the line via the beacons, which redundant the optical information of the signals, the on-board equipment automatically calculates the maximum speed of the train and the next braking point if necessary, taking into consideration the braking characteristics of the train and the track description data. This information is displayed to the driver through a dedicated normalized screen in the cabin, the Driver Management Interface (DMI). Train speed is constantly monitored by ETCS on-board equipment: ERTMS provides an Automatic Train Protection (ATP) service. The transmission performances for beacons on the ground may be impacted in case of linear motor traction providing relevant magnetic fields.

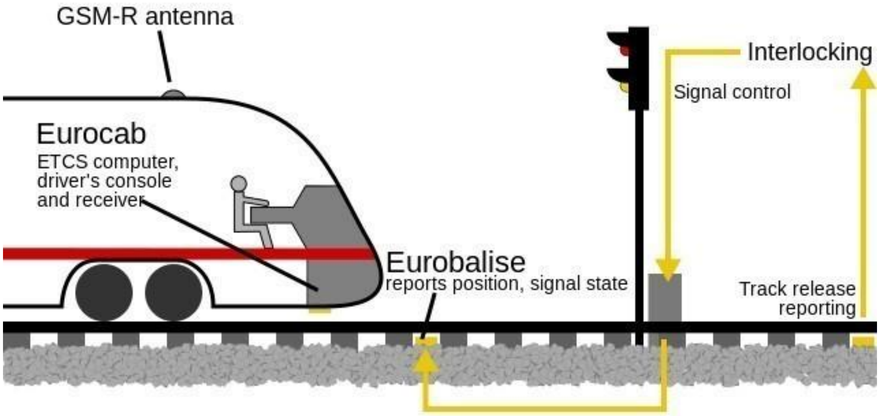


Figure 123.- ETCS level 1 scheme. (Source: https://transport.ec.europa.eu/transport-modes/rail/ertms/what-ertms-and-how-does-it-work/etcs-levels-and-modes_en)

5.4.7.3.2 ETCS Level 2

ERTMS Level 2 (Figure 124) does not require a MA sent by a beacon. It is communicated directly from the RBC to the ERTMS/ETCS equipment on board via GSM-R. Beacons are only used to convey fixed messages, such as position, gradient, speed limit, etc. A continuous flow of data informs the driver concerning the line-specific data and track signal status to follow, thus enabling reaching maximum or optimal speed while maintaining a safe braking distance. It is commonly used in Europe for high-speed passenger line systems running up to 320 km/h.

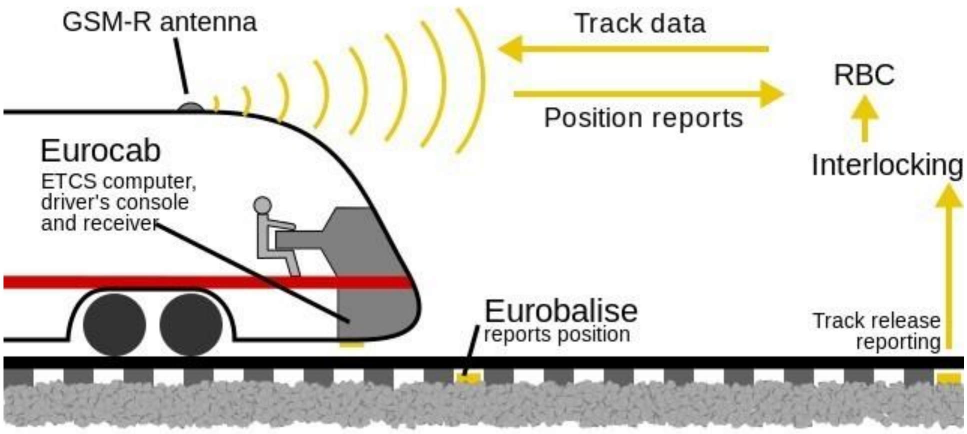


Figure 124.- ETCS level 2 scheme. (Source: https://transport.ec.europa.eu/transport-modes/rail/ertms/what-ertms-and-how-does-it-work/etcs-levels-and-modes_en)

5.4.7.3.3 ETCS Level 3

ERTMS Level 3 introduces a "mobile block" technology. With, precise and continuous position data is provided to the control centre directly from the train rather than from ground-based sensing equipment. As the train constantly monitors its own position and integrity, there is no need for fixed blocks and the moving block accompany the train. The localisation could be also provided by embedded satellite-based geolocation devices.

5.5 Operational principles

Analysis on potential MDS, mainly with reference to operational aspects, is summarised in the following synthetic prospects.

Figure 125 provides a geographical distribution of the investigated systems, classified according to the commercial operation, wherein YES refers to operational and commercial systems and NO refers to prototype systems and test-tracks.

Figure 126 provides an overview of the Technologically Readiness Levels of the investigated systems.

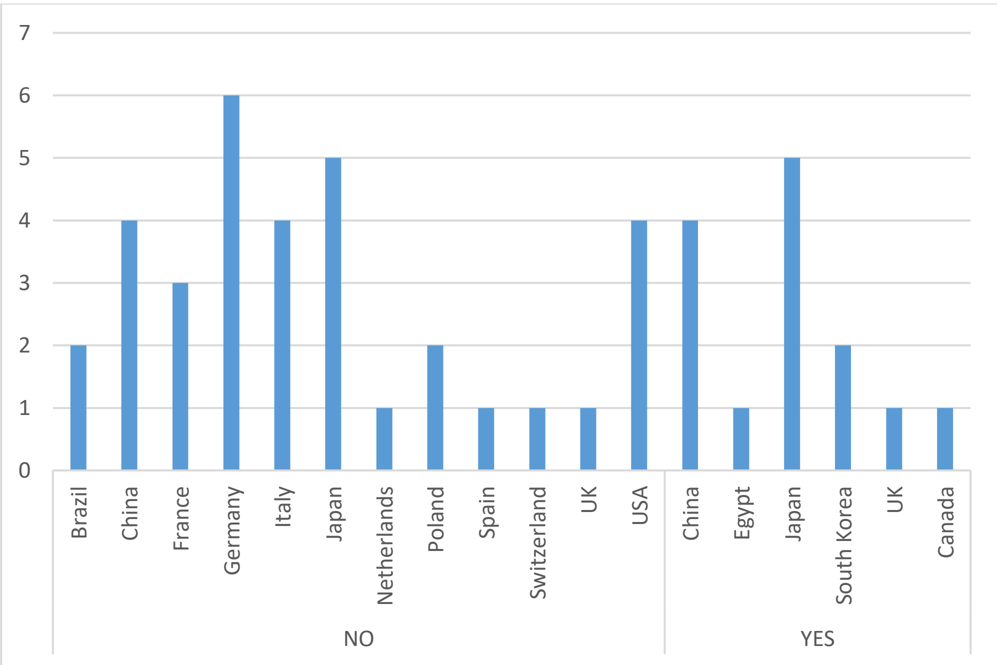


Figure 125.- Number of MDS per region based on operating lines (YES/NO). (Source: Ironlev)

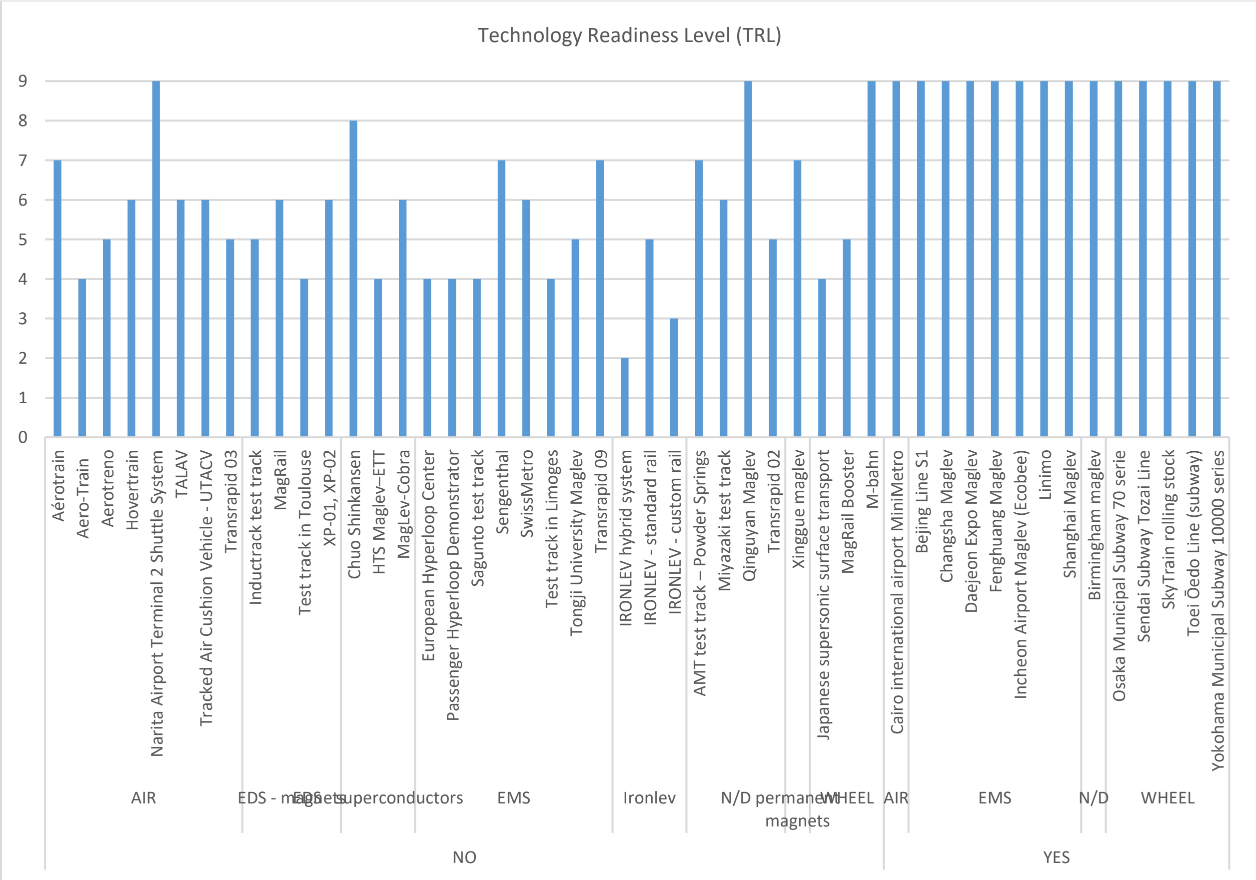


Figure 126.- TRL of MDS based on operating lines (YES/NO) and levitation/support technology.

Figure 127 provides an overview of the maximum speed declared for the investigated systems.

Figure 128 provides an overview of the maximum acceleration declared for the investigated systems.

Figure 129 provides an overview of the transport capacity declared for the investigated systems according to the operation planning.

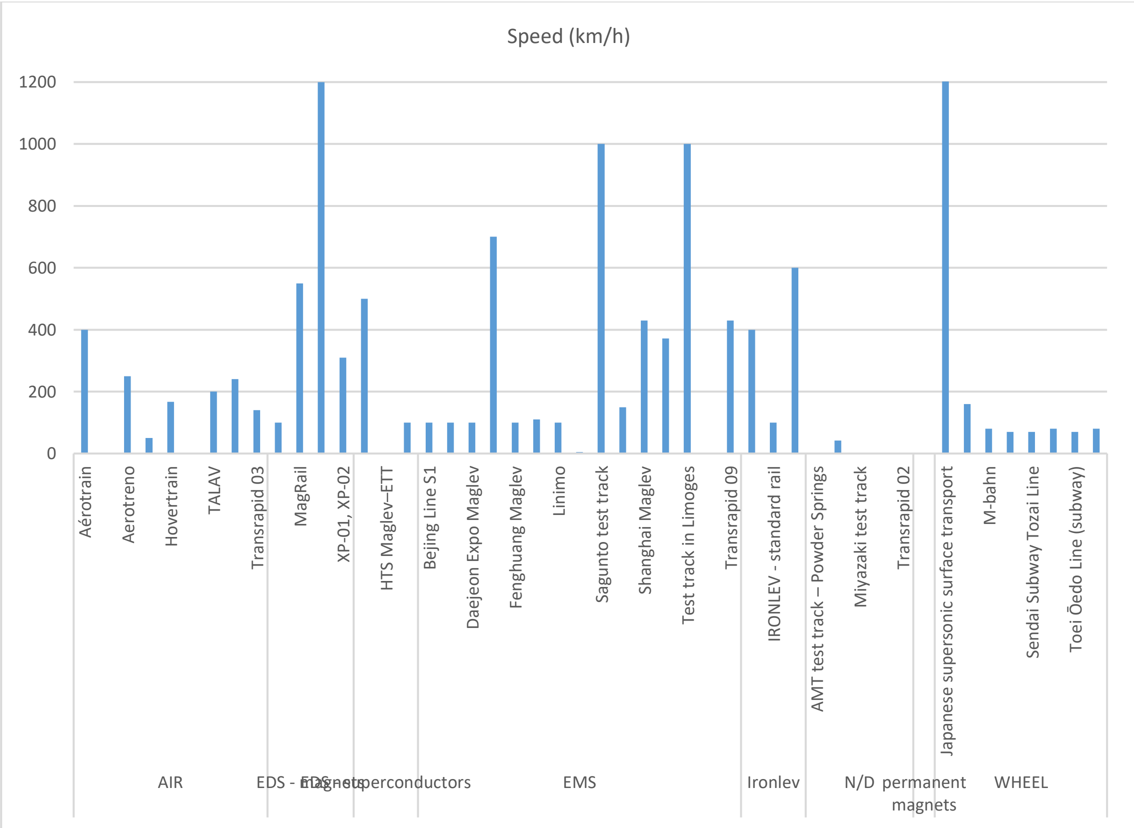


Figure 127.- Maximum speed (km/h) of MDS according to levitation/support technology.

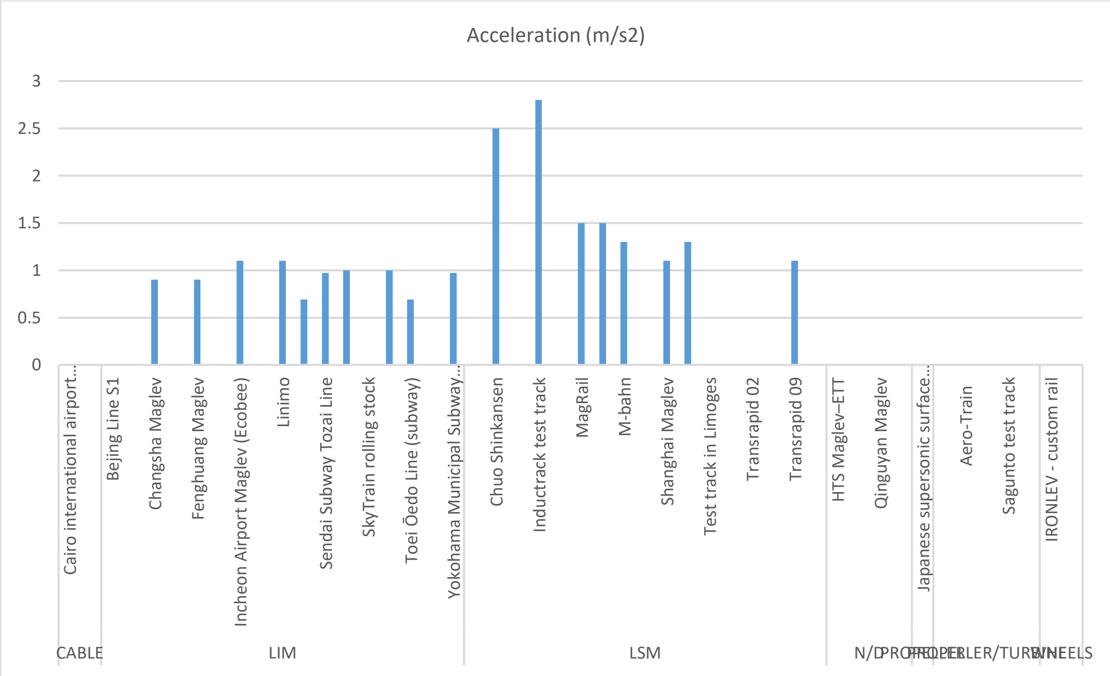


Figure 128.- Maximum acceleration (m/s²) of MDS according to propulsion technology.

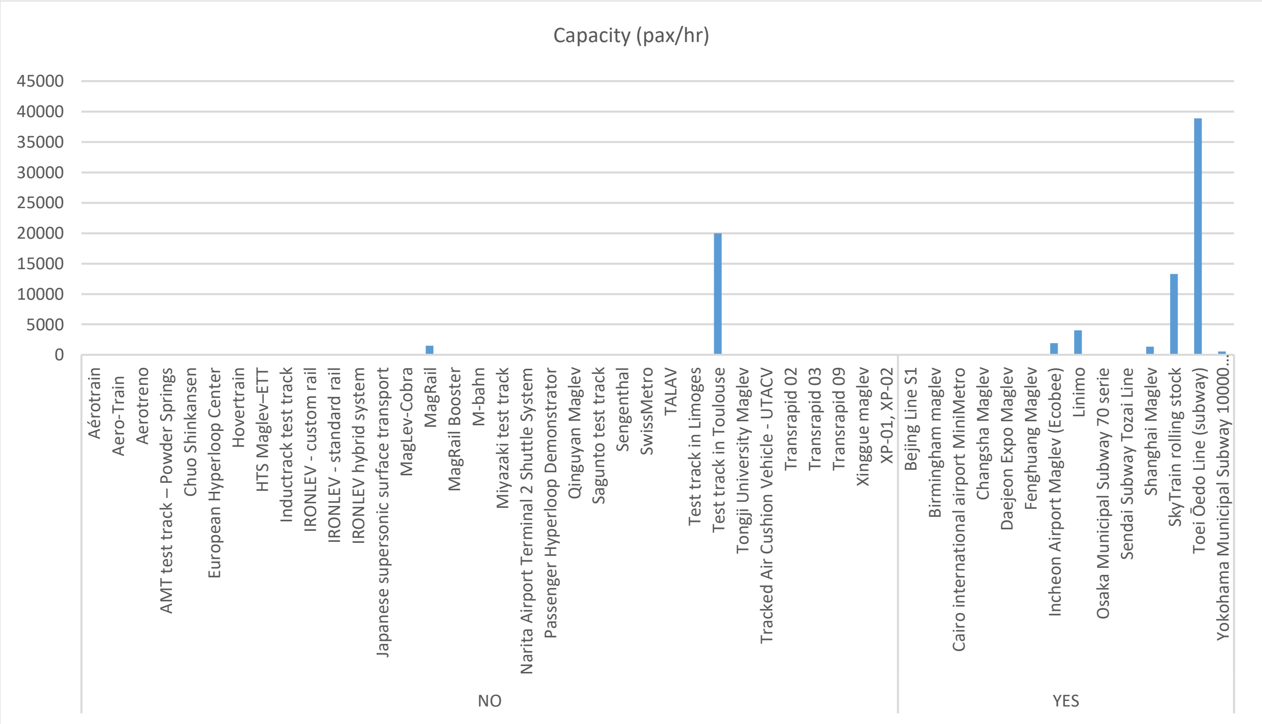


Figure 129.- Transport capacity of MDS according to operation planning

5.6 Economic viability

CAPEX (Capital Expenditure) and OPEX (Operational Expenditure) costs are normally intertwined. In the case of MDS this concept is emphasized. CAPEX costs are normally higher than for a conventional railway track with wheel/rail contact but, for example, a contactless system will generate poor wear on the track, with a drastic reduction of OPEX due to maintenance, as well as of external costs, due to the drastic reduction of noise emissions.

Based on the costs estimated in France available in MDS technology publications, the orders of magnitude of the CAPEX are as follows:

- Normal rail track: 10 MEUR/km,
- High-Speed Rail track: 25-30 MEUR/km (TGV)
- Normal rail track in long tunnel: 80-100 MEUR/km (Lyon-Turin project),
- Elevated Maglev track: 50-100 MEUR/km,
- Maglev track in long tunnel: 100-200 MEUR/km (Tokyo-Nagoya project)
- Elevated Aerotrain track: 25-50 MEUR/km (light vehicles and max speed 300km/h).

Regarding OPEX, the two fundamental parameters are the loads on the track and the speed, both affecting the kinetic energy potentially transferable from trains to track and catenary (for electrified systems).

Concerning the attractiveness and profitability of very high speed, in addition to the need to control maintenance costs, it is important to note that the travel time reduction is less than proportional to the maximum speed due to the limitations to access stations and terminals and running on switching zones.

Moreover, some MDS technologies may require the supply chain of critical materials (copper, etc.) and rare earths materials (magnet design, etc.), whit the related problem of permanent availability and high costs.

5.7 Environmental aspects of MDS

MDS could potentially contribute to environmental sustainability from various viewpoints. These systems would offer several advantages compared to traditional systems, but they also introduce some new potential issues to be carefully considered.

Greenhouse Gas (GHG) Footprint

MDS are generally considered more energy-efficient than conventional transportation systems like cars, buses, and even traditional trains due to several factors: 1) they could eliminate friction with tracks, reducing rolling resistances and energy consumption; 2) they use electromagnetic propulsion for smoother acceleration and regenerative braking to capture and reuse energy during braking; 3) their streamlined design could minimize air resistance at high speeds; 4) distributed power systems could optimize energy use; 5) their lightweight construction could further reduce energy consumption 6) using clean and renewable energy sources, such as solar or wind power, can enhance their sustainability.

Therefore, they can potentially reduce greenhouse gas emissions, especially when powered by clean energy sources like electricity generated from renewable resources [Qadir, 2021].

The climate change also plays a role in determining parameter for the choice of future transport systems, which will have to satisfy resilience requirements to limit the effects of climate related meteorological issues.

Noise Reduction

MDS could be quieter than traditional transportation systems because, whenever they eliminate or reduce the contacts between vehicles and infrastructure. This reduced noise pollution can have positive impacts on the environment and human health, promoting more sustainable cities. [Ivanov, 2017].

Reduced non-exhaust fine particle emissions

MDS that use electric propulsion produce no direct emissions, contributing to better air quality in urban areas where transportation is a significant source of air pollution.

Materials sustainability

The materials used in MDS, including superconducting or permanent magnets and materials for the guideway, can impact sustainability. The sourcing and manufacturing of these materials need to be considered for their environmental impact. Using sustainable materials and production processes can mitigate these concerns. The disposal of MDS components at the end of their lifecycle must be managed sustainably to minimize environmental impact. This includes recycling and proper disposal of materials to reduce waste.

Electromagnetic interference, compatibility, human exposure

Precautions must be taken for access to the track in the case of installing synchronous linear motors over a long distance, to comply with the safety standards in force (European directive 2004/108/EC).

Long-term durability and maintenance

Ensuring the durability and efficient maintenance of MDS is essential for their environmental sustainability. Proper maintenance practices can extend the lifespan of the system and reduce the need for frequent replacements or repairs.

In summary, MDS could offer several environmental advantages once deployed, including reduced GHG emissions, noise emissions, and air pollution. However, their sustainability depends on factors, such as the source of energy, materials used, and careful planning to minimize ecological impacts.

Therefore, to maximize the environmental benefits of MDS, it is essential to prioritize sustainability in their design, construction, and operation.

6 Comparison of the functional, technical, operational, and economical aspects of the conventional railway systems, traditional maglev systems and innovative MDS

6.1 Conventional railway system in terms of technical, functional, operational, economical overview

Definition

A transport system is defined as the set of infrastructures vehicles and services by means of which it is possible the movement of people and goods for the performance of the social and productive activities of a community of people. In particular, the railway transport system consists of the set of fixed installations (infrastructure), rolling stock (vehicles) and the services provided to ensure the mobility of passengers and goods (Ricci S. ,2011).

Overview of conventional railway system definitions

Tracks: conventional railways use a network of parallel steel tracks that are typically laid on a bed of ballast (crushed stones) and supported by wooden or concrete sleepers (ties). The tracks provide a stable and aligned path for the movement of trains.

Rolling stock: in a traditional railway system, different kinds of rolling stock make up the trains. Included in this are locomotives, which provide the propulsion, passenger, freight cars/wagons, which transport people or goods. Depending on the system and technology being used, locomotives can be electric, or diesel-electric powered.

Power source: conventional railways can be powered by different sources.

Diesel traction: diesel locomotives use internal combustion engines that burn diesel fuel to generate power. These locomotives are often used in areas without electrification.

Electric traction: electrified railways use overhead wires (catenary) or a third rail to supply electricity to electric locomotives. Electric systems are efficient and largely used, particularly in urban areas and high-speed rail networks.

Signalling and control: railway systems have a complex signalling and control infrastructure to ensure safe and efficient operation. This includes signals, switches, centralized control systems that manage train movements, track switching, traffic flows.

Stations and terminals: they are essential components of the railway system, serving as points of embarkation and disembarkation for passengers and the loading and unloading of freight. These facilities often include platforms, ticketing systems, waiting areas, cargo handling equipment (2).

Maintenance: regular maintenance of tracks, rolling stock, and infrastructure is critical to ensuring the safety and reliability of the railway system. Maintenance includes track inspections, locomotives and cars regular check and repair, replacement of aging infrastructure (Macchi M., Garetti M., Centrone D., Fumagalli L., Pavirani G., 2012).

Safety measures: safety is a top priority in railway systems. Measures include signalling systems, speed limits, grade crossings, procedures for emergency situations. These measures are in place to prevent accidents and ensure the well-being of passengers and railway workers.

Freight and cargo handling: conventional railway systems are often used for transporting freight over long distances. Specialized freight cars and handling equipment are used to facilitate the movement of goods.

Functional overview of a conventional railway system

Infrastructure: a conventional railway system consists of a fixed transportation infrastructure that includes tracks, stations, terminals. The tracks are laid out in a network, often with multiple lines or tracks running in parallel.

Passenger and freight movement: the primary function of a conventional railway system is to move passengers and freight from one location to another. Passenger trains carry people, while freight trains transport goods and cargo. This movement is achieved by the rolling stock (trains) traveling along the tracks.

Motive power: trains are powered by locomotives, which provide the necessary propulsion to move the train. Locomotives can be positioned at the front, rear, or distributed throughout the train, depending on the design and purpose of the train.

Efficiency and sustainability: railway systems are known for their energy efficiency and relatively low environmental impact, especially when electrified. They are an environmentally sustainable mode of transportation, contributing to reduced carbon emissions and energy consumption compared to some other forms of transport.

Logistics: railway systems are vital for the logistics industry. Freight trains transport bulk goods and containers over long distances, making them a crucial part of the supply chain for industries, such as manufacturing, agriculture, shipping (Milewicz J., Mokrzan D., Szymański G.M. ,2023).

Operational overview of a conventional railway system

Scheduling and Timetables: a conventional railway system operates based on predefined schedules and timetables. Trains are scheduled to depart and arrive at specific times, allowing passengers and freight operators to plan their journeys and shipments (Zeyu W., Zhou L., Guo B., Chen X., Zhou H. ,2021).

Dispatching and Control Centres: railway operations are monitored and controlled from dispatching and control centres. These centres oversee the movement of trains, track conditions, safety procedures. Dispatchers ensure that trains are routed efficiently and safely.

Train Operations: trains follow established routes and adhere to signalling and safety systems. They operate according to set speeds and schedules, with locomotive engineers responsible for driving and controlling the trains. Train conductors manage passenger services and freight operations on board.

Loading and Unloading: stations and terminals are critical hubs for loading and unloading passengers and cargo. Passenger trains stop at platforms to allow passengers boarding and disembarking, while freight trains may have dedicated facilities for loading and unloading goods.

Integration with other modes: many railway systems are integrated with other transport modes, such as buses, trams, metros. This integration allows for seamless transfers between different modes and encourages the use of public transportation (Givoni M., Rietveld P., 2007).

Environmental issues: railway operators are increasingly focusing on environmental sustainability. They may use technologies to reduce emissions, such as electrification or fuel-efficient locomotives and adopt eco-friendly practices for maintenance and infrastructure.

Economic overview of a conventional railway system

Infrastructure investment: building and maintaining the physical infrastructure of a conventional railway system requires significant upfront investment. This includes laying tracks, constructing stations and terminals, installing signalling and control systems. The capital expenditure is often substantial and may be funded by government agencies or private investors.

Operational costs: running a railway system involves ongoing operational costs, including labour (train crews, station staff, maintenance personnel), energy (fuel or electricity for locomotives), maintenance expenses (for tracks, rolling stock, infrastructures). These costs must be carefully managed to ensure the financial sustainability of the system.

Public Subsidies: many railway services, especially for passengers, rely on government subsidies to cover operating costs and maintain affordable fares for passengers. Governments may subsidize railways to promote public transportation, reduce road congestion, and lower environmental impact.

Freight transport economics: freight railways play a critical role in the economy by transporting bulk goods and raw materials. They often compete with other modes of transportation, such as trucks and ships. The economic viability of freight rail depends on factors like shipping demand, shipping rates, operational efficiency.

Economic impact: railway systems can have a significant economic impact on regions they serve. They create jobs in construction, operations, maintenance, support industries related to rail transportation. Railways can also stimulate economic development by improving connectivity and accessibility to markets.

Profitability and financial viability: the profitability of a railway system depends on factors like ridership or cargo volume, pricing strategies, operational efficiency, cost management. Profitability is crucial for private railway companies, while publicly funded systems may prioritize service quality and accessibility over it.

Investment in modernization: to remain competitive and efficient, railway systems often require ongoing investments in modernization. This includes upgrading tracks, replacing aging rolling stock with newer and more fuel-efficient models, adopting advanced signalling and control technologies.

Environmental considerations: railway systems are often considered environmentally friendly compared to other transportation modes due to their lower carbon emissions per passenger or ton of cargo moved. This can be a selling point for attracting environmentally conscious travellers and shippers.

Competitive landscape: the economics of a railway system can be influenced by competition of other modes of transportation, such as highways, airlines, maritime shipping. Pricing, service quality, and efficiency are key factors in maintaining a competitive edge.

Long-term sustainability: achieving long-term economic sustainability is a challenge for many railway systems. Balancing costs, revenue, and investments while meeting safety and environmental standards is essential to ensure the continued viability of the system.

Technical Specifications for Interoperability

Technical Specification for Interoperability (TSI), provided for in European Directive 2016/797 (8) was adopted by the European Parliament and the Council of the European Union on the interoperability of the European rail system in accordance with the ordinary legislative procedure.

This directive stipulates that the railway system is divided into 8 subsystems:

- Infrastructure,
- Traction energy,
- Control command and the trackside signalling,
- Control command and the on-board signalling,
- Rolling stock,
- Traffic operation and management,
- Maintenance,
- Telematic applications for passenger and freight services.

It also provides that a dedicated TSI is drawn up for each subsystem.

These TSI define the essential requirements of the above-mentioned European directives for specific cases and define a set of technical requirements that apply to new subsystems put into service.

These requirements constitute a set of conditions necessary for putting into service, but these conditions are generally not sufficient to guarantee safety, so they must be supplemented by some additional measures. They do not cover all the fields of the regulatory requirements, but for the fields they cover, they prevail over the national texts.

According to the above concepts, the TSI will represent a key reference, though not comprehensive, for the definition of the conventional railway systems.

6.2 Systematic comparison of MDS

6.2.1KPIs description and selection

Starting from the information collected within the database issued by Task 2.1 on Maglev or MDS, the next step is to compare and cross-check these systems with traditional railway. These activities are referred to subsystems and components, which make necessary to identify relevant Key Performance Indicators (KPI).

The nature of the indicators depends on the quality of the information available for subsystems and components. Wherever only qualitative descriptions are available, KPI correspond to classes defined by grouping the characteristics described, meanwhile whenever numerical values were available, quantitative KPI have been defined.

- Conventional railways were also considered with reference to four comprehensive typologies:
- High-Speed services (max speed > 250 km/h) for passengers (HS),
- Conventional services (max speed = 250 km/h) for passengers (CP),
- Conventional services (max speed = 250 km/h) for freight (CF),
- Metro and other urban transit (ME).

Finally, colours have been associated with the KPI values and with the defined classes to classify subsystems and components in terms of the degree of potential compatibility with conventional railways according to the scheme illustrated in Figure 130. For some subsystems and components, it was not possible to identify all the five classes.

	Potential compatibity
	Light lack of compatibilty
	Relevant lack of compatibility
	No compatibility
	Not relevant

Figure 130.- Colour scheme describing the level of potential compatibility with conventional railways of subsystems and components of Maglev and MDS.

The KPI refer to subsystems and components classified into the areas of:

- Technology,
- Operation/Cost/Lifecycle.

Technology

This section describes the technologies adopted by the various systems for propulsion, levitation, braking, guidance type, infrastructure power supply, on board power supply, interaction with infrastructure, superstructure, track switches, communication, command/control/signalling systems. Since the level of detail of the available information is not homogeneous, it was not always possible to identify numerical indicators, however classes were established based on some characteristics of subsystems and components to classify them in view of their potential compatibility with traditional railways.

The identified classes are as follows:

Propulsion: traction through wheel-rail adhesion - linear motor - cable traction - propeller or reaction propulsion,

Type of levitation: support via wheel-rail coupling - EDS/EMS/ ferromagnetic - levitation on an air cushion - sustenance via wings,

Braking: adhesion brake system - linear motor ropeways/braking - air braking - not relevant to assess the breaking type,

Guidance system: driving through wheels - driving by non-contact magnetic forces - driving by cable and U shape track,

Infrastructure power supply: none - catenary - additional rails - contactless - not classifiable,

On board power supply: battery pack - from infrastructure - turbojet engines,

Interaction with infrastructure: wheel-rail and pantograph-catenary - full contactless - cables,

Superstructure: standard railways - rails and other mounted elements - concrete tracks,

Track switches: standard rail switches - movable track portion,

Communication system - standard communication system - improved o modified standard - specific systems - incompletely described.

Command/control/signalling system: compatible with ERTMS - compatible with legacy systems but not with ERTMS - not compatible with legacy systems - incompletely described.

Operation/Cost/Lifecycle

For the categories included in this area, numerical values have been taken as KPI, as indicated in Table 4.

Table 4.- KPIs selected for the categories included in Operation/Cost/Lifecycle area

Category	**KPI**
Operating speed	Maximum Operating Speed [km/h]
Acceleration	Maximum Acceleration [m/s^2]
Maximum deceleration	Maximum Deceleration [m/s^2]
Vehicle capacity	Number of passengers/wagons
Vehicle composition	Number of wagons per trainset
Train capacity	Number of passengers per trainset
Energy consumption	Specific energy consumption [kWh/pax/km] [kWh/t/km]
Line capacity	Line transport capacity [pax/h] [ton/h]
Capital expenditure for vehicles	CAPEX-vehicle [EUR]
Capital expenditure for infrastructure	CAPEX-infrastructure [EUR/km]
Operational expenditure for vehicles	OPEX-vehicle [EUR/year]
Operational expenditure for infrastructure	OPEX-infrastructure [EUR/year/km]
Vehicle deployment speed	Vehicles building rate [vehicles/month]
Infrastructure deployment speed	Line building rate [km/month]

Even in the case of numerical KPI, classes have been defined for each subsystem and component, based on the definition of appropriate value ranges of single KPI. Similarly, colours have also been associated with these classes according to the colour scale previously described.

For the category *Climate robustness,* it has been just indicated the meteorological elements critical for the operation of the systems.

For *interoperability* area, the associated classes are simply *Yes* (Dark green) or *Not* (Red).

6.2.2Technical, functional, operational, economical comparisons

As the KPIs have been identified and assigned to the different MDS, the next step was to compare them with conventional railway systems, namely:

- High-speed (HS),
- Conventional passenger (CP),
- Conventional freight (CF),
- Metro (ME).

The aim of this comparison is to check potential compatibility of the MDS components and subsystems identified and reported from task 2.1 with traditional railways.

The reference for the compatibility assessment is the European interoperable railway system, defined according to the Technical Specification of Interoperability (TSI). Assessment criteria are based on the potential compliance of components and subsystems with the TSI themselves.

Potential systems not aligned with TSI (e.g., metro, and urban transit *closed systems*, not connected with the interoperable European network) are considered as ancillary potential applications fields of studied MDS but not as main references.

That means that any MDS component or subsystem envisaged as potentially applicable to *not interoperable rail networks only*, has been considered *not potentially compatible* with the conventional railways and has been excluded by the next technical and economic analyses in WP2 and in the MaDe4Rail project itself.

The results of this analysis are allocated in the matrix *MaDe4Rail_Task2.2_MDS_Assessment of Technologies* (Appendix 2) that is also the final product of Task 2.2. The first result of this comparison was to identify the MDS classified as *not compatible* with the conventional railway system for any of their subsystems and components, which are reported in Table 5.

Once that one component or subsystem was classified as potentially compatible, a second result was obtained by assigning the potentially compatible MDS system to one or more of the conventional railway systems (High-speed, Conventional passenger, Conventional freight, Metro). This assignment was made by considering the available descriptive quantitative and qualitative elements that characterise the various components and subsystems. These elements are taken from the columns Basics and Technology of the matrix.

An extract of the matrix, including the technical assessment is reported in Table 6.

Table 5.- Maglev Derived Systems not compatible with traditional railways.

MDS name
Aérotrain
Aero-Train
Aerotreno
Cairo international airport MiniMetro
Hovertrain
HTS Maglev–ETT
Japanese supersonic surface transport
Maglev-Cobra
Miyazaki test track
Narita Airport Terminal 2 Shuttle System
Qinguyan Maglev
TALAV
Transrapid 02
Xinggue Maglev
XP-01, XP-02
Test track in Toulouse
Sagunto test track
European Hyperloop Center
Test track in Limoges
Passenger Hyperloop Demonstrator

Table 6.- Extract of MDS assessment matrix.

BASICS	BASICS	TECHNOLOGY	TECHNOLOGY
MDS name	**Application**	**Propulsion type**	**Levitation type**
AMT test track – Powder Springs	Passenger	PM long stator synchronous linear motor	N/D
Beijing Line S1	Passenger	LIM (Linear Induction Motor)	EMS (electromagnetic suspension)
Birmingham Maglev	Passenger	LIM (Linear Induction Motor)	N/D
Changsha Maglev	Passenger	SLIM (short-stator linear induction motor)	EMS (Electromagnetic Suspension)
Chuo Shinkansen	Passenger	infrastructure side: stator with multi-phase winding, conducting sheet, solid iron	EDS (Electrodynamic Suspension)
Daejeon Expo Maglev	Passenger	LIM (Linear Induction Motor) Vehicle side: 3-phase motor having 8 poles, Infrastructure side: plate of aluminium	EMS (Electromagnetic Suspension) (attraction forces) Vehicle side: electromagnet winding technology with DC chopper control, Track side: steel reaction rail
Fenghuang Maglev	Passenger	LIM	EMS (Electromagnetic Suspension)

The result of the assessment is a first comprehensive selection including MDS subsystems and components detected as potentially compatible with the conventional railway system.

These systems are listed and qualified in terms of potential application fields in Table 7.

The activities planned in the following Work-Packages will be dedicated to further assess these MDS from different viewpoints as a basis for the future effective implementation and integration in the conventional railway systems themselves.

Table 7.- MDS potentially compatible with traditional railways.

BASICS		Potential application fields to conventional railways			
MDS name	**Compatibility**	**High-speed - Passengers**	**Conventional - Passengers**	**Conventional - Freight**	**Metro**
AMT test track – Powder Springs	Yes		x	x	x
Beijing Line S1	Yes				x
Birmingham Maglev	Yes				x
Changsha Maglev	Yes				x
Chuo Shinkansen	Yes	x	x	x	
Daejeon Expo Maglev	Yes				x
Fenghuang Maglev	Yes				x
Incheon Airport Maglev (Ecobee)	Yes		x		x
Inductrack test track	Yes				x
IRONLEV applied to standard railway shape/tracks	Yes				x
IRONLEV hybrid system	Yes	x	x		x
IRONLEV with custom rail	Yes	x	x		x
Linimo	Yes				x
MagRail	Yes	x	x	x	x

MagRail Booster	Yes		x	x	x
M-bahn	Yes				x
Sengenthal	Yes		x	x	x
Shanghai Maglev	Yes	x			
SwissMetro	Yes	x			
Tongji University Maglev	Yes	x			
Tracked Air Cushion Vehicle - UTACV	Yes		x		

7 Breakdown structure of essential technologies and identification of technical enablers for the systems identified and definition of a common architecture.

Breakdown structure is a hierarchical representation of system that breaks it down into smaller, more manageable components or tasks. This structure helps in organizing and managing complex projects, making it easier to plan, execute and monitor progress. The breakdown structure includes three levels of the hierarchy: Top level, Intermediate level and lower levels. The top level represents the highest level of the hierarchy and serves as the overarching category or container for the entire project or system. It defines the project's primary objective or goal, providing a high-level perspective. Below the top level, there are intermediate levels that further break down the project into more manageable components. These levels group related activities or tasks based on their common characteristics or objectives. The number and depth of intermediate levels can vary depending on the complexity of the project. At the lowest levels of the breakdown structure, the project is broken down into individual tasks or work packages. Each work package represents a specific, discrete piece of work that needs to be completed. Work packages are typically small enough to be manageable and are defined by their scope, duration, and the resources required to complete them.

This breakdown structure provides a comprehensive view of the entire project hierarchy, from the high-level project phases down to the smallest manageable units of work. It allows project managers to allocate resources, assign responsibilities, track progress, and manage the project efficiently, ensuring that all aspects of the project are thoroughly planned and executed.

7.1 MDS breakdown structure

As already defined in Chapter 5, MDS are innovative, fast track-bound transportation system for rail application that use maglev-based technologies, such as linear motors with magnetic or pneumatic levitation, as their foundation. It can be stand-alone system with its own dedicated infrastructure or can be, in principle, integrated within the existing railway infrastructure. The top level of the MDS architecture includes four fundamental subsystems: Vehicle, Infrastructure, Energy, Command and Control (Figure 131).

It is worth noting that these subsystems reflect the nomenclature of TSI which is intended to facilitate the introduction of interoperable MDS systems into the European rail market.

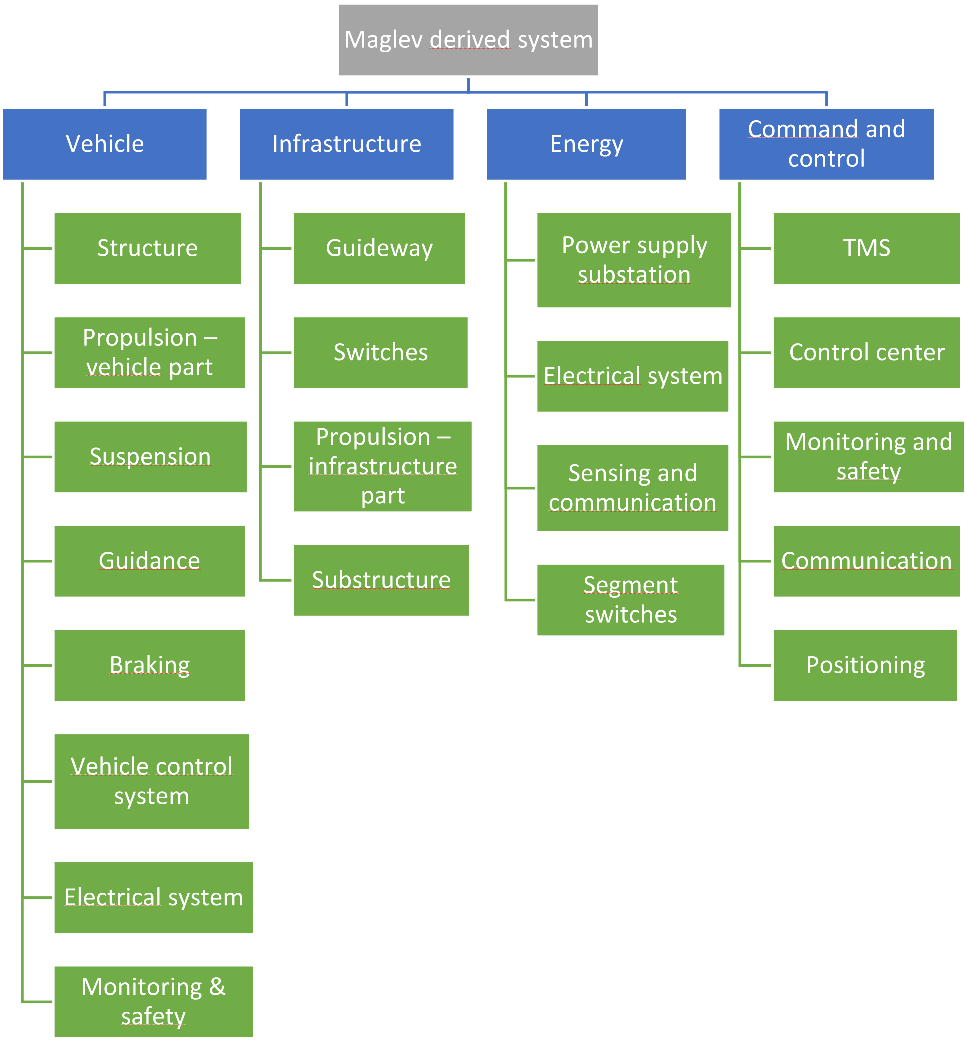


Figure 131.- MDS breakdown structure.

The MDS vehicle is a train designed to operate on the infrastructure with respect to the railway regulations and the TSI. The MDS infrastructure include elements such as rails, switches, propulsion systems, and substructures. The rails provide the physical pathway for the train, while switches enable the routing of trains to different tracks or segments within the MDS infrastructure. The propulsion subsystem plays a vital role in controlling the vehicle's movement, encompassing functions like acceleration and deceleration, ensuring a smooth and controlled ride. The substructure provides the necessary support and stability to the entire system. A significant focus is placed on the integration and efficiency of energy systems, which are main components that contribute to optimal performance, efficient energy utilization, and sustainability within the MDS. These systems are essential for powering and managing the train's operations. The command-and-control system is a vital component overseeing vehicle movement, safety protocols, alignment, communication, and vehicle positioning. It ensures precise vehicle localisation, monitors component health, and coordinates with infrastructure systems for seamless operation. Additionally, it may provide passenger information, contributing to the safe and efficient functioning of MDS.

In the Figure 131 the system breakdown structure was proposed. To avoid any ambiguities in further phases a set of respective definitions has been prepared. One note must be done at this point. All the definitions are constructed to describe the function each subsystem or component has in the MDS. Such an approach enables being technology-agnostic and preventing from narrowing the framework from the very beginning.

Table 8.- MDS breakdown structure – definitions

Subsystem	**Component**	**Definition**
Vehicle		The MDS movable subsystem which is used to transport passengers and goods along predefined guideway.
	Structure	Refers to the vehicle structure which could be frame or monocoque used to transfer the loads and mount other vehicle components. It may be new or retrofitted using existing rolling stock.
	Propulsion – vehicle part	System component that enables longitudinal movement of the MDS vehicle. It enables both acceleration and deceleration. It may be electromagnetic (LSM), electrodynamic (LIM), friction-based (wheels), or combined.
	Suspension	Component that enables counteracting vertical load and/or maintaining the vertical position of the MDS vehicle. It may be electromagnetic, electrodynamic, mechanical (wheels), pneumatic, passive or combined.

	Guidance	Subsystem that enables maintaining the lateral position of the MDS vehicle. It may be electromagnetic, electrodynamic, mechanical (wheels), pneumatic, or combined.
	Braking	Combination of parts that either progressively reduces the speed of the moving vehicle or brings the vehicle to a halt and/or holds it stationary or fulfills both functions. It may be integrated with the propulsion system or mounted as a separate subsystem.
	Vehicle Control System	Refers to the vehicle component that supervises electronically the vehicle movement, accelerations and deceleration curves, emergency responses and health checks. Usually connected to the Command and Control subsystem.
	Electrical system	Component essential to power all electrical and electronic devices in the vehicle which deals with the conversion, transmission, storage or switching of electric power with or without control of that power.
	Monitoring & Safety	Subsystem or set of subsystems that enables monitoring the vehicle state and condition, also preventing unwanted events (e.g., anti-collision system).
Infrastructure		The MDS subsystem that is a sum of all the permanent way components of the transport system.
	Guideway	Linear infrastructure elements that constrain the vehicles in a certain lateral position, for the purpose of guiding in straight track and negotiating curves.
	Switches	Point infrastructure elements that allow the vehicles to change the direction of

		movement between different guideways, or that allow a guideway to fork into two different ones.
	Propulsion – infrastructure part	Infrastructure component of propulsion subsystem that enables longitudinal movement of the MDS vehicle. It enables both acceleration and deceleration. It may be electromagnetic (LSM), electrodynamic (LIM), friction-based (wheels), or combined.
	Substructure	Substructure refers to the structural components that support the guideways and hold them in place. It is typically composed of different layers of earthworks with distinct properties. It may be ballasted or ballastless.
Energy		MDS subsystem used to provide demanded power to all of the MDS components.
	Power supply station	Component used to change the voltage and frequency of power supply to the needed frequency of the current and feed the power to the infrastructure.
	Electrical system	Component that generally derives power from the driving system for its propulsion and braking mechanism. The electrical system constitutes components such as levitation, guidance, propulsion, input power transfer and control, if applicable.
	Sensing and communication	Component used to monitor and control the state of the energy system, especially the operation of the linear motor. Sensors gather information about the currents, voltages and phases, and send it back to the motor control device.
	Segment switches	The trackside long stator of the MDS is divided into different stator segments. Only the segment with MDS vehicle is energized to save energy and reduce impedance.

		When the train is passing from one energized segment to another segment, the segment switches are used to electrically switch on and off different segments. Used in long-stator linear motors.
Command and Control		Refers to the onboard and trackside structures and equipment designed to ensure the safe operations of railway and MDS vehicles, directing traffic and keeping trains clear of each other.
	TMS	Component that provides permanent control across the network, automatically sets routes for both railway and MDS vehicles' movements as well as detects and solves potential routing conflicts.
	Control Centre	Component that ensures safe movement of the vehicle at specific line segment.
	Monitoring & Safety	Component that enables monitoring the vehicle, infrastructure, energy, and CCS subsystems' state and condition, also preventing unwanted events. It operates at the TMS level.
	Communication	Component or combination of components that enables communication between vehicles, infrastructure, energy and external systems.
	Positioning	Component used to determine the position and speed of the vehicle which is necessary to keep the clearances between the vehicles.

7.2 Identification of Technical Enablers

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

7.2.1 ATO

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

7.2.2 Advanced Magnetic Materials

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

7.2.3 Sustainable and long-duration energy storage systems

The next technical enabler is the implementation of sustainable and long-duration energy storage systems. These systems significantly enhance line capacity management and energy efficiency during the acceleration and deceleration of MDS vehicles. By efficiently storing and managing energy, they contribute to smoother operations, reduced energy consumption, and overall improved sustainability in MDS. This advancement aligns with the growing demand for eco-friendly and energy-efficient transportation solutions, making it a pivotal component of the MDS's technical capabilities.

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

7.2.4Cybersecurity Measures

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

7.2.5Secure Communication Systems

Secure communication systems equipped with enhanced throughput capabilities constitute a pivotal technical enabler within the system. These communication systems are designed to facilitate the exchange of text and media in a highly secure manner, ensuring the confidentiality and integrity of transmitted information. The foundation of these secure communication systems lies in advanced encryption techniques, secure protocols, and dedicated channels for data transmission. They enable the seamless and rapid exchange of text messages, images, videos, and other media formats while safeguarding against potential eavesdropping, interception, or data tampering. The higher throughput offered by these systems translates into faster and more efficient communication, improving operational responsiveness and decision-making. Whether for operator information, system monitoring, or emergency response, secure communication systems with enhanced throughput play a vital role in enhancing the overall efficiency, security, and reliability of the MDS. By prioritizing secure and high-throughput communication, the system ensures the protection of sensitive information, supports real-time data sharing, and strengthens its resilience against emerging cyber threats, making it an indispensable component of the MDS's technical capabilities.

7.2.6Virtual Coupling

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

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

7.2.7Regulatory Framework

The establishment of a comprehensive regulatory framework stands as a critical technical enabler within the system. This framework is designed to provide clear guidelines, standards, and oversight for the operation and integration of MDS into existing transportation networks. The regulatory framework encompasses a range of essential aspects, including safety standards, operational protocols, interoperability requirements, and environmental regulations. It ensures that the MDS adheres to the highest safety and performance standards, fostering passenger and system safety. Moreover, this technical enabler promotes seamless integration with other modes of transportation, such as traditional railways, urban transit systems, and road networks. By providing a structured and well-defined regulatory environment, it encourages the expansion and interconnectivity of the MDS, enhancing its versatility and utility. The regulatory framework serves as a foundational element, underpinning the safe, efficient, and sustainable operation of the MDS. It ensures compliance with established standards while fostering growth and integration within broader transportation networks.

8 Conclusions

Currently, the railway systems are operating on principles developed around 200 years ago. Surely, the subsystems are getting more and more sophisticated, thus, the system gets more and more safe. However, using the wheel-rail principle causes a set of limitations that nowadays are even more visible since the traffic and usage of the railway system is increasing systematically.

Deliverable 2.1 offers an overview of MDS and categorizes them based on maturity and technology (Chapter 5). A thorough analysis compares these systems to conventional railways, highlighting their pros and cons (Chapter 6). The goal is to pinpoint where MDS can benefit the European railway industry. The conclusion proposes a standardized MDS architecture as a reference for future work (Chapter 7).

Regarding further works in the other Work Packages within the MaDe4Rail project, this document offers an in-depth overview of MDS, essential for evaluating potential MDS solutions that can potentially be imported back into the EU railways. It includes a comparative analysis of current and emerging systems, vital for feasibility studies within the Project's Work Stream 2. Additionally, D2.1 establishes a shared system architecture and key definitions that are crucial for WP3, WP4, and WP5. This framework aids in the risk assessments in WP3, vehicle structure breakdowns in WP4, and MDS alignment with the System Pillar in WP5.

The main conclusions that could be drawn from this Deliverable are:

- The state-of-the-art results have shown that there are many existing transport systems that meet the definition mentioned in 5.1. These include systems that are operational whereas like Chinese and Japanese maglevs or metro systems propelled by linear motors. However, none of these systems were designed to be interoperable with the EU railway network.
- Other conclusion of the state-of-the-art analysis is that there are interoperable MDS under development. These include systems like MagRail or MagRail Booster proposed by Nevomo or MDS components being developed by Ironbox or TACV Lab.
- Although the analysed systems have different suspension systems like magnetic levitation, wheels, or air cushions, they share the same type of propulsion which are linear motors – both induction and synchronous ones. Therefore, it is worth to focus in the next WPs on achieving the compatibility of linear motors with the railway network. Regarding the suspension systems the most mature ones are standard wheels and magnetic levitation. Air cushion suspension systems are also under development, however less mature than the other types.

- Regarding communication systems, it must be noted that even FRMCS is designed for high-speed railway systems with maximum velocity limited to 500 km/h. It may be a limiting factor for ultra-high-speed MDS compatibility in the future, however this is still a matter of several years to address this challenge.

- The MDSs which were not intended to be interoperable with railway systems, show a potential compatibility. It shows that there are certain existing technologies and subsystems that could be considered when pursuing the railway-MDS compatibility, especially for urban applications.
- Based on the MDS overview and the railway compatibility assessment, the conclusion may be drawn that at the subsystems level, the MDS shows alignment with the railway system. It was reflected in the proposed System Breakdown Structure for MDS, whereas the main components have been aligned with the TSI constituents. It will serve as the baseline for further work within the MaDe4Rail project and also facilitate the next steps towards creating a regulatory framework for MDS.

This serves as the foundational phase of the MDS framework. The recommended future work is i.e. identifying where the MDS is already well aligned with EU railway regulations and where are some divergences that should be addressed during the next steps, recognizing the interfaces between the MDS components (will be done in the further stage of the following project) and, as most significant, pursuing the selection of a narrow group of interoperable MDS configurations that show the most potential of implementation from technical, regulatory and economic perspectives.

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10 Appendices

10.1 Appendix 1. Review articles, and most cited and most recent articles

Table 9.- Main review papers.

Document title	Authors	Source	Year	Citations
Comparison of high-speed rail and maglev systems	Najafi, F.T., Nassar, F.E.	Journal of Transportation Engineering, 122(4), pp. 276–281	1996	17
Review of Maglev train technologies (Hyung-Woo Lee et al., 2006)	Lee, H.-W., Kim, K.-C., Lee, J.	IEEE Transactions on Magnetics, 42(7), pp. 1917–1925, 1644911	2006	664
Review of Coupled Vibration Problems in EMS Maglev Vehicles (Zhou et al., 2010)	Zhou, DF; Hansen, CH; (...); Chang, WS,	INTERNATIONAL JOURNAL OF ACOUSTICS AND VIBRATION, 15 (1), pp.10-23	2010	
Superconductivity and the environment: A Roadmap (Nishijima et al., 2013)	Nishijima, S., Eckroad, S., Marian, A., ...Hassenzahl, W.V., Izumi, M.	Superconductor Science and Technology, 26(11), 113001	2013	115
Review and research progress of wireless power transfer for railway transportation (Wang and Li, 2019)	Wang, H., Li, X.	IEEJ Transactions on Electrical and Electronic Engineering, 14(3), pp. 475–484	2019	14
Control Methods for Levitation System of EMS-Type Maglev Vehicles: An Overview (Li et al., 2023)	Li, F., Sun, Y., Xu, J., He, Z., Lin, G.	Energies, 16(7), 2995	2023	1

Permanent Magnet Electrodynamic Suspensions Applied to MAGLEV Transportation Systems: A Review (Beauloye and Dehez, 2023)	Beauloye, L and Dehez, B,	IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, Mar | 9 (1) , pp.748-758	2023	

Table 10.- 50 top most cited papers.

Document title	Authors	Source	Year	Citations	Topics
Review of Maglev train technologies (Hyung-Woo Lee et al., 2006)	Lee, H.-W., Kim, K.-C., Lee, J.	IEEE Transactions on Magnetics, 42(7), pp. 1917–1925, 1644911	2006	664	General
Superconductor bearings, flywheels and transportation (Werfel et al., 2012)	Werfel, F.N., Floegel-Delor, U., Rothfeld, R., ...Wippich, D., Schirrmeister, P.	Superconductor Science and Technology, 25(1), 014007	2012	385	High temperature superconductors Magnet Magnetic bearings
Challenges toward wireless communications for high-speed railway (Ai et al., 2014)	Ai, B., Cheng, X., Kurner, T., ...Michelson, D.G., Briso-Rodriguez, C.	IEEE Transactions on Intelligent Transportation Systems, 15(5), pp. 2143–2158, 6808529	2014	375	Communications
Aerodynamics of high-speed trains (Schetz, 2001)	Schetz, J.A.	Annual Review of Fluid Mechanics, 33, pp. 371–414	2001	272	Aerodynamics
Japan's superconducting Maglev train (Ono et al.,	Ono, M., Koga, S., Ohtsuki, H.	IEEE Instrumentation	2002	151	General

2002)		and Measurement Magazine, 5(1), pp. 9–15			
Adaptive Neural-Fuzzy Robust Position Control Scheme for Maglev Train Systems with Experimental Verification (Sun et al., 2019b)	Sun, Y., Xu, J., Qiang, H., Lin, G.	IEEE Transactions on Industrial Electronics, 66(11), pp. 8589–8599, 8611297	2019	146	Control
Development and application of the Maglev transportation system (Luguang Yan, 2008)	Yan, L.	IEEE Transactions on Applied Superconductivity, 18(2), pp. 92–99, 4517518	2008	143	General
Sliding wear behavior of copper-graphite composite material for use in maglev transportation system (Ma et al., 2008)	Ma, X.C., He, G.Q., He, D.H., Chen, C.S., Hu, Z.F.	Wear, 265(7-8), pp. 1087–1092	2008	134	Behavior of materials
Self-powered wireless smart sensor based on maglev porous nanogenerator for train monitoring system (Jin et al., 2017)	Jin, L., Deng, W., Su, Y., ...Zhu, M., Yang, W.	Nano Energy, 38, pp. 185–192	2017	132	Train monitoring
Superconductivity and the environment: A Roadmap (Nishijima et al., 2013)	Nishijima, S., Eckroad, S., Marian, A., ...Hassenzahl, W.V., Izumi, M.	Superconductor Science and Technology, 26(11), 113001	2013	115	General
Multicriteria evaluation of high-speed rail, Transrapid Maglev and air passenger transport	Janic, M.	Transportation Planning and Technology, 26(6), pp. 491–512	2003	115	General

in Europe (Janic, 2003)					
Adaptive sliding mode control of maglev system based on RBF neural network minimum parameter learning method (Sun et al., 2019a)	Sun, Y., Xu, J., Qiang, H., Chen, C., Lin, G.	Measurement: Journal of the International Measurement Confederation, 141, pp. 217–226	2019	99	Control
RBF Neural Network-Based Supervisor Control for Maglev Vehicles on an Elastic Track with Network Time Delay (Sun et al., 2022)	Sun, Y., Xu, J., Lin, G., Ji, W., Wang, L.	IEEE Transactions on Industrial Informatics, 18(1), pp. 509–519	2022	87	Infrastucture
Internet of Things-Based Online Condition Monitor and Improved Adaptive Fuzzy Control for a Medium-Low-Speed Maglev Train System (Sun et al., 2020)	Sun, Y., Qiang, H., Xu, J., Lin, G.	IEEE Transactions on Industrial Informatics, 16(4), pp. 2629–2639, 8818315	2020	80	Control
The compression wave produced by a high-speed train entering a tunnel (Howe, 1998)	Howe, M.S.	Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 454(1974), pp. 1523–1534	1998	79	Aerodynamics
Review of coupled vibration problems in EMS maglev vehicles (Zhou et al., 2010)	Zhou, D., Hansen, C.H., Li, J., Chang, W.	International Journal of Acoustics and Vibrations, 15(1), pp. 10–23	2010	72	Structure
Deep Learning Based Semi-Supervised Control for Vertical Security of Maglev	Sun, Y., Xu, J., Wu, H., Lin, G., Mumtaz, S.	IEEE Transactions on Intelligent Transportation Systems, 22(7),	2021	65	Control

Vehicle with Guaranteed Bounded Airgap (Sun et al., 2020)		pp. 4431–4442, 9312475			
Dynamics of maglev vehicle/guideway systems (I) - Magnet/rail interaction and system stability (Zhai, 2005)	Zhai, W., Zhao, C.	Jixie Gongcheng Xuebao/Chinese Journal of Mechanical Engineering, 41(7), pp. 1–10	2005	64	Gridance
Investigation of forces in linear induction motor under different slip frequency for low-speed maglev application (Lu et al., 2013)	Lu, Q., Li, Y., Ye, Y., Zhu, Z.Q.	IEEE Transactions on Energy Conversion, 28(1), pp. 145–153, 6365251	2013	62	Propulsion
Numerical study on wave phenomena produced by the super high-speed evacuated tube maglev train (Zhou et al., 2019)	Zhou, P., Zhang, J., Li, T., Zhang, W.	Journal of Wind Engineering and Industrial Aerodynamics, 190, pp. 61–70	2019	58	Aerodynamics
Outlook of the superconducting maglev (Sawada, 2009)	Sawada, K.	Proceedings of the IEEE, 97(11), pp. 1881–1885	2009	58	General
Design and analysis of a new fault-tolerant linear permanent-magnet motor for maglev transportation applications (Wenxiang Zhao et al., 2012)	Zhao, W., Cheng, M., Ji, J., ...Du, Y., Li, F.	IEEE Transactions on Applied Superconductivity, 22(3), 5200204	2012	57	Propulsion
PID control to maglev train system (Liu et al., 2009)	Liu, H., Zhang, X., Chang, W.	Proceedings - 2009 International Conference on Industrial and Information Systems, IIS 2009,	2009	56	Control

		pp. 341–343, 5116368			
Faster than a speeding bullet train (Holmer, 2003)	Holmer, P.	IEEE Spectrum, 40(8), pp. 30–34	2003	55	General
Investigation of end effects in linear induction motors by using the finite-element method (Selcuk and Kurum, 2008)	Selçuk, A.H., Kürüm, H.	IEEE Transactions on Magnetics, 44(7), pp. 1791–1795, 4520274	2008	54	Propulsion
An adaptive vibration control method to suppress the vibration of the maglev train caused by track irregularities (Zhou et al., 2017)	Zhou, D., Yu, P., Wang, L., Li, J.	Journal of Sound and Vibration, 408, pp. 331–350	2017	53	Infrastructure
Environmental rebound effects of high-speed transport technologies: a case study of climate change rebound effects of a future underground maglev train system (Spielmann et al., 2008)	Spielmann, M., de Haan, P., Scholz, R.W.	Journal of Cleaner Production, 16(13), pp. 1388–1398	2008	53	General
An iterative interacting method for dynamic analysis of the maglev train-guideway/foundation-soil system (Yang and Yau, 2011)	Yang, Y.B., Yau, J.D.	Engineering Structures, 33(3), pp. 1013–1024	2011	52	Modelling and simulation Guidance
Aerodynamic vibrations of a maglev vehicle running on flexible guideways under oncoming wind actions	Yau, J.D.	Journal of Sound and Vibration, 329(10), pp. 1743–1759	2010	52	Aerodynamics

(Yau, 2010)					
The linear motor powered transportation development and application in China (Luguang Yan, 2009)	Yan, L.	Proceedings of the IEEE, 97(11), pp. 1872–1880	2009	52	Propulsion Linear motor
Dynamic simulation of the maglev vehicle/guideway system (Ren et al., 2010)	Ren, S., Romeijn, A., Klap, K.	Journal of Bridge Engineering, 15(3), pp. 269–278	2010	50	Modelling and simulation Guidance
Aerodynamics of high-speed maglev trains passing each other in open air (Huang et al., 2019)	Huang, S., Li, Z., Yang, M.	Journal of Wind Engineering and Industrial Aerodynamics, 188, pp. 151–160	2019	49	Aerodynamics
A Study of Non-Symmetric Double-Sided Linear Induction Motor for Hyperloop All-In-One System (Propulsion, Levitation, and Guidance) (Ji et al., 2018)	Ji, W.-Y., Jeong, G., Park, C.-B., Jo, I.-H., Lee, H.-W.	IEEE Transactions on Magnetics, 54(11), 8410607	2018	48	Propulsion Linear motor Guidance
Recent development of high temperature superconducting maglev system in China (Wang et al., 2009)	Wang, J., Wang, S., Zheng, J.	IEEE Transactions on Applied Superconductivity, 19(3), pp. 2142–2147, 5166722	2009	48	General
Fatigue strength evaluation of a bogie frame for urban maglev train with fatigue test on full-scale test rig (Han et al., 2013)	Han, J.-W., Kim, J.-D., Song, S.-Y.	Engineering Failure Analysis, 31, pp. 412–420	2013	47	Structural performance
Aerodynamic simulation of evacuated tube maglev trains with	Chen, X., Zhao, L., Ma, J., Liu,	Journal of Modern Transportation,	2012	47	Aerodynamics

different streamlined designs (Chen et al., 2012)	Y.	20(2), pp. 115–120			
Preliminary study of a superconducting bulk magnet for the Maglev train (Fujimoto et al., 1999)	Fujimoto, H., Kamijo, H., Higuchi, T., ...Murakami, M., Yoo, S.-I.	IEEE Transactions on Applied Superconductivity, 9(2 PART 1), pp. 301–304	1999	47	High temperature superconductors Magnet
Persistent current HTS magnet cooled by cryocooler (1)-project overview (Igarashi et al., 2005)	Igarashi, M., Nakao, H., Terai, M., ...Yamashita, T., Yamaji, M.	IEEE Transactions on Applied Superconductivity, 15(2 PART II), pp. 1469–1472	2005	45	High temperature superconductor Magnet
Three-Dimensional Numerical Analysis and Optimization of Electromagnetic Suspension System for 200 km/h Maglev Train Considering Eddy Current Effect (Ding et al., 2018)	Ding, J., Yang, X., Long, Z., Dang, N.	IEEE Access, 6, pp. 61547–61555, 8502075	2018	44	Modelling and simulation Suspension
Measurements and analysis of track irregularities on high speed maglev lines (Shi et al., 2014)	Shi, J., Fang, W.-S., Wang, Y.-J., Zhao, Y.	Journal of Zhejiang University: Science A, 15(6), pp. 385–394	2014	44	Infrastructure
Nonlinear vibration behaviors of high- T_c superconducting bulks in an applied permanent magnetic array field (Li et al., 2017)	Li, J., Li, H., Zheng, J., ...Huang, H., Deng, Z.	Journal of Applied Physics, 121(24), 243901	2017	43	Modelling and simulation

A novel magnetic-levitation system: Design, implementation, and nonlinear control (Hasirci et al., 2011)	Hasirci, U., Balikci, A., Zabar, Z., Birenbaum, L.	IEEE Transactions on Plasma Science, 39(1 PART 1), pp. 492–497, 5518447	2011	42	Design Control
Optimization of a linear superconducting levitation system (Motta et al., 2011)	Motta, E.S., Dias, D.H.N., Sotelo, G.G., ...Norman, J.H., Stephan, R.M.	IEEE Transactions on Applied Superconductivity, 21(5), pp. 3548–3554, 6007057	2011	41	Design
Applications of coilgun electromagnetic propulsion technology (Kaye et al., n.d.)	Kaye, R.J., Turman, B.N., Shope, S.L.	IEEE Conference Record of Power Modulator Symposium, pp. 703–707	2002	41	Propulsion

Table 11.- 50 top most recent papers.

Document title	**Authors**	**Source**	**Year**	**Citations**	**Topics**
Inductance Analysis of Transverse Flux Linear Synchronous Motor for Maglev Trains Considering Three-Dimensional Operating Conditions	Lv, G., Cui, L., Zhi, R.	IEEE Transactions on Industrial Electronics, 71(1), pp. 769–776	2024	0	Propulsion Motor
Numerical simulation and optimization on opening angles of aerodynamic braking plates sets for a maglev train	Wang, X., Hu, X., Wang, P., ...Deng, Z., Zhang, W.	Advances in Aerodynamics, 5(1), 8	2023	0	Simulation Aerodynamic braking
Research on coupled vibrations between the low-to-medium speed maglev train and a long-span	Xu, C., Luo, H., Gan, X., Liu, M., Guo, H.	Structures, 56, 104927	2023	0	Simulation Vibration Infrastruct

continuous beam bridge					ure
Research on sectional constant slip control of linear induction motor based on parameter self-tuning	Hu, H., Zhong, J., Chen, Y., Ge, Q., Wang, T.	Energy Reports, 9, pp. 979–989	2023	0	Propulsion Control
Novel method to detect the speed and position of the HTS Maglev train by using the TMR sensor and the magnet arrays	Jiang, S., Deng, Z., Liang, L., ...Liu, J., Zhang, H.	Measurement: Journal of the International Measurement Confederation, 219, 113280	2023	0	Operation Control
Deformation mapping between pier settlement and maglev track for high-speed multi-span simply supported maglev bridge	Gong, J., Zhai, W., Wang, W., ...Sun, T., Kechine, W.A.	Structures, 55, pp. 1980–1991	2023	0	Infrastructure
On the future sustainable ultra-high-speed maglev: An energy-economical superconducting linear thrusting system	Dong, F., Hao, L., Park, D., Iwasa, Y., Huang, Z.	Energy Conversion and Management, 291, 117247	2023	0	Superconductors Energy General
A suction method to mitigate pressure waves induced by high-speed maglev trains passing through tunnels	Chen, Z.-W., Guo, Z.-H., Ni, Y.-Q., Liu, T.-H., Zhang, J.	Sustainable Cities and Society, 96, 104682	2023	0	Tunnel pressure waves
A novel vented tunnel hood with decreasing open ratio to mitigate micro-pressure wave emitted at high-speed maglev tunnel exit	Zhang, J., Guo, B., Wang, Y., ...Krajnović, S., Gao, G.	Journal of Wind Engineering and Industrial Aerodynamics, 240, 105459	2023	0	Tunnel pressure waves
Airtightness Performance Test and Failure Models for Low-to-Vacuum Maglev Train Tunnel Joints	Shi, L., Wang, D., Zhou, J., Cui, K.	Journal of Testing and Evaluation, 51(5)	2023	0	Tunnel pressure waves

Dynamic Characteristics and Performance Assessment of Improved Suspension Frame System	Zhang, M., Yang, X., Zhang, L., Li, M., Liu, L.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4), pp. 827–835	2023	0	Suspension Simulation
Permanent World-Leading Position of High-Speed Railways in China in Engineering	Xiong, J., Shen, Z.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4), pp. 711–719	2023	0	General
Influence of Speed on Levitation Force of Medium−Low-Speed Maglev Train	Wang, Y., Liu, F., Liu, S., Luo, C., Wu, Q.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4), pp. 792–798	2023	0	General
Anomaly Detection of Suspension System in Maglev Train Based on Missed Detection Rate	Zhou, X., Wen, T., Long, Z.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4), pp. 903–912	2023	0	Suspension Control
Electromagnetic Force Analysis of Medium−Low-Speed Maglev Considering Remanence	Liu, Q., Shan, L., Ma, W., Lu, X., Luo, S.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4)	2023	0	Simulation Suspension
Review on Electrodynamic Suspension Trains and on-Board Superconducting Magnets	Liu, S., Wang, L., Wang, L., Wang, Q.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest	2023	0	General Suspension

		Jiaotong University, 58(4), pp. 734–753			Superconducting magnets
Self-Learning Model Reference Adaptive Levitation Control Strategy	Chen, P., Shi, T., Yu, M., Shan, L.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4), pp. 799–807	2023	0	Suspension Control
Calculation of Power Generation Characteristics of Linear Harmonic Generator for Electrodynamic Suspension Maglev Train	Lyu, G., Guo, X.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4), pp. 783–791	2023	0	Superconductors Energy Suspension Simulation
Technologies Research Review of Electro-Magnetic Suspension Medium–Low-Speed Maglev Train Levitation Frame	Ma, W., Hu, J., Li, T., Luo, S., Liu, S.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4), pp. 720–733	2023	0	General
Scale Effect of Aerodynamic Characteristics in Evacuated Tube Maglev Transport	Hu, X., Ma, T., Wang, X., ...Zhang, K., Peng, F.	Xinan Jiaotong Daxue Xuebao/Journal of Southwest Jiaotong University, 58(4), pp. 808–819	2023	1	Aerodynamics Tunnels
Measurement and numerical analysis on dynamic performance of the LMS maglev train-track-continuous girder coupled system with running speed-	Wang, D., Li, X., Wang, C.	Measurement: Journal of the International Measurement Confederation, 217, 113052	2023	0	LMS Maglev Vibrations

up state					
Mechanical responses of CFRP/PVC foam sandwich plate impacted by hailstone	Zhou, Y., Xue, B., Guo, Y., Zhang, W., Wang, R.	International Journal of Impact Engineering, 178, 104631	2023	0	Materials
Analysis for AC Loss by Electromagnetic Disturbance in HTS Magnet for Maglev Train	Mun, J., Lee, C., Choi, J., ...Oh, Y., Kim, S.	IEEE Transactions on Applied Superconductivity, 33(5), 5901305	2023	0	High temperature superconductors Magnet
Operating Characteristics of Wireless Multi-Charging Module Based On Multi-Magnetic Resonance Couplings for High Speed Superconducting MAGLEV Train	Chung, Y.D., Lee, C.Y.	IEEE Transactions on Applied Superconductivity, 33(5), 3600406	2023	0	Wireless charging
Energy and emissions analysis of the hyperloop transportation system	Hirde, A., Khardenavis, A., Banerjee, R., Bose, M., Pavan Kumar Hari, V.S.S.	Environment, Development and Sustainability, 25(8), pp. 8165–8196	2023	0	Energy emissions
Research on vibration mechanism of the low-to-medium-speed maglev train-track-at-ground-structure system	Wang, D., Li, X.	Advances in Structural Engineering, 26(10), pp. 1803–1817	2023	0	LMS Maglev Vibrations Infrastructure
Propagation characteristics of vibration induced by medium-low-speed maglev train running on subgrade	Yang, J., Zhao, L., Zhao, C., Feng, Y., Zhu, S.	Transportation Geotechnics, 41, 100986	2023	0	Maglev Vibrations Infrastruct

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Analysis on pre-camber forms of high-speed EMS maglev bridge	Chen, X.-L., Xiang, H.-Y., Tian, X.-F., Li, Y.-L., Zeng, M.	Zhendong Gongcheng Xuebao/Journal of Vibration Engineering, 36(3), pp. 652–661	2023	0	Intrastructure
Simulation Analysis and Online Monitoring of Suspension Frame of Maglev Train	Wang, Y., Gao, H.	Machines, 11(6), 607	2023	0	Suspension Vibration Simulation
Operation Control Method for High-Speed Maglev Based on Fractional-Order Sliding Mode Adaptive and Diagonal Recurrent Neural Network	Zhang, W., Lin, G., Hu, K., Liao, Z., Wang, H.	Energies, 16(12), 4566	2023	0	Propulsion Control Neural network
Study on Electromagnetic Relationship and Dynamic Characteristics of Superconducting Electrodynamic Maglev Train on Curved Track	Wang, X., Huang, J.	IEEE Transactions on Intelligent Transportation Systems, 24(6), pp. 6146–6164	2023	0	Propulsion Simulation
A modified electromagnetic force calculation method has high accuracy and applicability for EMS maglev vehicle dynamics simulation	Feng, Y., Zhao, C., Bai, Z., Tong, L., Shu, Y.	ISA Transactions, 137, pp. 186–198	2023	0	Simulation
Vertical Dynamic Response Analysis of HTS Maglev Vehicle Excited by a Designed Coreless-Typed PMLSM	Zhou, X., Li, H., Wang, L., ...Liang, L., Deng, Z.	IEEE Transactions on Transportation Electrification, 9(2), pp. 3421–3433	2023	0	HTS Maglev Propulsion Simulation

Quasi-Synchronous Operation Principle of a Variable Air-Gap Doubly Fed Linear Motor for High-Speed Maglev Application	Zhong, Z., Shao, Z., Yang, M., ...Xiao, Q., Wang, Y.	IEEE Transactions on Transportation Electrification, 9(2), pp. 2929–2940	2023	0	Propulsion, simulation
Field experimental tests and analyses of suspension frame vibration of low-medium speed maglev train	Ou, F., Liao, X., Yi, C., Chen, Z., Lin, J.	Journal of Low Frequency Noise Vibration and Active Control, 42(2), pp. 496–508	2023	0	LMS Maglev Vibrations Suspension Infrastructure
Periodic Traction Force Fluctuations Suppression Strategy of Maglev Train Based on Flux Linkage Observation and Harmonic Current Injection	Cao, X., Ge, Q., Zhu, J., Zhao, L., Zeng, D.	IEEE Transactions on Transportation Electrification, 9(2), pp. 3434–3451	2023	0	Propulsion Simulation
Improved SEM Current Ringing Suppressor for Maglev Trains	Liang, D., Xiao, S., Zhang, K., Wang, Y., Zhang, H.	IEEE Transactions on Transportation Electrification, 9(2), pp. 2238–2254	2023	0	Suspension Simulation
Adaptive neural network control for maglev vehicle systems with time-varying mass and external disturbance	Sun, Y., Xu, J., Lin, G., Sun, N.	Neural Computing and Applications, 35(17), pp. 12361–12372	2023	15	Control Neural networks
Vertical Vibration Suppression Methods of Superconducting Electrodynamic Suspension System With a Field-circuit-motion Model	Hu, D., Feng, X., Ma, X., Shen, S., Zhang, Z.	Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical	2023	0	Suspension Simulation

		Engineering, 43(10), pp. 3972–3985			
Structure improvement of ironless permanent magnet linear synchronous motor with Halbach array for middle speed maglev trains	Wang, H., Du, Y., Zhang, R., ...Guo, K., Wang, P.	Dianji yu Kongzhi Xuebao/Electric Machines and Control, 27(5), pp. 46–55	2023	0	Structure
Time-variant magnetic field, voltage, and loss of no-insulation (NI) HTS magnet induced by dynamic resistance generation from external AC fields	Zhong, Z., Wu, W., Lu, L., ...Hong, Z., Jin, Z.	Superconductor Science and Technology, 36(5), 055010	2023	0	HTS Maglev, Simulation
Safety analysis of high temperature superconducting maglev train considering the aerodynamic loads under crosswinds	Wang, X., Hu, X., Wang, J., ...Deng, Z., Zhang, W.	Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 237(10), pp. 2279–2290	2023	0	HTS Maglev Aerodynamics
Effect of long-wave deviation of stator plane on high-speed maglev train and guideway system	Tian, X., Xiang, H., Zhu, J., Li, Y., Zeng, M.	JVC/Journal of Vibration and Control, 29(9-10), pp. 2348–2362	2023	1	Guidance Vibration Simulation
Adaptive Fixed-Time Antilock Control of Levitation System of High-Speed Maglev Train	Zhang, T., Shen, D., Jiang, S., Xu, H.	IEEE Transactions on Intelligent Vehicles, 8(5), pp. 3394–3404	2023	0	HTS Maglev Control
Effect of line space on aerodynamic performance of two high-speed maglev trains passing by each other at the speed of 600 km/h in open	Wang, F., Zhang, L., Yang, M., Yin, X.	Kongqi Donglixue Xuebao/Acta Aerodynamica Sinica, 41(4), pp.	2023	0	HTS Maglev Aerodynamics

air		31–40			
Effect of bionic sphere form on drag reduction of high-speed maglev train	Zhou, D., Chen, H., Meng, S., Li, J.	Zhongnan Daxue Xuebao (Ziran Kexue Ban)/Journal of Central South University (Science and Technology), 54(4), pp. 1592–1602	2023	0	HTS Maglev Aerodynamics
Sliding mode periodic adaptive learning control method for medium-speed maglev trains	Zhang, W.-J., Ruan, Y.-X., Gao, Y.-P., ...Yue, Q., Xu, H.-Z.	Jiaotong Yunshu Gongcheng Xuebao/Journal of Traffic and Transportation Engineering, 23(2), pp. 264–272	2023	0	LMS Maglev Operation Control
Study on Electromagnetic Radiation Characteristics Based on HTS Maglev Levitation Test Line	Zhang, H., Zhang, J., Deng, Z., ...Tang, X., Zhang, W.	Electronics (Switzerland), 12(8), 1776	2023	0	HTS Maglev Electromagnetic radiation Simulation
Dynamic Behavior of HTS Levitation Pendulum Driven with a Fluctuating External Magnetic Field	Qi, X., Cai, F., Li, S., ...Feng, Y., Zhao, Y.	Journal of Superconductivity and Novel Magnetism, 36(4), pp. 1109–1120	2023	0	HTS Maglev Levitation pendulum Simulation
Control Methods for Levitation System of EMS-Type Maglev Vehicles: An Overview	Li, F., Sun, Y., Xu, J., He, Z., Lin, G.	Energies, 16(7), 2995	2023	1	General Control

10.2 Appendix 2. Maglev-derived system state-of-the-art matrix

Due to the size and complexity of the MDS matrix, it is attached as a separate file.