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POTENTIAL APPLICATION OF MAGLEV DERIVED SYSTEM TO IMPROVE RAILWAY PERFORMANCE

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Abstract

The paper provides with a categorized overview of existing Maglev-Derived Systems (MDS) and delineates their maturity levels and the technologies employed therein. The analysis focuses on the main functional, technical, and operational, parameters, with a systematic discussion of merits and limitations of the various technologies, aiming at identifying available avenues for the potential integration of MDS into the existing railway network within the European Union. The paper also presents the formulation of a standardized MDS architecture, serving as a foundational reference for deeper and broader development. The paper highlights various existing transport systems, all using linear motors, but not designed for EU railway compatibility. However, emerging interoperable MDS systems, such as MagRail, MagRail Booster, Ironbox subsystems, etc. are arising as promising solutions, and their feasibility is worth assessing. Despite different suspensions, magnetic levitation, wheels or air cushions, almost all MDS primarily employ linear motors, whose compatibility with conventional railways require deeper analysis. Nevertheless, the focus of the paper is the potential of MDS solutions to operate within the current EU railway network. Therefore, sample generic use cases are also presented, taking into consideration the various configurations of the MDS. The achievements described in the paper are the first results of the ongoing MaDe4Rail Project, funded under the Europe's Rail Joint Undertaking Research and Innovation programme.

Keywords: railway, maglev derived systems, integration, compatibility, interoperability

1 Introduction

The railway system stands as the backbone of the Trans-European transport network, a position it should continue to uphold. Currently, railway systems are operating on principles developed around 200 years ago, despite increasing sophistication in their subsystems. Considerable investments are dedicated to innovation, research and technological development to increase performances and safety within the railway system, aiming to preserve its central role in the European transport landscape and supporting further expansion. . This paper overviews MDS as potential instruments to enhance the railway system and categorizes them based on maturity and technology. A thorough analysis compares these systems to conventional railways, highlighting their pros and cons. 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.

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2 Technology and maturity of categorized MDS

A Maglev-Derived System (MDS) is an innovative, fast track-bound transport system for rail application that uses maglev-based technologies, such as linear motors with magnetic or pneumatic levitation. It can be a stand-alone system with its own dedicated infrastructure and vehicles or integrated within the existing railway infrastructure. From the extended state-of-the-art analysis emerged that the main principle that MDS have in common is the linear motor. Based on this, the following groups of MDS have been recognized:
1) maglev systems based on magnetic suspension;
2) air-cushion systems based on pneumatic suspension;
3) wheeled MDS moving on railway or dedicated infrastructures.

2.1 Maglev systems based on magnetic suspension

Maglev systems are defined as transportation systems adopting methods and principles of magnetic levitation to suspend carriages, counteracting gravitational forces by means of magnetic fields. Different methods to generate the electromagnetic forces, the most common differentiation includes:
1) Electromagnetic Suspension (EMS);
2) Electrodynamic Suspension (EDS);
3) Passive Suspension.

Electromagnetic systems
The electromagnetic forces are here generated by means of electromagnets on a magnetically conductive track. The Transrapid [1], a German-developed high-speed monorail, is a paramount example of this typology, in which both levitation and guidance are provided by electronically controlled support magnets located on both sides along the entire length of the vehicle. The propulsion and the braking systems are guaranteed by a synchronous long-stator linear motor. The Transrapid reached the Technology Readiness Levels (TRL) of prototypal demonstrations in an operational environment (TRL = 7). Another EMS in operation in Japan is Limino. For this system, the suspension and guidance forces are provided by a typical U-core electromagnet. The propulsion is generated by Linear Inductive Motors (LIM). The Limino system has been proven in operational environment (TRL = 9). ECOBEE is an EMS-based system, developed for a circular line traveling along the coastline of Yeongjongdo Island (South Korea), with U-shaped magnets and LIMs for levitation and propulsion. The guidance forces are provided by the lift magnets. The mechanical brakes, used with the LIMs. ECOBEE too, reached a TRL = 9. In China two urban MDS systems were develop: Changsha and Beijing maglev trains, both based on normal conducting EMS guiding technology and a Stator Linear Induction Motor (SLIM) as traction technology. For these applications, it was reached TRL = 9. Other EDS systems are under development, as Sengenthal (Germany) consisting of wagons powered by short stator linear motors. The vehicles use electromagnetic levitation for propulsion, being on skids when stationary, developed at TRL = 7.

Electrodynamic suspensions
The electromagnetic forces are generated as an effect of relative motion between the conductive element and a source of electromagnetic field (permanent magnets with aluminium track, or with superconductive electromagnets). The first EDS train was the Chuo Shinkansen in Japan, under construction on high-speed railway between Tokyo and Nagoya. Propulsion, levitation, 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 with levitation and guidance forces.

The propulsion method is the iron-cored long-stator LSM and the superconducting magnets are also used as the field for LSM. The guideway has a U-shape made of concrete. Each bogie has 8 magnets (2 magnetic poles/side). The 3-phase primary windings of LSM are installed in between inner and outer layers of the side wall, with TRL = 8. Other systems use superconductive principles demonstrated in relevant environments (TRL = 6), such as Maglev Cobra in Brazil (TRL = 6) [2] and the Evacuated Tube Transport (ETT). Another approach is the permanent magnetic levitation. In this case repelling magnetic forces are produced by the interaction of a flux-concentrated magnetic field, produced by permanent magnets arranged in a Halbach array of electromagnets, with an inductively loaded closed electric circuit. This technology was used in the USA by Inductrack (TRL = 5) and in China with the Maglev train Xingguo (TRL = 7).

Passive Suspensions

There are other methods of force generation based on forces produced by passive elements, such as permanent magnets not based on dynamic effects, e.g., ferromagnetic levitation. Ironbox technology is based on the principle of magnetic induction between materials with different permeability through the interaction of a slider with a ferromagnetic rail. The slider is realized with appropriately arranged permanent magnets in a U-shaped ferromagnetic profile. The rail is made of high magnetic permeability material. Lateral guidance and propulsion can be based on different technologies according to specific requirements and infrastructure design. Ironlev technology can be applied to standard railway track thanks to the ferromagnetic properties of the iron rail itself. The magnetic slider interacts with the head of the rail creating the suspension force. Ironlev bogie system is composed by two sliders connected by kinematic elements that allow to adapt to railway gauge changes. Propulsion and regenerative braking can be obtained by electric motors connected to lateral centring wheels. Slider centring and magnetic gap control is obtained by using electric actuators. Another solution by Ironlev is based on the coupling of a standard wheel-based bogie with a series of bogie systems. On the infrastructure side, the system is applied in a standard track with traditional switching systems. Ironlev bogie system is designed to be anchored and disconnected to the rail based on the operating phase of the vehicle: at low speed, the 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 operates in a hybrid configuration. For high efficiency and high-speed applications, Ironlev slider is coupled with a custom rail designed to minimize eddy currents, composed of a laminated head connected to a T-shape steel drawn profile. According to the application, guidance and traction are based on lateral wheels or electromagnetic systems. The Ironlev system with custom rails can be adopted in combination with traditional wheeled systems to obtain a hybrid system architecture: hybrid system with EMS guidance, hybrid system with lateral centring wheels. The Ironlev technology reached TRL = 5 for the application to standard railway shape/tracks. Finally, MagRail is a high-speed transport system developed by Nevomo, whose vehicles are propelled by a linear electric motor and equipped with an EDS. MagRail infrastructure includes the linear motor, which is a permanent magnet synchronous motor with a long stator. The tests in 2023 proved the operation of the system at a speed of 130 km/h.

2.2 Air Cushions transport suspension

The principle behind air cushion suspension is rooted in creating a differential pressure between the air inside and outside an air chamber. This generates enough mechanical force to lift an object. In the middle of the 20th century many prototypes were developed, including the Aérotrain. Several updates of this prototype were figured out until it reached TRL = 7, a Transrapid version based on air cushions technology, LIMRV, TALAV in Brazil, various Personnel Rapid Transit (PRT) systems, which never reached a commercial operation. Other systems based on the same principle are the horizontal elevators at Narita International Airport (Japan), Automated People Movers (APM) by Otis Hovair® in Austria and Switzerland and the Cairo Airport MiniMetro by Otis and Leitner that reached TRL = 9.

2.3 Maglev-derived systems operating on wheels

These systems take advantage of traditional wheel-rail contact as support means, while relying on other forms of propulsion. The MagRail Booster designed by Nevomo does not use a magnetic levitation system, but wheels for rolling and guidance not for transmitting traction forces. One key advantage of this system is that single Booster wagons can operate independently without being connected to a locomotive. At the state of art, the MagRail Booster reaches TRL = 5 (validation in a relevant environment). TCV Lab developed the U-CARS system [3], a rail shuttle boosted by U-shaped Linear Induction Motors (U-LIMs), which can be carried by the vehicle or installed in the track depending on the length and degree of the slopes to overcome. On the same principle, Yokohama Municipal Subway 10000 series is a linear motor-powered Electric Multiple Unit (EMU) operated at TRL = 9.

3. Standardized MDS architecture

The subsystems of the MDS architecture are vehicle, infrastructure, energy and Command, Controll and Signalling (CCS). All the definitions of the subsystems and components describe their functions by a technology-agnostic approach.

3.1 Vehicle subsystem

The vehicle subsystem of the MDS corresponds to the movable subsystem of a MDS used for the transport of passengers and goods along predefined guideways. The structure plays a crucial role, serving as the framework or monocoque responsible for bearing loads and accommodating other vehicle components. It can be designed specifically for the MDS or retrofitted by using existing rolling stock. Another component is the propulsion, which enables longitudinal movement of the vehicle, including acceleration and deceleration. The propulsion system might be electromagnetic (LSM), electrodynamic (LIM), friction-based (wheels), or with combined mechanisms. Figure 1 represents the TRL detected for various subsystems and components of the MDS described in section 1.

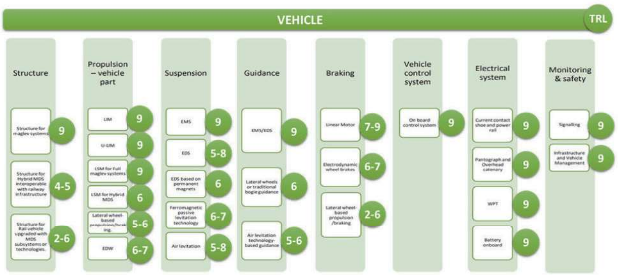

Figure 1 TRL of vehicle components and subsystems

3.2 Infrastructure subsystem

The MDS infrastructure subsystem consists of a combination of components essential for its operation. This includes guideway, switches, propulsion, substructure. The guideway constrains vehicles in a lateral position, guiding navigation through straight tracks and curves. The propulsion component enables longitudinal movement of the vehicle through electromagnetic (LSM), electrodynamic (LIM), or friction-based (wheels). Finally, the substructure provides structural support for guideways, layers of earthworks with distinct properties and a ballasted or ballast-less superstructure. Figure 2 represents the TRL detected for various subsystems and components of the MDS described in section 1.

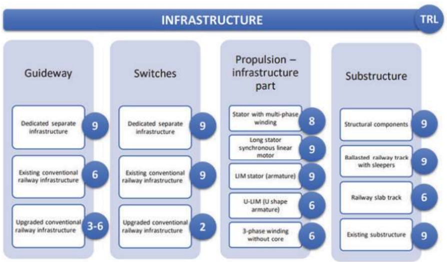

Figure 2 TRL of infrastructure components and subsystems

3.3 Energy subsystem

The energy subsystem provides demanded power to all MDS components, including power supply stations, electrical systems, sensing and communication, segment switches. The power supply station adjusts the voltage and frequency to meet the requirements and feed power to the infrastructure. The electrical system drives power for propulsion and braking, encompassing components like levitation, guidance, propulsion, power transfer and control. The sensing and communication component serves to monitor and control the energy system's state, in terms of the operation of the linear motors, by collecting data on currents, voltages and phases, transmitting it back to motor control devices. The segment switches component, used in linear motors, switches various segments based on MDS location to save energy and reduce impedance. Figure 3 represents the TRL detected for various subsystems and components of the MDS described in section 1.

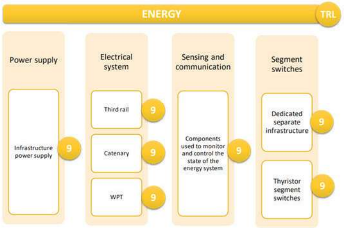

Figure 3 TRL of energy components and subsystems

3.4 Command, control and signalling subsystem

Command, Control and Signalling in MDS operations refers to both onboard and trackside equipment aimed to ensure safe operations of vehicles, traffic direction and prevention of collisions. The Traffic Management System (TMS) provides permanent control across the network by automatic setting routes for the vehicles, while detecting and resolving potential routing conflicts. The Control Centre ensures safe movement of the vehicles at specific line segments. The monitoring & safety component refers to systems that operate at the TMS level, enabling monitoring of vehicle, infrastructure, energy, and CCS subsystems' state and condition. The communication component facilitates seamless interaction between vehicles, infrastructure, energy, external systems. Finally, positioning components are used to determine vehicle position and speed, essential to maintain safe clearances between vehicles in operation. Figure 4 represents the TRL detected for various subsystems and components of the MDS described in section 1.

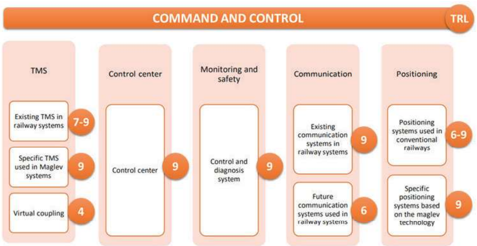

Figure 4 TRL of CCS components and subsystems

4 Potential use cases of MDS and benefits for their implementation in the European railway market

In order to identify possible use cases, 3 possible configurations for MDS based on their TRL, scalability, adaptability, impact on existing infrastructure and their potential compatibility with the railway system are: 1) hybrid maglev MDS; 2) hybrid air-levitation MDS; 3) traditional rail vehicle and infrastructure upgraded with MDS components. A hybrid configuration refers to a MDS deployed on existing railway infrastructure with full interoperability and integration, allowing for the operation of both traditional railways and levitating pods. Several applications are possible for such configurations. Starting from the urban context, where introducing MDS systems in existing metro or tram could improve dynamic performances, capacity and reduce the friction, which could lead to less maintenance cost and energy savings. In addiction, introducing pods could help to increase the flexibility of the system, to offer on-demand services and new and innovative business models.

In the field of passenger transport, the introduction of MDS technologies promises numerous advantages. The levitation capabilities result in reduced friction, leading to decreased noise levels and lower maintenance costs. Additionally, a key shared benefit across various potential applications is the enhancement of dynamic performances and corresponding reduced acceleration and deceleration times. This improvement is for long-distance and local journeys, making MDS technologies viable for updating regional lines too. They could have applications in conventional railway services, boosting the reactivation and repurpose of existing regional lines or allowing innovative business models based on flexible operations. They could also have applications in high-speed lines, allowing an upgrade in performances and allowing flexible operations. In the field of freight transport, the introduction of MDS could result in benefits. Railway vehicles and infrastructure upgraded with MDS components, such as linear motors, would ensure additional traction efforts, increasing performances, particularly useful in areas with significant gradient. The utility of MDS technologies in freight sector extends beyond the mainline. Various applications are envisaged within rail yards, freight villages, etc. by enabling automated operations and efficient freight management.

5 Conclusions

The study offered an in-depth overview of MDS, essential for evaluating MDS solutions that can potentially be imported into the EU interoperable railways. It includes a comparative analysis of current and emerging systems, describes an established system architecture and a crucial framework for further studies and implementations. The main conclusions are described here below:

- Many existing transport systems meet the requirements for potential integration of conventional railways. These include systems that are operational whereas like Chinese and Japanese maglevs or metro systems propelled by linear motors, though none of these systems were designed to be interoperable with the EU railway network.
- There are MDS under development, such as MagRail or MagRail Booster proposed by Nevomo or MDS components being developed by Ironbox or TACV Lab that are being designed to be potentially interoperable solutions.
- Although the analysed systems have different suspension systems, like magnetic levitation, wheels, or air cushions, they share the linear motors propulsion. Therefore, it is worth to focus in following studies on achieving the compatibility of linear motors with the conventional railway network. Regarding the suspension systems, the most mature are standard wheels and magnetic levitation. Air cushion suspension systems are also under development, though with lower TRL.
- The MDS not intended to be interoperable with railway systems, show anyway a potential compatibility. It means that there are 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 overall alignment with the railway system with some subsystems (e.g. linear motors) that need further development and testing to ensure full integration and compatibility with the railway superstructure. This alignment will facilitate the next steps towards creating a regulatory framework for MDS.

The recommended future work is the identification of MDS aligned with EU railway regulations and standards, detect the divergences, recognizing the interfaces between MDS components and configurations that show the most potential of implementation from technical, regulatory, economic perspectives. The ongoing research will continue with exploration of regulations, standards, Technical Specifications for Interoperability (TSI), discerning potential compatibility and interoperability of MDS, required interfaces, configurations with future potential integration, understanding technical and economic feasibility in use cases selected according to the promising configurations identified in section 3.

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