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POPULAR SCIENCE

# Magnetic Levitation Applied to Transport

*Levitación magnética aplicada al transporte*

**RSO JST magazine interview team**

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## Abstract

Magnetically levitated trains improve overall performance by avoiding the mechanical transmission of motion in the wheel-rail pair and, simultaneously, bring sustainability to the system.

According to recent studies, railways worldwide meet 60 % of their total energy demand with petroleum products (IEA, UIC, 2017). This is the main motivation for promoting the development of magnetic levitation and applying it to rail transport. As it is an electrified system, it makes it congruent with the use of renewable energy resources, bringing sustainability to the system (UIC, 2018b).

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## Resumen

El artículo ahonda en las características de los trenes de levitación magnética, que permiten mejorar los rendimientos generales al evitar la transmisión mecánica del movimiento en el par rueda-riel y, a su vez, aportan sustentabilidad al sistema. Según estudios recientes, los ferrocarriles en todo el mundo satisfacen el 60 % de su demanda total de energía con productos derivados del petróleo (IEA, UIC, 2017). Aquí se encuentra la principal motivación para fomentar el desarrollo de la levitación magnética y aplicarla al transporte ferroviario. Al tratarse de un sistema electrificado, lo hace congruente con el uso de recursos energéticos renovables, aportando sustentabilidad al sistema (UIC, 2018b).

## Introduction

The increase in the world's population and the established demographic organization have led to a transport system crisis, resulting in environmental degradation (UIC, 2018a). According to recent studies, railways worldwide meet 60% of their total energy demand with petroleum-derived products (IEA, UIC, 2017). This is the primary motivation for promoting the development of magnetic levitation and applying it to railway transport. Being an electrified system, it aligns with the use of renewable energy resources, thus contributing to sustainability in the system (UIC, 2018b).

Magnetic levitation allows connecting two bodies without any mechanical coupling between them. In other words, magnetic fields are transformed into forces to levitate and guide an object. These systems have various applications, such as active magnetic bearing (AMB), flywheels, magnetic levitation trains, among others.

When analyzed comparatively, while high-speed railway networks, which are widely spread worldwide, have achieved operating speeds in the range of 300 to 350 km/h (Leboeuf, 2018; Lawrence et al., 2019), magnetic levitation trains (MagLev), on the other hand, have reached speeds of up to 600 km/h (CRRC, n.d.). On April 21, 2015, the SCMAGLEV train of the Central Japan Railway Company even set a Guinness World Record at 602 km/h (JRC, n.d.).

The main objective of this work is to review the state of the art on the topic of MagLev trains. The document provides various concepts of magnetic levitation systems and information on the level reached in different countries. This is intended to introduce the subject to the Argentine scientific-academic community and generate a knowledge base to define the development priorities for such a system at the national level.

## Background

MagLev trains were first tested in July 1977 in the city of Miyazaki, Japan. The ML-500 reached a speed of 517 km/h on an inverted T-shaped guideway in 1979. Later, the guideway was changed to a U-shaped one, MLU001, and a speed of 405 km/h was achieved in 1987. In the same year, tests were conducted with a prototype MLU002 (Takeda, 1989).

In 1979, the first magnetic train approved for passenger transport, the Transrapid, began operating at the international transport exhibition in Hamburg (IVA 79). This vehicle transported more than 50,000 people. Subsequently, in Birmingham, England, between 1984 and 1995, a magnetic levitation train was put into service, connecting the airport to the city's railway station (Money, 1984).

## Principle of Operation

A MagLev vehicle levitates without contact with any ground structure and only generates aerodynamic noise. The intensity of the magnetic field is approximately 2 mT on the floor in the passenger cabin of the MLU002 and around 0.6 mT at 600 mm above the floor. The method used to achieve levitation can be a system based on magnetic repulsion or magnetic attraction (Thornton, 2009; Saied and Al-Shaher, 2009).

> ***"According to recent studies, railways worldwide meet 60% of their total energy demand with petroleum-derived products. This is the primary motivation for promoting the development of magnetic levitation and applying it to railway transport.*** "

There are different types of MagLev systems: electromagnetic suspension (EMS), hybrid electromagnetic suspension (HEMS), electrodynamic suspension (EDS), and permanent magnet (PM-EDS).

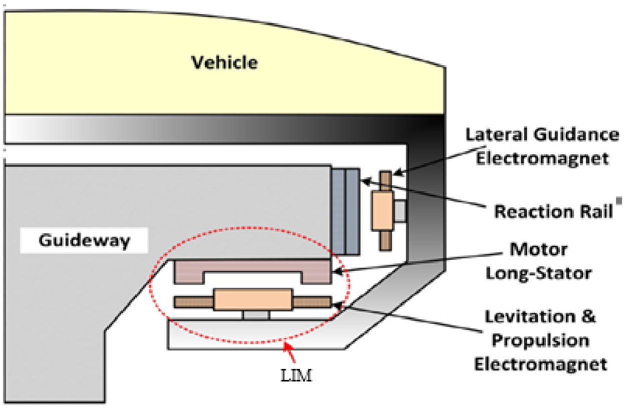
## Electromagnetic Suspension (EMS)

This system uses the attractive force between electromagnets installed on the vehicle, located on its underside, below the ferromagnetic track and ferromagnetic rails used as guideway. It does not have permanent magnetism (He, Rote, and Coffey, 1992). This design can levitate even at zero velocity (Holmer, 2003; Kaye and Masada, 2004). The vehicle has ferromagnetic cores with an inductive coil, and the magnetized core generates an attractive field with a ferromagnetic guideway (Eastham and Hayes, 1988).

EMS uses standard electromagnets, distinguishing it from the EDS system, which uses superconducting materials (Meins and Miller, 1988). This means that the resulting magnetic fields are of lower intensity inside the passenger cabin, making the journey more comfortable for passengers.

The described system is used in German models Transrapid and M-Bahn, the Japanese high-speed HSST, the South Korean UTM, and the British Birmingham system. EMS was developed by the MagnetBahn Transrapid consortium and by Japanese airlines for implementation at Birmingham airport. It features two groups of electromagnets located on the vehicle. The first group's attractive forces allow levitation, and the second group's forces allow centering on the track (see Figure 1).

*Figure 1. EMS system with side guideway*




*Source: Electrical Components of Maglev Systems: Emerging Trends, 2019.*

The track is fixed, and the electromagnets move toward it, lifting and centering the entire train. It has position sensors that close a control loop that regulates the current in the coils. The train can travel at a distance (GAP) of approximately 10 mm (He, Rote, and Coffey, 1992). The GAP between the vehicle and the track depends on the electrical power used in the electromagnets and should not be too large. The magnetic field is concentrated in the GAP area between the vehicle and the track, so there is no need for shielding for passengers.

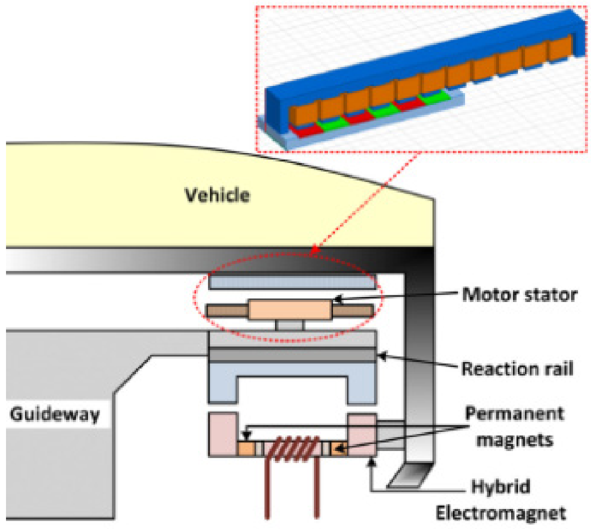
EMS system trains have limitations, with the main one being instability. When the GAP decreases, the attraction force increases, and although the electric current in the electromagnets can be regulated, there is a danger that the train may touch the guide track (Ahmadi et al., 2018). This makes precision in track construction critical and requires complex control systems. Therefore, this system is recommended for low to medium-speed applications (Holmer, 2003). The EMS train, when slowing down and approaching 10 km/h, is supported by braking skids. However, it can remain levitated while stationary.

## Hybrid System (HEMS)

HEMS is a modified form of conventional EMS, as shown in Figure 2. It uses permanent magnets along with electromagnets to reduce electrical energy consumption and allows for larger air GAP's (Chin and Soulard, 2003; Zhang et al., 2013). At the beginning of the movement, it uses both electromagnets and permanent magnets (PM) together to achieve levitation. After achieving a stable GAP, the PMs keep the vehicle levitated, canceling out the electromagnets. PMs generate a constant magnetic flux; therefore, adjusting the excitation of the electromagnet provides the necessary gap control (Chin and Soulard, 2003). Due to this situation, the use of a variable input source is required to excite the electromagnets (Zhang et al., 2013).

This system is currently used by an experimental MagLev, the CMS04, designed by the National University of Defense Technology in Tangshan, China. The system requires low to medium speed to achieve stable levitation. Additionally, the use of hybrid magnets requires a sophisticated control system. However, this technology is under research for its robustness and high stability. Its application shows many future prospects in the field of contactless technology for high-speed transport systems (Zhang et al., 2013).

*Figure 2. HEMS System*



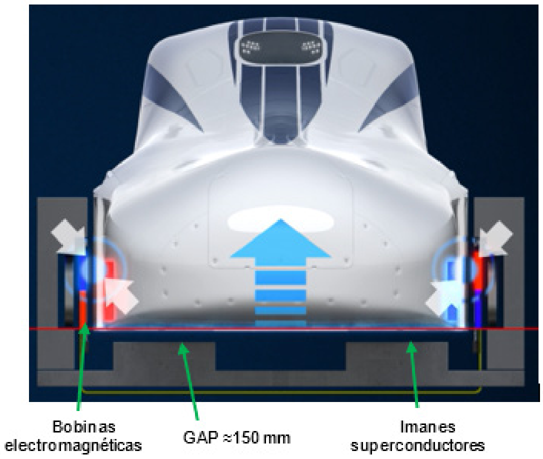

*Source: Electrical Components of Maglev Systems: Emerging Trends, 2019.*

## Electrodynamic System (EDS)

This MagLev system uses the magnetic effect of superconducting magnets for levitation and guidance. It relies on the repulsion between the magnetic force induced by current in non-ferromagnetic conductor coils and the magnetic force of superconducting magnets located on the vehicle (Meissner effect). It involves the disappearance of the magnetic field's flux within a superconducting material below its critical temperature, meaning the superconducting magnet repels magnetic field lines so that they do not pass through its interior.

The term superconductivity refers to the property of certain materials that, when cooled to near absolute zero, exhibit almost zero electrical resistance. In the EDS system, developed by the Japanese National Railways, vehicles have superconducting magnets in a cryogenic environment with temperatures around 4 K. These magnets are located on the sides, at the bottom of the vehicle, while the coils are positioned on the track. The magnetic fields produced by these interact with the superconducting magnets on the train and generate the levitation and guidance force (see Figure 3).

*Figure 3. EDS System*



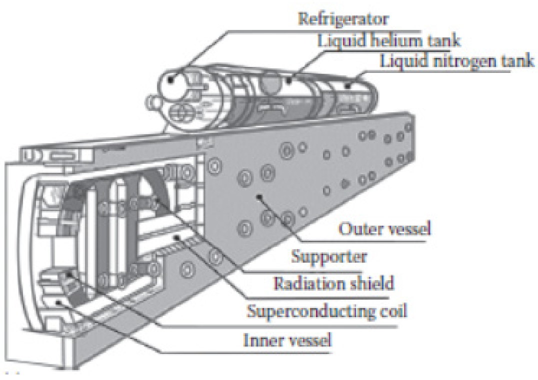

*Source: Japanese superconducting Maglev. Present State and Future Perspective, 1989.*

The EDS system is characterized by a GAP of 100 to 150 mm at high speeds; as a result, the guides are less precise but more stable. The levitation force depends on the speed and needs to reach around 100 km/h to achieve separation (Prasad et al., 2019). At lower speeds, a retractable wheel system is used.

One disadvantage of this system is the use of large magnetic fields near the passenger cabin, necessitating the installation of insulation systems for health protection. Another drawback to mention is the need for refrigeration equipment to maintain superconductors at low temperatures.

The superconducting magnet system used in the MLU002 (see Figure 4) consists of an aluminum alloy outer vessel and a stainless-steel inner vessel, facilitating heat exchange with nitrogen pipes.

*Figure 4. MLU002 Superconducting Magnet*




*Source: SCMAGLEV. https://scmaglev.jr-central-global.com/about/*

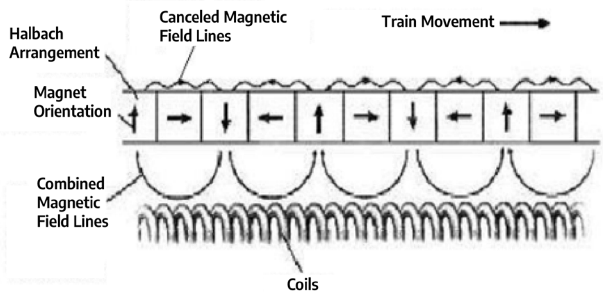
The superconducting coils installed are made of Nb-Ti alloys [8] and copper aggregate (1% by weight), which helps reduce the weight of the coils. Nitrogen exchanges heat with helium, and the evaporated liquid helium is liquefied again for reuse in a refrigerator. There are two sets of coils: propulsion, and levitation and guideway.

## Permanent Magnet Electrodynamic Suspension (PM-EDS)

In the year 2000, Richard Post and Dmitri Ryutov introduced an innovation in MagLev technology called the Inductrack. Instead of superconducting materials, this system utilizes permanent magnets at room temperature arranged in a Halbach array (see Figure 5). This unique distribution of permanent magnets allows for the generation of sufficient levitation forces for the MagLev train.

The Halbach arrangement consists of magnets placed in such a way that the magnetic field of each magnet is oriented with the adjacent magnet. This arrangement produces a sinusoidal magnetic field on the underside of the array while completely canceling it on the upper side. Unlike the EDS system, this system does not use superconducting magnets, eliminating the need for cryogenic cooling (Uzuka, 2013; Schultz et al., 2005).

*Figure 5. Halbach Array*




*Source: Study of Practical Applications of Magnetic Levitation, 2003*

However, it requires auxiliary wheels to accelerate the vehicle until it achieves levitation force (Long, He, and Xue, 2011). It can be said that it is a lower-cost option.

This technology has been tested at General Atomics in the USA, with the suspension magnets separated from the propulsion magnets (Saied and Al-Shaher, 2009). The Inductrack track has coils that act as rails. Each of these rails is surrounded by two Halbach array configurations of magnets located in the lower part of the vehicle, one positioned above the rail and the other below it (see Figure 6). In this case, the rail coils are in a short circuit, and the magnets provide the induction as they move over the track (inducing a current in the coils, and then the magnetic field of these coils repels the magnets). Since the effect is electrodynamic, it is necessary to use wheels to support the weight until the train achieves levitation

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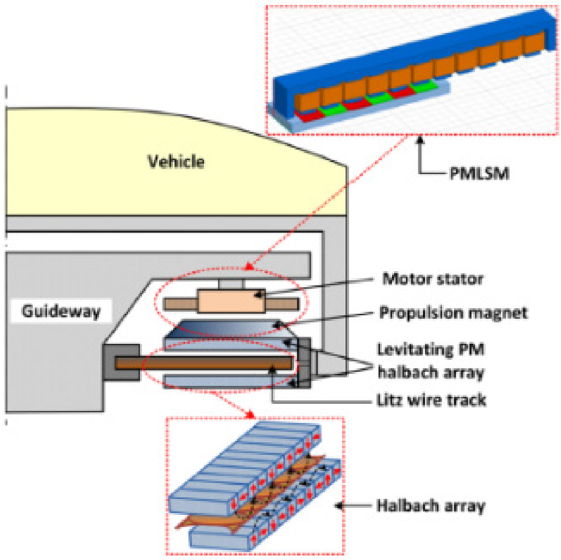
The main losses would be caused by air friction and by the electrical resistance in the short-circuit coils.

*Figure 6. Inductrack Track with Halbach Array Configuration*




*Source: Electrical Components of Maglev Systems: Emerging Trends, 2019.*

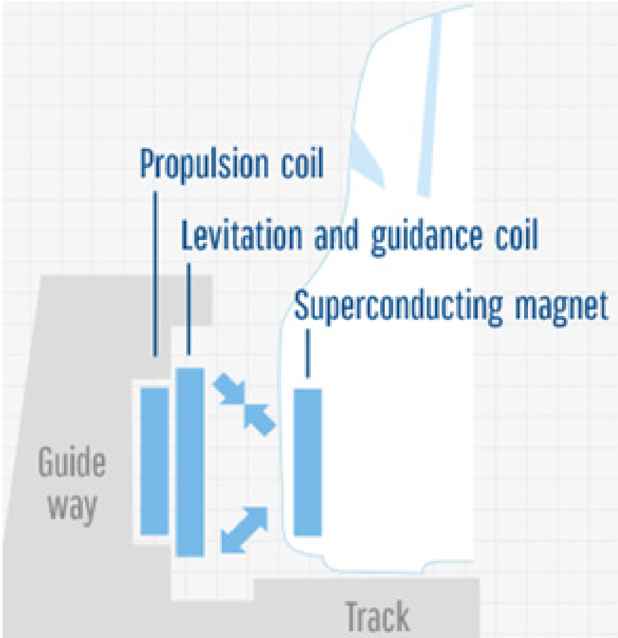
## Guideway Systems

MagLev vehicles are guided to prevent lateral displacements (Boldea et al., 2018). This orientation mechanism generally uses magnetic-repulsive or attractive forces (Schultz et al., 2005).

The null-flux system is used, consisting of a guideway produced by a cross coupling, applied as the stator core of the linear motor, mounted on both sides. The coils on both sides of the guideway are interconnected. Therefore, the net electromotive force (emf) induced in the coils is zero when there is no lateral displacement (Cassat and Jufer, 2002).

If the train moves to one side, the net magnitude of the induced emf increases, generating a repulsive force on the side closest to the guiding coils, forcing the vehicle to center itself (Takeda, 1990). Japanese MLU technology integrates the guideway system with propulsion, while MLX integrates the guideway system with the levitation system. In the latter application, as seen in SCMAGLEV, there are two sets of coils: propulsion, and levitation and guideway. The propulsion coils provide forward force to the train, while the levitation and guideway coils are used to levitate the train and guide it to the center of the guide track (see Figure 7).

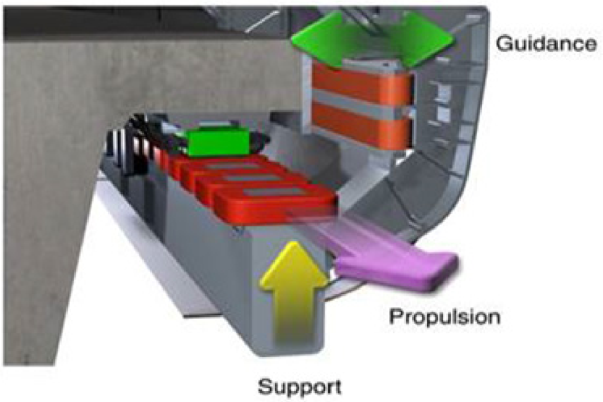
*Figure 7. Propulsion, guideway and levitation*




*Source: SCMAGLEV. https://scmaglev.jr-central-global.com/about/*

The German Transrapid also uses repulsive forces between the electromagnets on the vehicle and the side coils to fulfill the guideway function. The levitation and propulsion systems are kept separate to avoid magnetic interference (see Figure 8).

*Figure 8. Propulsion, guideway and levitation of the Transrapid*




*Source: Transrapid. http://www.siemens.com/transportation*

## Power Supply System

In a MagLev system, the transfer of electrical energy from the ground is crucial for producing levitation, propulsion, and other onboard services (Uzuka, 2011). For speeds of up to 300 km/h, a pantograph can be used to transfer the required power (Long, He, and Xue, 2011). However, for speeds greater than 300 km/h, linear motors and generators are used (Mundrey, 2010; Powell and Danby, 2007). Together, they form the contactless power supply system.

The power supply from the public grid at 110 kV goes through power transformers of 110/20 kV (He, Rote, and Coffey, 1992). It then undergoes a transformation stage from 20 kV/1.2 kV and rectification to DC. Inverters and associated devices are used to obtain a voltage range of 0 to approximately 1,500 V and a variable frequency from 0 to 215 Hz. This three-phase system is directly connected to the windings of the long stator armature. Output transformers are used to increase the voltage to a maximum of 7,800 V. The maximum motor current is 1,200 A.

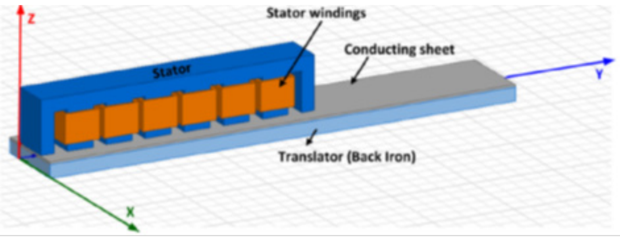
## Propulsion

To propel a MagLev train, a linear motor is used. It can be either a DC or asynchronous AC motor (Hellinger, Mnich, 2009; Boldea et al., 2018). The use of linear DC motors is still in the research and testing stage because it has disadvantages in the brush systems used for power supply (Rivera, 2007).

An AC linear motor operates on the same principle as conventional induction motors but produces rectilinear motion. Unlike rotary motors, they can provide a levitation effect (Vijayvargiya et al., 2018). There are two types of motors: the linear induction motor (LIM) and the linear synchronous motor (LSM).

The LIM uses high frequency pulsed magnetic fields and is known as a short stator motor. It consists of a stator containing excitation windings and a linear rotor (LR) composed of a metal sheet placed over a ferromagnetic layer (see Figure 9).

*Figure 9. Linear Induction Motor (LIM)*




*Source: Electrical Components of Maglev Systems: Emerging Trends, 2019.*

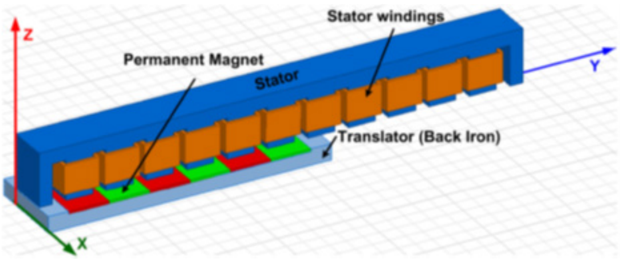
The LR is used in the vehicle as the moving part, while the stator forms the fixed guideway (Kaye, Masada, 2004). LIM-based propulsion systems are widely accepted for MagLev applications. This motor offers good reliability, robustness, and low maintenance. Additionally, they have excellent responsiveness in the speed range and the ability to operate in harsh conditions. However, they have a high weight, which reduces the vehicle's payload capacity (Vijayvargiya et al., 2018).

The LIM has less response and efficiency compared to the LSM for speeds exceeding 300 km/h. This is due to higher losses from parasitic currents. Consequently, it has lower propulsion force density and a lower power factor (Cho et al., 2008).

The LSM motor, known as the long stator, is the most used propulsion system for train applications. A circuit of coils through which controlled three-phase alternating current flows is used as the stator (see Figure 10). It resembles the stator of a LIM.

The LR incorporates a magnetic source, making the motor doubly excited. In high-performance propulsion systems, excitation is provided by the inclusion of permanent magnets (PM) (Cho et al., 2008).

*Figure 10. LSM with Permanent Magnets*




*Source: Electrical Components of Maglev Systems: Emerging Trends, 2019.*

Some MagLev systems also use electromagnets. In the case of an EMS system, the LR motor consists of electromagnets on the train, and in an EDS system, it consists of superconducting magnets. The alternating current in the stator generates a magnetic field with alternating north and south poles. Simultaneously, the LR is also energized, creating a magnetic flux. The interaction between these two magnetic fluxes forces the vehicle to move at a synchronous speed (Vijayvargiya et al., 2018; Cho et al., 2008).

Due to its higher force density, greater efficiency, and higher power factor, this motor has been the most widely used for magnetic levitation applications (El-Refaie, 2013; Lee et al., 2013), with the stator coils used as the guideway (Park et al., 2013). This configuration is suitable for high-speed applications as it does not require a current collector.

The energy that moves the train is supplied by the tracks, allowing the tracks to be energized in sections so that only the track sections the train is passing through are active (Kuntz, Burke, and Slemon, 1978).

The use of these motors allows MagLev trains to traverse slopes of up to 10°, in contrast to conventional railways that can only navigate slopes of up to 4°.

The linear motor is also used for train braking. To do this, the polarity of the current in the stator must be reversed to generate a force opposite to the forward motion. The deceleration is the same as acceleration: 1.8 $m/s^2$ (suitable for passengers). In emergencies, it can reach 3.5 $m/s^2$.

The MagLev vehicle braked from 300 km/h using sliding shoes made of a molybdenum alloy acting on the guideway. Brakes with aerodynamic panels installed on the body also demonstrate high performance (Barone, González, and Vilella, 2018; Prasad, Jain, and Gupta, 2019).

## CONCLUSIONS

The need to increase transport capacity, improve energy efficiency, and reduce environmental impact has led to advances in MagLev technology. It is proposed as a sustainable and cleaner alternative. This article has provided an overview of MagLev technology, with a special focus on the components of the electromagnetic system. Different levitation, guideway, and propulsion technologies have their capabilities and limitations. SCMAGLEV technology is considered the most suitable for speeds above 350 km/h, with a gap of approximately 150 mm. However, it has a fundamental limitation because it uses superconducting magnets, which require cryogenic systems and generate high magnetic fields that could be uncomfortable inside the vehicle. This is why hybrid systems, incorporating permanent magnets, are the focus of current research.

The technological advancement of MagLev systems makes it possible to compete with railway transportation. Developing magnetic levitation systems is a challenging task that must be undertaken to project a sustainable future in our country.

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