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# 48. Application Potential of Maglev Technology in Transport Systems

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**ABSTRACT**

*Magnetic levitation is a promising technology for transport application. Compared to traditional transport technologies, such as rail-wheel systems, it offers total friction-less (EMS) or almost friction-less motion (EDS). Today (year 2024) there exist two fundamentally different maglev system technologies, the electromagnetic system (EMS) and the electrodynamic system (EDS). Both system technologies are in competition with conventional rail-wheel systems, mainly in high-speed transportation (EM and EDS) but also in low- and medium speed transportation (EMS). In high-speed transportation maglev systems can compete even with air transport. On a world-wide scale, there exist maglev systems for the high-speed and medium-speed sector, some in commercial operation and some in testing phase. The paper discusses the costs and benefits of the two maglev system technologies based on technical, environmental, social and economic aspects and criteria. These include energy consumption, emissions as well as investment for the infrastructure and estimation of operational costs. In addition, some soft criteria such as passenger comfort and acceptance are considered. As far as available, testing data and operational experience from operating maglev systems and application projects are used. The pros and cons of each system technology (EMS and EDS) for high-speed, medium-speed, passenger and freight transport are discussed in order to evaluate the application potential of maglev technologies.*

**Keywords**: Maglev system technologies, environmental aspects, technical and economical aspects, comparison with existing transportation technologies

## 1. INTRODUCTION

Magnetic levitation is an innovative and promising technology for transportation, offering several advantages over conventional rail-wheel systems. Although the first concepts of magnetic levitation emerged in the 1920s, it took several decades before the development of practical technical demonstrators. Beginning in the 1970s, research institutions and industrial companies in various countries constructed experimental vehicles. Broadly speaking, two distinct maglev technologies have been developed: the Electromagnetic Suspension (EMS) system and the Electrodynamic Suspension (EDS) system.

Since then, both low- and high-speed maglev transportation systems have been developed. Some are now in commercial operation, while others are still in testing or the planning phase. Maglev technology competes with traditional transportation systems, including urban and regional trains, tramways, and high-speed rail. In the high-speed sector, maglev systems even have the potential to serve as alternatives to air travel.

To evaluate the potential of maglev technology within the transportation sector, it is necessary to compare it with conventional systems using a range of technical, environmental, and socio-economic criteria. Key considerations include energy consumption, emissions, transport capacity, infrastructure investment, and costs associated with operation, maintenance, and repair. From the passenger's perspective, critical factors include travel time, comfort, and safety, with safety being a particularly important aspect influencing public acceptance of the technology.

## 2. MAGLEV TECHNOLOIES

### 2.1 Electromagnetic system (EMS)

Electromagnetic Suspension (EMS) technology relies on the attractive or repulsive forces generated by electromagnetic fields produced by electromagnetic coils. One set of coils is integrated into the guideway, while the other is installed in the vehicle. The EMS system is composed of two primary subsystems: the suspension system and the linear drive and guidance system. Power for the electromagnetic system is supplied externally, either through a physical contact slider or via contactless induction.

Unlike EDS technology, EMS allows for continuous levitation, even at lower speeds, without the need for additional wheels. This makes EMS technology versatile for various speed ranges and more adaptable in different operational environments.

### 2.2 Electrodynamic system (EDS)

The Electrodynamic Suspension (EDS) technology utilizes electrodynamic induction to generate the magnetic field required for levitation. As the vehicle moves, electromagnetic coils are exposed to time-varying magnetic fields, producing a repulsive force. Levitation and guidance coils are embedded on both sides of the guideway. As the vehicle’s onboard coils pass along the guideway at higher speeds, they induce electric currents in the levitation and guidance coils, creating the necessary repulsive force for suspension.

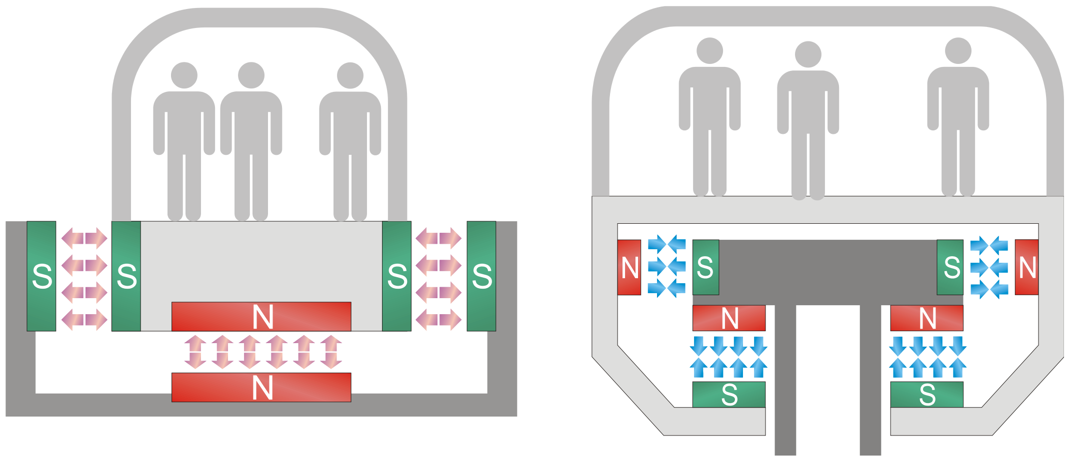


**FIGURE 1:** *Illustration of the EDS technology (left) and the EMS technology (right) [1].*

One key advantage of EDS technology, particularly with the use of superconducting magnets in the vehicle, is that it allows for larger gaps between the vehicle and the guideway, improving ride stability. However, a notable drawback is that the suspension system only becomes effective at higher speeds. At lower speeds, the vehicle requires additional support from wheels. The principles behind both EDS and other maglev technologies are illustrated in FIG. 1.

For high-speed transportation, the EDS technology with superconducting magnets in the vehicle and normally conducting coils in the guideway is used in the Japanese Chuo Shinkansen system, whereas the EMS technology is used in the Maglev trains based on Transrapid technology.

### 2.3 The linear drive system

The propulsion in maglev systems is achieved through a linear motor drive system. In this system, the stator and rotor coils of a traditional motor are "unrolled," creating linear rather than rotational force along the length of the guideway. The stator coils are embedded within the guideway, while the rotor coil is installed in the vehicle. The magnets used in the system can be either permanent magnets or electromagnets, depending on the design. This linear motor drive system efficiently generates the necessary propulsion force, as illustrated in FIG. 2.

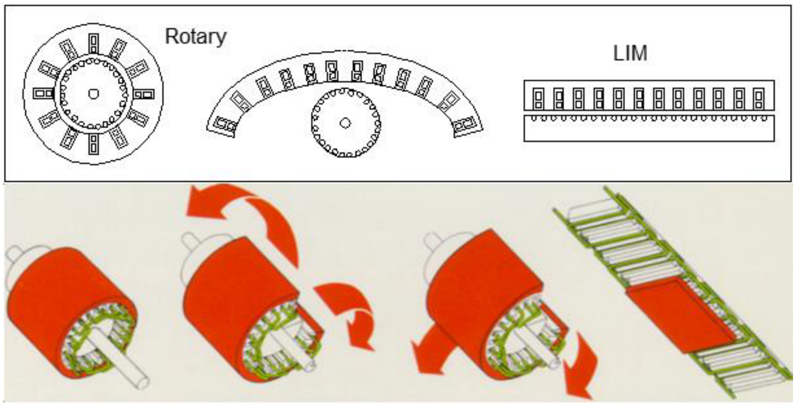


**FIGURE 2:** *Conversion of rotary machine into a linear induction motor (LIM) [2].*

## 3. MAGLEV SYSTEMS FOR TRANSPORTATION

Conventional track-bound transportation systems, based on rail-wheel technology, date back to the 16th century and have been continuously refined over the last four centuries. With the advent of electricity and advancements in magnetic materials, the concept of magnetic levitation for transportation became feasible in the second half of the 20th century. The viability of maglev systems for transportation has since been demonstrated through experimental prototypes in various countries.

Since their inception, maglev systems have faced strong competition from conventional rail-wheel transportation. In the high-speed transportation sector, maglev systems also compete directly with airplanes. Thus, the primary areas of competition for maglev systems can be defined as follows:

| Transportation | Competitor |
|---|---|
| Low speed (urban maglev) | suburban train<br>light rail transit |
| Medium speed (regional maglev) | regional train |
| High speed (high-speed maglev) | high-speed train<br>airplane |

**Table 1:** *Fields of competition*

In conventional railway systems, friction between the rails and wheels is essential for movement. However, this friction leads to significant abrasive wear on the rails, wheels, and braking systems, which increases with speed. The replacement of these components constitutes a major portion of maintenance and repair costs. Additionally, the wear debris generated by this abrasion is emitted into the environment, containing particulate matter composed of various metal compounds. This pollution poses environmental concerns and health risks for both personnel and passengers.

In contrast, maglev train systems offer nearly frictionless motion due to their magnetic levitation suspension. As a result, maglev systems are either completely or nearly free of particulate matter emissions, which translates to reduced maintenance and repair efforts. This near-zero emission is a further environmental benefit. Moreover, the magnetic suspension, combined with the linear drive system, allows maglev trains to achieve a gradeability more than twice that of conventional railway systems, offering an additional advantage in challenging terrains [3].

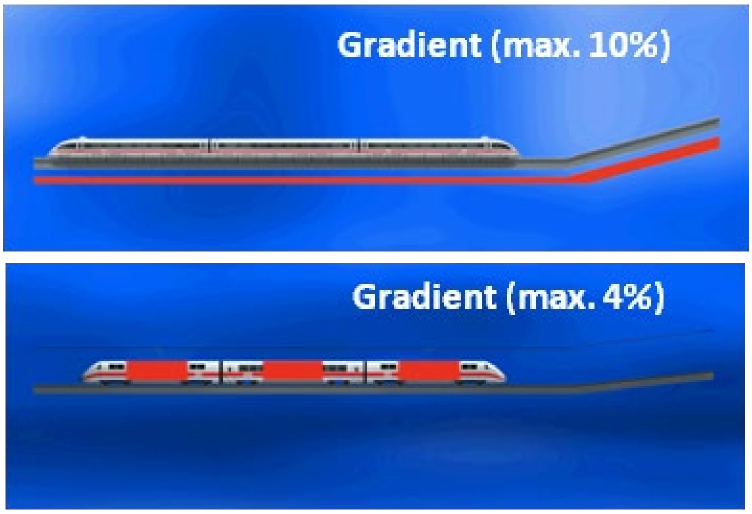


**FIGURE 3:** *Comparison of the gradeability of maglev with railway systems [3].*

This reduced need for tunnels in hilly areas is a notable advantage of maglev systems. While maglev systems are not compatible with conventional railway infrastructure, requiring significant investment in an entirely new infrastructure, this can be viewed either as a drawback or as an opportunity. From a forward-looking perspective, it offers the potential to leapfrog existing rail limitations, allowing for the development of a more advanced and future-proof transportation network, free from the constraints of ageing infrastructure.

### 3.1 High-speed transportation systems

In the field of high-speed transportation, maglev trains compete with both high-speed railways and domestic or continental flights. Airplanes typically operate at speeds between 600 and 900 km/h, while maglev systems have operational speeds ranging from 300 to 500 km/h, with a top speed of 600 km/h. However, the overall travel time for air travel includes additional factors, such as transport from the city center to the airport and time spent on check-in and security procedures. As a result, the average total travel time for airplanes becomes comparable to that of high-speed maglev trains, except for very long-distance journeys (700 to 1000 km or more) where air travel maintains a distinct speed advantage.

#### 3.1.1 The Transrapid system

The first high-speed maglev train in commercial operation is the Transrapid SMT which has been developed in Germany. It connects the Pudong International Airport with the New International Expo Center in Shanghai.

The Transrapid uses the EMS technology for levitation and a linear drive system for propulsion. The principle of the Transrapid system is illustrated in FIG. 4.

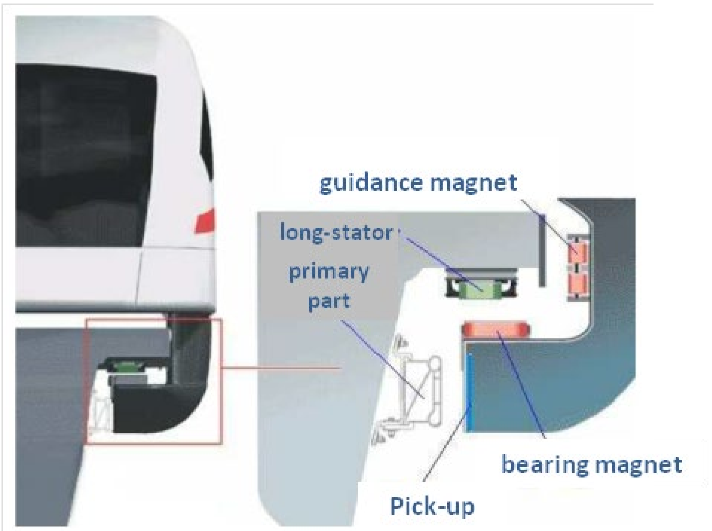


**FIGURE 4:** *Illustration of the Transrapid levitation, guidance and propulsion system [4].*

The air gap between the vehicle and the track is about 10, mm. The operational speed of the SMT is in the range between 430 and 500 km/h.

**FIGURE 5:** *The SMT in Shanghai.*

### 3.1.2 The Japanese JR Maglev system: Chuo Shinkansen

As of 2024, the current operational speed record for maglev trains is held by the Japanese Chuo Shinkansen, which reached a speed of 603 km/h along the Yamanashi test line. The development of the Chuo Shinkansen began in the 1970s, and once completed, it will connect Tokyo with Nagoya and Osaka, partially replacing the existing Tokaido Shinkansen line, which is nearing its transport capacity.

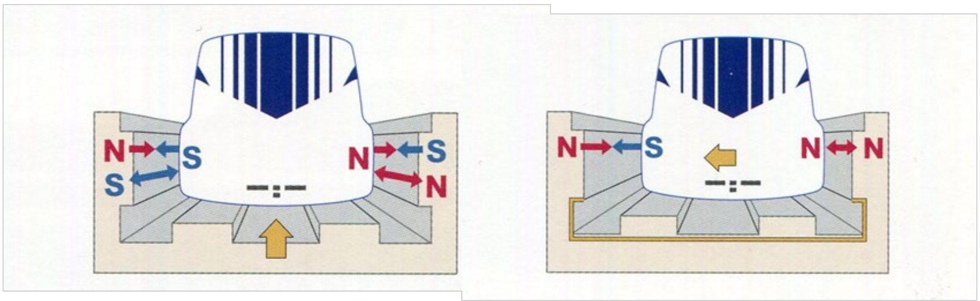


**FIGURE 6a:** *Illustration of the levitation and guidance concept of the Chuo Shinkansen [5].*

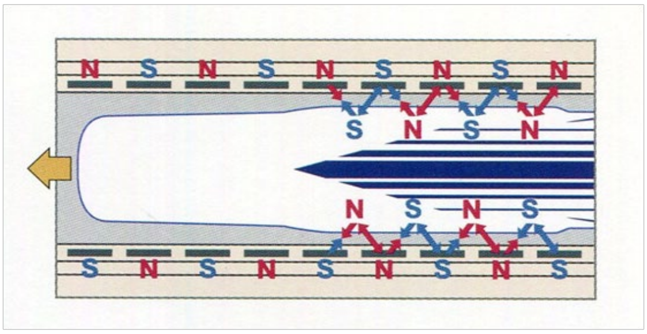


**FIGURE 6b:** *Illustration of the propulsion concept of the Chuo Shinkansen [5].*

The Chuo Shinkansen utilizes Electrodynamic Suspension (EDS) technology, incorporating superconducting magnets in the vehicle. Electromagnetic levitation and guidance coils are integrated into the sidewalls of the track. The use of superconducting materials allows for a larger gap between the vehicle and the track—approximately 10 cm—enabling the train to hover. The interaction between the superconducting magnets and the electromagnetic coils provides propulsion for the train. Due to the EDS technology the levitation starts at a speed of about 150 km/h. In the low speed range an additional gear with wheels are needed.

**FIGURE 7:** *The JR Maglev train.*

### 3.1.3 The Chinese maglev system

The prototype of the Chinese maglev train developed by CRRC is based on German Transrapid technology. This system represents an advancement of the original Transrapid design, building on the operational experience gained from the Shanghai Maglev Train (SMT). The Chinese maglev is engineered for an operational speed of 600 km/h, significantly extending the capabilities of the original technology.

**FIGURE 8:** *The prototype of the Chinese Maglev train [6].*

## 4. LOW- AND MEDIUM SPEED SYSTEMS

World-wide several maglev systems have been developed for urban transportation. Examples are:

- Linimo in Nagoya (Japan)
- Rotem Ecobee (South Korea)
- Cobra in Rio de Janeiro (Brazil)
- Transports System Boegl (TSB, Germany)
- Urban transportation systems in several cities in China


**FIGURE 9a:** *The Linimo in Nagoya.*


**FIGURE 9b:** *The Rotem Ecobee at Incheon International Airport (South Korea).*

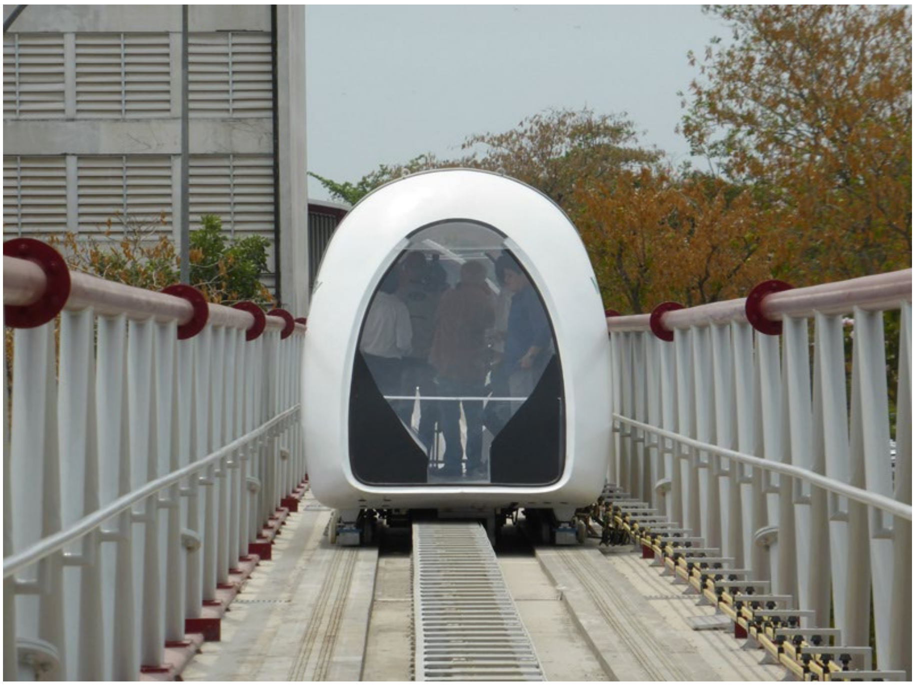

**FIGURE 9c:** *The Cobra system of Rio de Janeiro State University (Brazil).*

The application of maglev technology is not limited to passenger transport; it can also be effectively utilized for cargo transport. In logistics, where speed and time are generally less critical than in passenger transport, low- and medium-speed maglev systems present a viable and potentially attractive option. One example of such a system is the Transport System Bögl (TSB), developed by the German construction company Max Bögl, as shown in FIG. 9d. This system is a modification of the urban maglev system, specifically adapted for the transportation of containers.


**FIGURE 9d:** *The Transport System Bögl (TSB) for cargo transportation [7].*

Other systems for urban transportation have been developed in China, some are in operation in several cities in China.


**FIGURE 10:** *China's first commercial maglev 3.0 train completed a series of tests on March 10, 2022 (Photo: cnsphoto).*

# 5. RESULTS AND DISCUSSION - TECHNICAL, ENVIRONMENTAL AND SOCIO-ECONOMIC EVALUATION

## 5.1 Technical evaluation

Among technical criteria, energy consumption is particularly important. For the comparison, the German ICE and the French TGV high-speed trains are chosen as reference systems. For maglev systems, the Transrapid and the Chuo Shinkansen are selected, with energy consumption evaluated both at the same speeds as the reference trains and at their respective operational speeds of 430 km/h and 500 km/h [8]. The specific energy consumption, measured in watt-hours (Wh) per seat-kilometer, is presented in FIG 11.

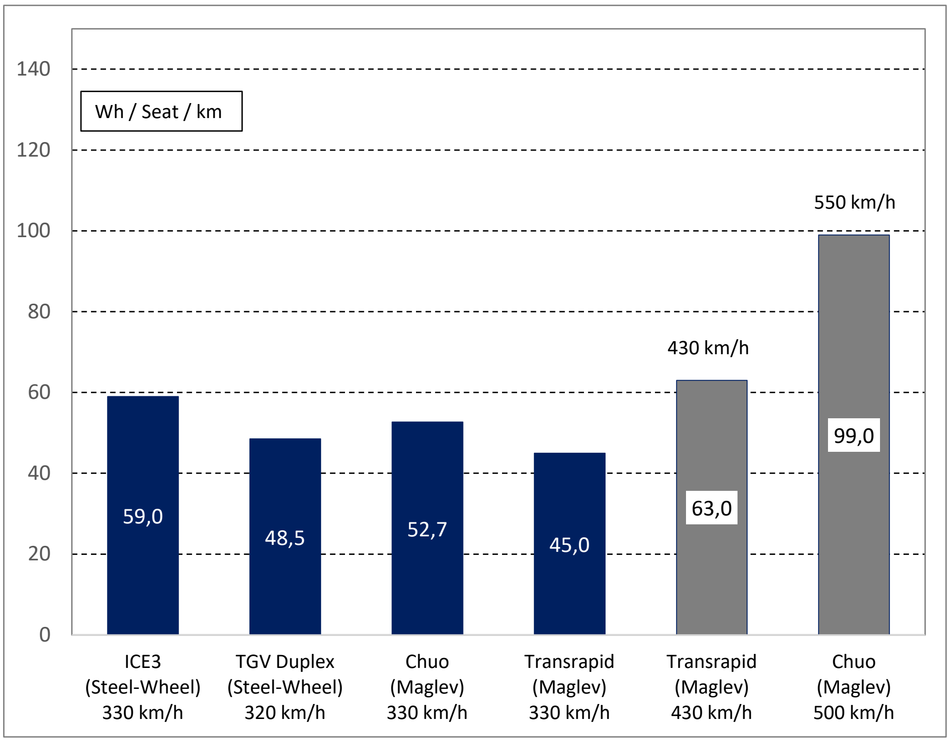


**FIGURE 11:** *Comparison of the specific energy consumption in Wh per seat-km at 330, 430 and 500 km/h [8].*

The energy consumption increases with increasing speed of the train. Therefore, the energy consumption of the maglev trains at their normal cruising speed is considerably higher.

### 5.2. Environmental evaluation

For the environmental evaluation, key criteria include emissions such as particulate matter, noise, and electromagnetic fields. Since all systems under consideration are electrically powered, CO2 emissions are excluded from this analysis. The associated CO2 emissions depend on the energy mix used for electricity generation, which varies by region and is not directly tied to the transport system itself.

#### 5.2.1 Emission of particulate matter

The issue of particulate matter emissions is gaining increasing importance in efforts to protect both people and the environment from the harmful effects of pollution. Public and regulatory attention to this topic has risen significantly in recent years. While rail-guided transportation generally produces lower levels of particulate matter emissions compared to motor vehicles, the nature and characteristics of the emissions differ substantially. The type, quality, and peak emission occurrences in rail systems are distinct from those generated by road vehicles, warranting a specific focus on mitigating these emissions in rail transport.

**Wheel-rail systems**

Primary sources of particulate matter emission from track-guided transport systems are

1. Wear on the brakes
2. Abrasion on wheel and rail
3. Abrasion on catenary wire and pantograph
4. Whirling up of existing ('old') particulate matter

We concentrate on high-speed train systems, such as the German ICE and the Transrapid and the Japanese Chuo Shinkansen.

The bandwidth of specific particulate matter emissions of the German ICE train is shown in FIG. 12. The best case value is calculated from annual replacements of wheels, brakes and rails. The upper (extrapolation value is obtained from Swiss measurements and mapping on German high-speed transportation conditions [9].

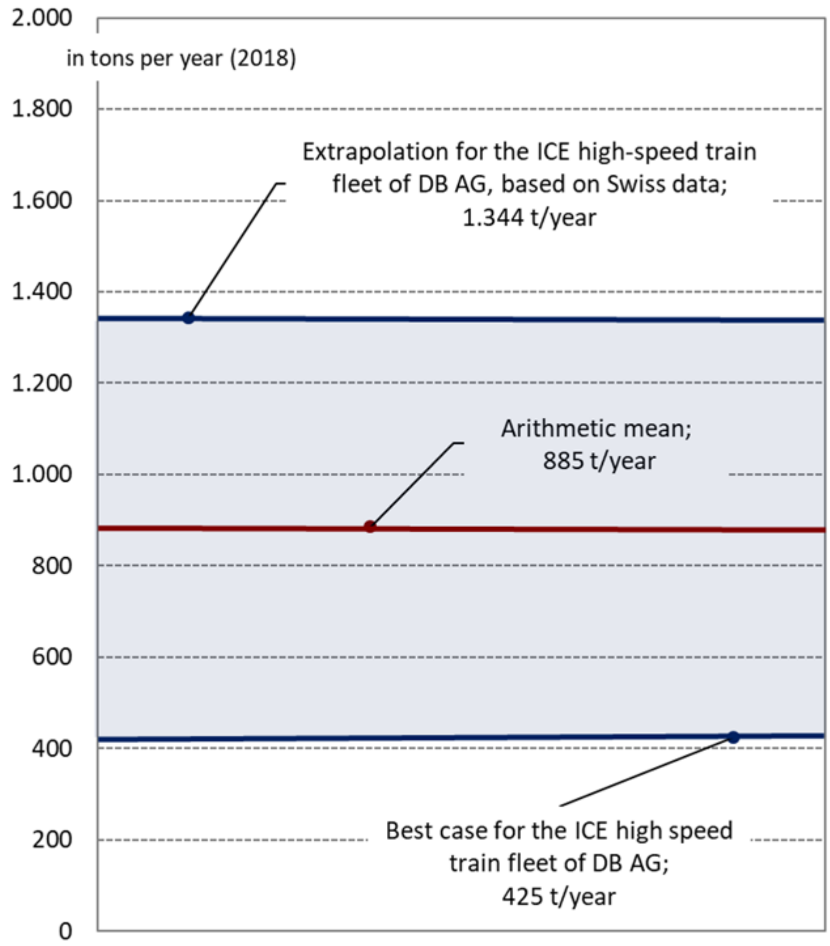


**FIGURE 12:** *Range of particulate matter emissions from the ICE high-speed train, in grams per kilometer, for the year 2018 [9].*

**Maglev systems**

Since the levitation of EMS systems is completely frictionless, there is no generation of particulate matter. In case that the power to the vehicle is supplied by induction, the operation is completely free of particulate matter emission.

| Abrasion on …. | EMS-Maglev | Total emission |
|---|---|---|
| Brakes | Friction-free | 0 t/year |
| Guideway | Friction-free | 0 t/year |
| Onboard power supply | Friction-free | 0 t/year |
| **Total** | | **0 t/year** |

**TABLE 2:** *Abrasion and particulate matter emission of EMS-based maglev systems [9].*

The situation is different for Electrodynamic Suspension (EDS)-based systems. In the lower speed range, these trains require the support of wheels until they reach a speed at which the inductive force is strong enough to sustain levitation. Currently, no official data are available regarding the abrasive wear of the wheel material in EDS systems. However, it can be reasonably assumed that particulate matter emissions from EDS systems are significantly lower than those of conventional rail-wheel systems. The corresponding evaluation for EDS systems is presented in Table 3.

| Abrasion on …. | EDS-Maglev | Total emission |
|---|---|---|
| Brakes | Friction-free | 0 t/year |
| Guideway | Rubber abrasion during braking, e.g. when entering a station | Unknown quantity and form |
| Inductive onboard power supply | Friction-free (as of 2021) | 0 t/year |
| **Total** | | **Rubber particles** in unknown quantity and form |

**TABLE 3:** *Abrasion and particulate matter emission of EDS-based maglev systems [9].*

### 5.2.2 Electromagnetic fields

The electric power supplied to the drive systems generates electromagnetic fields. The peak power may achieve a value of several megawatts (MW). The corresponding current value is in the range between several hundreds and a few kiloamps (kA). In general, two different situations for the exposure to electromagnetic fields need to be considered:

(1) the emission of electromagnetic fields to the external environment, i.e. the impact on the neighboring environment along the track, and

(2) the exposure of passengers inside the train.

Among the two field components the magnetic induction is the relevant one.

**Railway systems**

Again, the German ICE train is selected as example of a high-speed train. The power is supplied via the inverter stages to the motors via a three-stage transformation/conversion system. As a result, a maximum efficient current value of 250 A is flowing to each motor at a constant maximum speed of 330 km/h on a flat track. In FIG. 13 the total magnetic induction inside the train is shown as a function of the distance from the location of the field generation together with the limit given by the German regulation for magnetic induction in the corresponding frequency range.

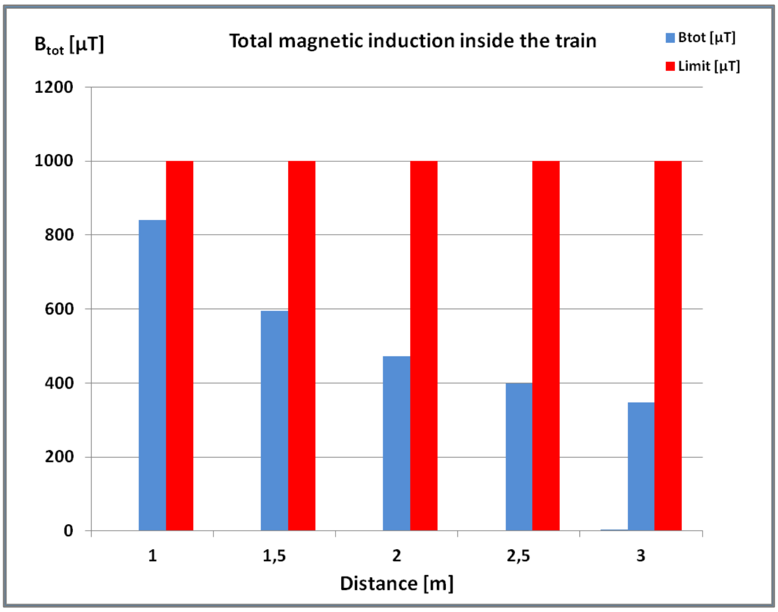


**FIGURE 13:** *The maximum total magnetic induction as a function of the distance from the location of the field generation [10].*

### Maglev systems

The power for the levitation, guidance and propulsion systems is supplied via coils integrated into the guideway, or track. The magnetic induction strongly depends on the location and the arrangement of the magnets and the electromagnetic coils. Again, we consider the German Transrapid and the Japanese Superconducting Maglev train.

### The Transrapid system

The Transrapid maglev system does not rely on rolling motion; instead, it hovers above the guideway. Electronic systems ensure that the magnetic gaps for both the levitation and guidance subsystems remain consistent at a nominal clearance of 10 mm during operation. At speeds above 100 km/h, the levitation system and all onboard electronics are powered by energy recovered from the harmonic oscillations of the magnetic field generated by the track's linear motor. At lower speeds, power is supplied through a physical connection to the track.

In the event of a power failure in the track's propulsion system, the Transrapid vehicle utilizes onboard backup batteries to maintain power to the levitation system, making it independent of the propulsion system. Electronically controlled support magnets, located along both sides of the vehicle, pull it upward toward ferromagnetic stator packs mounted beneath the guideway. Guidance magnets, also situated along both sides of the vehicle, ensure lateral stability and keep the vehicle aligned on the track.

The Transrapid vehicle is capable of hovering for up to one hour without external power. While in motion, onboard batteries are recharged through linear generators integrated into the support magnets. The long-stator linear synchronous motor (LSM) serves dual functions, providing both propulsion and braking. For efficiency and propulsion reasons, the LSM is divided into sections, with typical stator lengths ranging between 500 and 2,000 meters. This design reduces energy losses and optimizes system performance. The system is illustrated in FIG. 4.

The magnetic induction in the neighborhood of the guideway as well as inside the vehicle is considered. The measured values of the induction in the environment of the guideway ist shown in FIG. 14a.

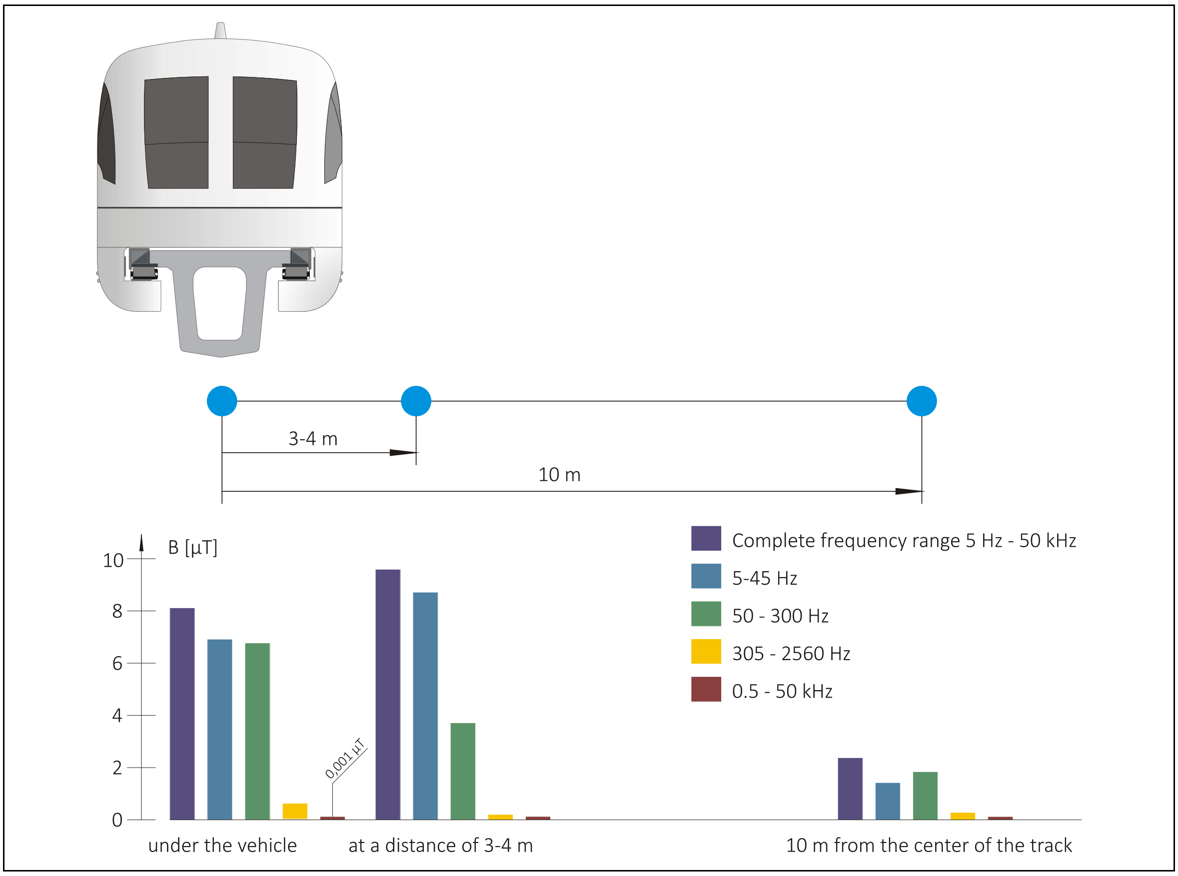


**FIGURE 14a:** *Magnetic induction along the guideway [11].*

The induction values inside the vehicle are shown in FIG. 14b.

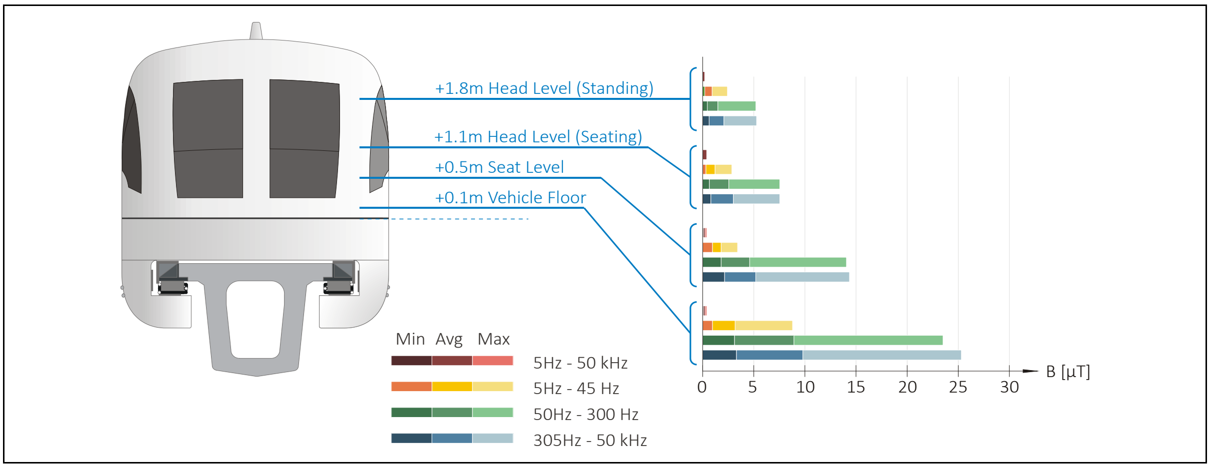


**FIGURE 14b:** *Magnetic induction values inside the vehicle [11].*

Due to the design of the levitation and propulsion system the values measured inside the Transrapid are even below the range of the earth's magnetic field (30-50 T).

**The SC Maglev system**

Regarding the Japanese superconducting maglev system, only limited public information and data are available. The data used in the present comparison are therefore taken mainly from Japanese literature.The levitation and the guidance concept of the superconducting maglev is shown in FIG 15a and FIG 15b, respectively.

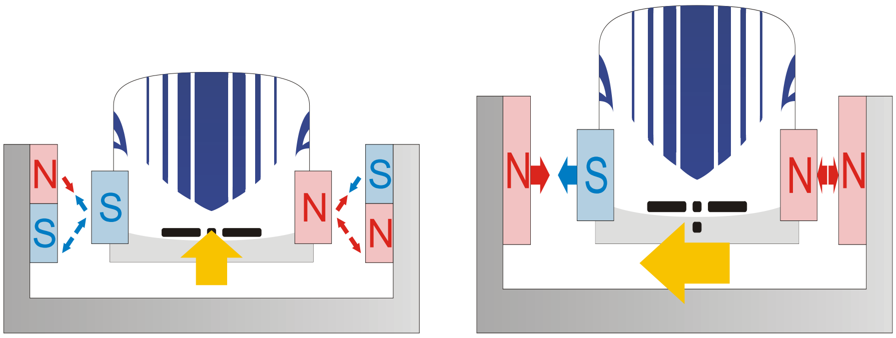


**FIGURE 15:** *Levitation (a) and guidance (b) concept of the SC Maglev [12].*

The measured maximum magnetic induction values inside the Maglev train depending on the location are shown in FIG. 16.

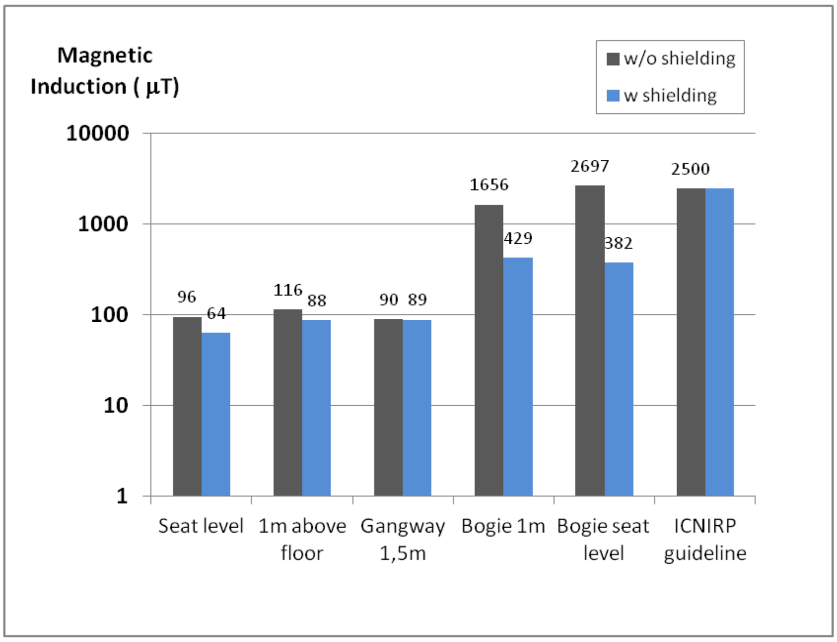


**FIGURE 16:** *Measured maximum induction values inside the SC Maglev train, depending on the location [13].*

The high maximum induction values in the SC Maglev train are due to the arrangement of the strong superconducting magnets in the vehicle, the electromagnetic coils in the guideway and the large gap. The values are at least 2-3 times higher than in the Transrapid system. Effective shielding measures are required to protect the passengers from the electromagnetic fields. A comparison of the maximum induction values of the rail-wheel system ICE and the two maglev systems is shown in FIG. 17.

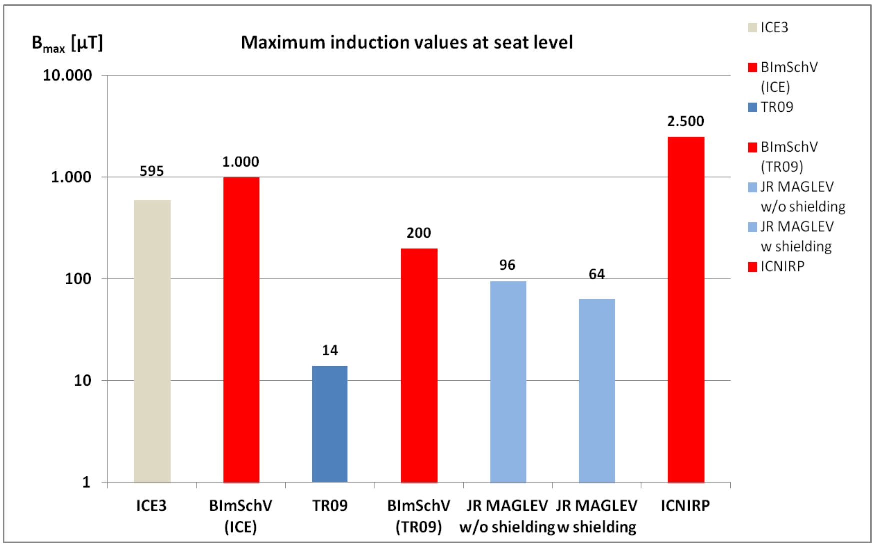


**FIGURE 17:** *Comparison of the maximum induction values inside the vehicle at a passenger's position. The red columns are the corresponding limits of BImSchV and ICNIRP [14]*

### 5.3 Economic evaluation

The main topics for the economic evaluation are

(1) investment for the infrastructure and the vehicles

(2) cost for maintenance and repair

(3) costs for operation

For the cost comparison, the investment for a high-speed maglev system is estimated relative to that of a high-speed ICE railway system. The values used in this comparison are based on data from the LCC report [15].

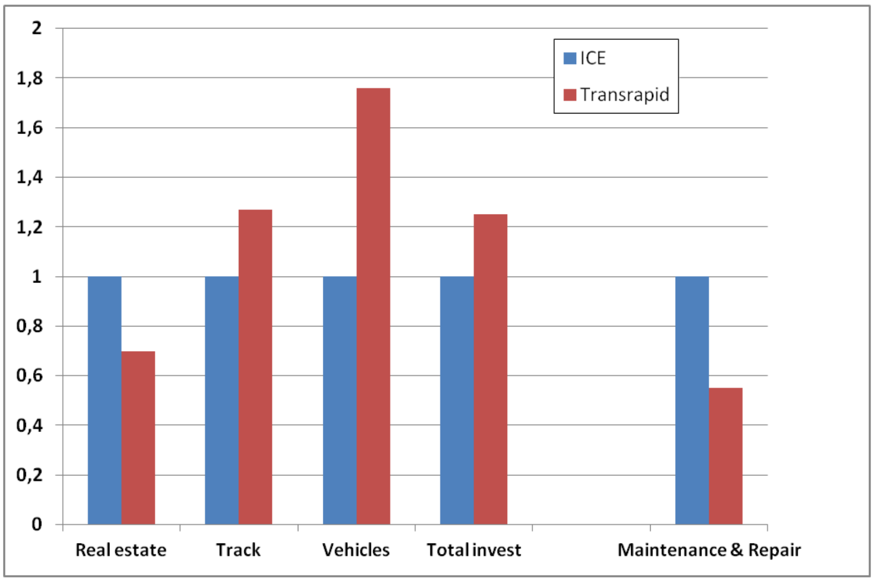


**FIGURE 18:** *Cost comparison of investment, maintenance and repair for the ICE high-speed railway and the Transrapid maglev system [15].*

Figure 18 illustrates the comparison of the infrastructure investment required for the ICE high-speed railway system and the Transrapid maglev system. The maglev system demands approximately 25% higher total investment for infrastructure. However, due to magnetic levitation and the absence of abrasive wear, the maintenance and repair costs for the maglev system are significantly lower. In this comparison, the best-case scenario (lower costs) has been considered for the ICE, while the worst-case scenario (higher costs) has been used for the Transrapid.

Operational costs are a critical factor in determining the long-term economic viability of a transportation system. The long-term economic balance of a public transport system is often more significant in innovation decisions than short-term investment costs. Since publicly available data on operational costs is limited, a qualitative estimation can be derived from a survey conducted among transportation experts.

In the case of urban and regional transportation systems, experts have estimated that the operational costs of maglev systems could be about the same or somewhat lower than those of metro systems and regional trains [16]. For high-speed transportation, operational costs depend on the distance traveled.

### 5.4 Soft criteria

The acceptance of a transportation system by society is shaped by soft criteria that are not directly tied to technical data and specifications. Factors such as the image of a system, which can be influenced by technological innovation, play a crucial role. For the general public, important criteria for choosing a mode of transport include overall travel time, interoperability, comfort, and, most importantly, passenger safety.

Maglev systems, particularly those based on Electromagnetic Suspension (EMS) technology like the Transrapid, are inherently safe by design. Due to the nature of the guideway and guidance system, derailments, such as those that can occur in rail-wheel systems, are effectively eliminated. The safety features of Electrodynamic Suspension (EDS) systems are similar. Nevertheless, emergency protocols, such as evacuation procedures following emergency stops, have been developed and implemented in maglev systems to ensure passenger safety.

High-speed maglev systems operate at speeds ranging from 300 to 600 km/h, surpassing the typical speed range of high-speed railway systems. Their acceleration is also significantly higher, which results in a substantial reduction in travel time compared to rail. Additionally, the levitation technology provides passengers with a comfortable, vibration-free ride. Although maglev systems utilize completely different infrastructure, which may initially appear to limit interoperability with conventional transport modes, this limitation can be mitigated by integrating maglev stations into conventional rail stations in major cities.

At high speeds, maglev trains are competitive with air travel. Maglev stations can be located in city centers, eliminating the need for long commutes to airports typically situated outside urban areas, and reducing the number of necessary transfers. Furthermore, maglev travel does not require the time-consuming check-in process typical of air travel, which offsets the speed advantage of airplanes, thus reducing overall travel time.

## 6. CONCLUSION

The track-bound public transportation sector is predominantly based on railway systems, which were invented nearly 200 years ago. The technical feasibility of magnetic levitation (maglev) technology for transportation has been successfully demonstrated in several projects, including low- and medium-speed passenger transport, as well as high-speed passenger applications. However, despite its innovative nature, maglev technology faces significant opposition due to competition with the well-established railway systems. Key concerns raised against maglev adoption include infrastructure costs, energy consumption, safety, and environmental impact.

This paper compares these two competing technologies—railways and maglev systems—in terms of energy consumption, particulate matter emissions, electromagnetic fields, and costs associated with investment, maintenance, and repair. Additionally, non-technical factors such as passenger comfort and overall travel time are also examined.

The main findings are as follows:

**I.** The investment required for constructing a high-speed maglev guideway depends significantly on the topographical conditions. In regions with relatively undemanding topography, the cost of a maglev guideway is approximately 25% higher than that of a conventional high-speed railway system. In mountainous areas, maglev construction costs can be significantly lower than those for conventional high-speed rail due to the maglev system's superior gradient-handling capability, reducing the need for extensive tunneling.

**II.** Even eventually higher initial investment in maglev systems is offset over time by significantly lower maintenance and repair costs.

**III.** High Speed Maglev trains consume less energy than conventional railway trains at equivalent speeds. Should a railway train operate at typical maglev speeds, not only would its energy consumption increase, but maintenance and repair costs would also rise due to greater wear and tear.

**IV.** In terms of emissions, maglev systems are either entirely free (Electromagnetic Suspension, EMS) or nearly free (Electrodynamic Suspension, EDS) from particulate matter emissions, depending on the specific technology.
In the case of the Transrapid maglev system, electromagnetic induction levels inside the vehicle are well below those in conventional high-speed rail systems. EDS technology, on the other hand, requires appropriate shielding to achieve similar induction levels as the Transrapid.

**V.** Maglev trains offer superior passenger comfort compared to traditional railway trains due to their levitation mechanism. Additionally, their higher speeds and faster acceleration reduce overall travel time, making high-speed maglev systems competitive even with air travel.

## DISCLOSURE OF INTERESTS

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