Jacek F. GIERAS
ORCID: 0000-0002-1934-9048

DOI: 10.15199/48.2025.06.05

Status of maglev ground transportation in the world

Przegląd kolei magnetycznych (maglev) na świecie i opis ich funkcjonowania

***Abstract**. The article focuses on commercial maglev lines in the world. The difference between electromagnetic (EML) and electrodynamic (EDL) levitation has been explained. Classification of maglev systems according to speed has been given. The seven operational maglev lines in the world have been described (Daejon Expo Maglev, Transrapid in Shanghai, Linimo, Incheon Maglev, Changsha Maglev, Beijing S1 Metro, Fenghuang Maglev).At present time there are two more maglev lines under construction: Quingyuan Maglev, Chuo Shinkansen and three functioning maglev test lines: Yamanashi Maglev, General Atomics Maglev and TSB Sengenthal. Birmingham Airport Maglev, Emsland test facility and Maglev Cobra lines have been abandoned. The article is ended with conclusions.*

***Streszczenie.** Artykuł opisuje komercyjne koleje magnetyczne (maglev) na świecie. Wyjaśniono różnicę między lewitacją elektromagnetyczną (EML) a elektrodynamiczną (EDL). Podano klasyfikację systemów maglev wg prędkości. Opisano siedem działających linii maglev na świecie (Daejon Expo Maglev, Transrapid w Szanghaju, Linimo, Incheon Maglev, Changsha Maglev, Beijing S1 Metro, Fenghuang Maglev). Obecnie w budowie są dwie kolejne linie maglev: Quingyuan Maglev, Chuo Shinkansen oraz prowadzone są badania na trzech liniach eksperymentalnych maglev: Yamanashi Maglev, General Atomics Maglev, TSB Sengenthal. Birmingham Airport Maglev, Emsland test facility oraz Maglev Cobra zostały zlikwidowane. Artykuł kończy się wnioskami.*

Keywords: magnetic levitation, ground transportation, commercial maglev lines
Słowa kluczowe: lewitacja magnetyczna, transport naziemny, linie komercyjne maglev

Introduction

Levitation (from Latin levitas-atis = lightness) refers to raising an object against the force of gravity in such a way that it remains suspended without any physical contact. This concept was known in occultism as the supernatural belief of being able to rise any object and hold it in mid-air by the use of spiritual energy. In physics and engineering levitation can be achieved with the aid of electromagnetic field. There are two types of magnetic levitation [1]:

1) Electromagnetic levitation (EML) – attraction forces between electromagnet with controlled air gap and ferromagnetic plate (guide rail);
2) Electrodynamic levitation (EDL) – repulsive forces between currents induced in nonferromagnetic conductive body and source field (AC electromagnet).

In the case of EML electromagnets with controlled air gap operating in closed control loop are used (Fig. 1).

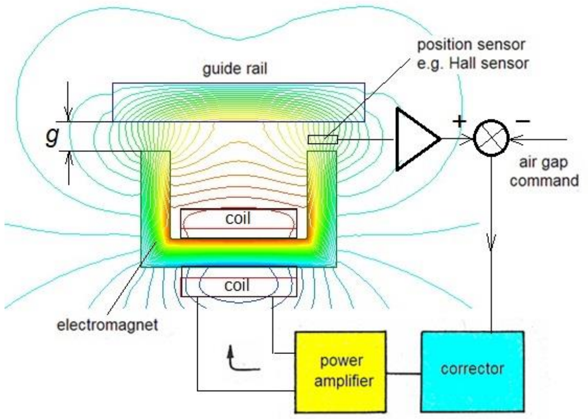

Fig. 1. Principle of electromagnetic levitation (EML). Author's simulation using the FEM

In the case of EDL classical or superconducting (SC) electromagnets induce currents in nonferromagnetic conductive plates or shorted windings. Electromagnetic field generated by secondary induced currents and primary field of electromagnets produce repulsive forces (Fig. 2).

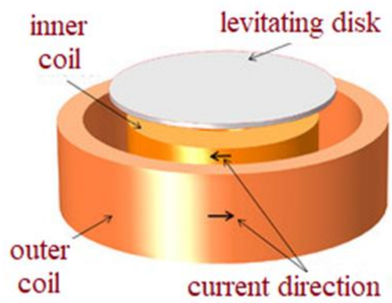

Fig. 2. Electrodynamic levitation (EDL) of a nonferromagnetic conducting disk using AC coils

The term EDL also includes quantum levitation (superconductivity is a quantum phenomenon), i.e., levitation of rare-earth permanent magnet (PM) on a superconductor (Fig. 3). The magnetic field is expelled from a high temperature superconductor (HTS) during its transition to the superconducting state due to internal currents (Meissner–Ochsenfeld effect).

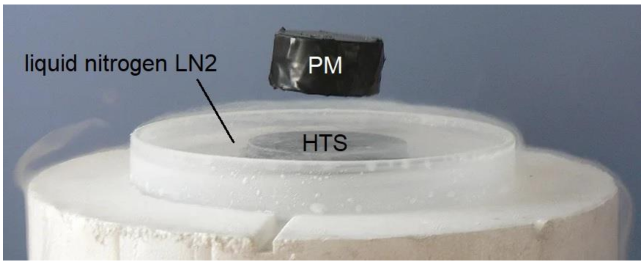

Fig. 3. Quantum levitation of a permanent magnet (PM) on a high temperature superconductor (HTS). Public domain photo

Classification of maglev systems according to speed

So far, magnetic levitation is mainly used in ground transportation. According to speed, ground transportation maglev systems can be classified into three categories:

(a) Low speed maglev trains – up to 120 km/h (Daejeon Expo Maglev, Linimo, Incheon Airport Maglev, Changsha Maglev, Beijing S1 Maglev, Fenghuang Maglev or Phoenix Maglev) [2];

(b) Medium speed maglev trains – around 180 km/h (Transport System Bögl or TSB)
(c) High speed maglev trains – over 400 km/h (Transrapid in Shanghai, Yamanashi Maglev Test Line near Tokyo)

The low and medium speed maglev systems operate on the principle of EML (Fig. 4). The C-shaped steel guiderails are placed on each side of the track and serve as armatures of the electromagnets. The electromagnets are fixed to undercarriage brackets at each side of the vehicle. Salient poles of the electromagnets and C-shaped guiderails provide lateral stabilization. The primary units of single-sided linear induction motors (LIMs) are fixed to undercarriage brackets of the vehicle. The aluminum plate is mounted on the top of the steel guiderail (armature of the electromagnet) thus forming the secondary of LIMs.

This technology is based on an earlier generation of *Transrapid* version, the TR04, and the original technology was purchased from *Transrapid* in 1974 by Japan Air Lines.

The drawback of this system is speed limited to about 180 k/h. As the speed increases, the eddy-currents induced in poles of the guiderail reduce the attraction force between electromagnets and guiderails [3]. It requires increase in the current of electromagnets (Fig. 5).

Second drawback is attraction force between reaction rail and primary unit of LIMs which is in opposite direction to the attraction force of electromagnets.

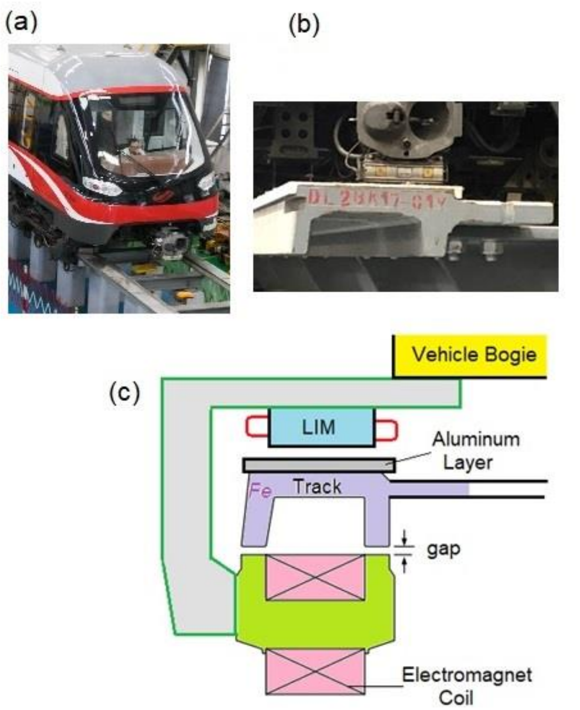

Fig. 4. Low and medium speed magnetic levitation system: (a) vehicle and elevated track; (b) guiderail installed in the track; (c) levitation and propulsion system with electromagnet and single-sided LIM. Photos taken by the author.

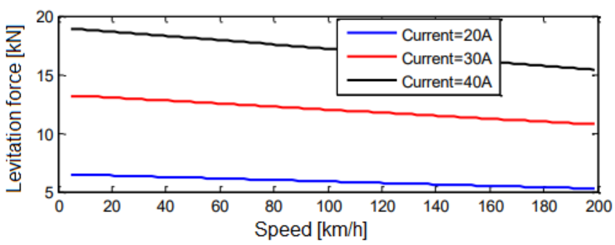

Fig. 5. Influence of speed on levitation force in EML systems [3]

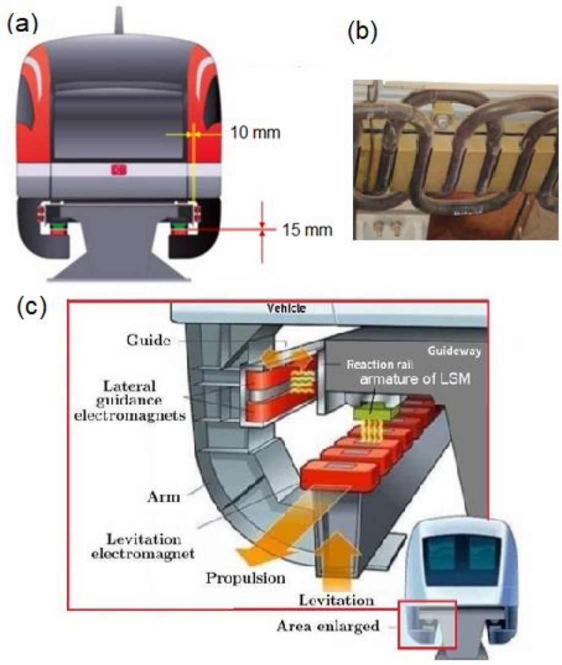

Fig. 6. High speed magnetic levitation system: (a) vehicle and elevated track; (b) track with primary unit of LSM; c) principle of operation [4]

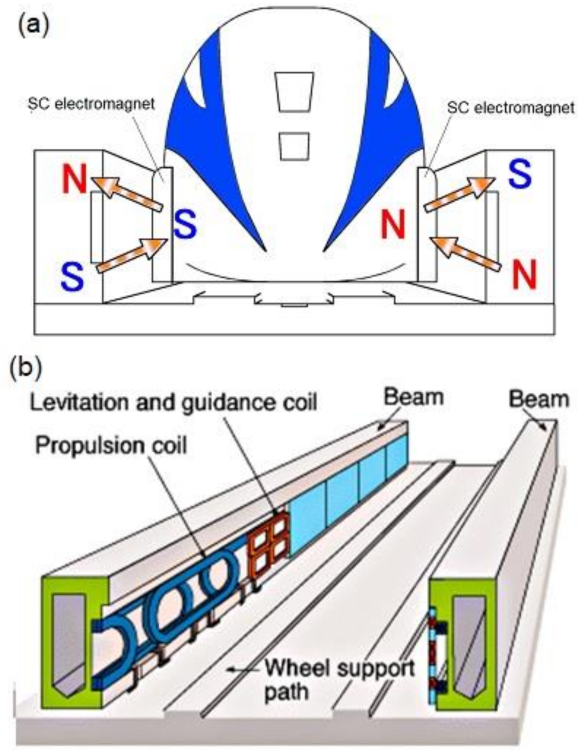

Fig. 7. High speed magnetic levitation system used at Yamanashi Maglev Test Line: (a) vehicle with SC electromagnets; (b) track with primary windings of LSM and levitation and guidance coils [5].

High-speed magnetic levitation systems are shown in Figs 6 and 7. Fig. 6 shows *Transrapid* EML system [4] with linear synchronous motors (LSMs). The long primary units of LSM with laminated core and three-phase windings made of aluminum cable are located at both side of the track. The vehicle-mounted electromagnets below primary units provide both levitation forces and field excitation for LSMs. Another system of electromagnets at each side of the vehicle provides lateral stabilization of the vehicle. The air gap between levitation electromagnet cores and LSM cores is 15 mm, while the air gap between lateral stabilization electromagnets and track-mounted rail is 10 mm.

Different high-speed EDL levitation system with superconducting (SC) electromagnets mounted on both sides of the vehicle is shown in Fig, 7. This system is implemented in Yamanashi Maglev Test Line, Yamanashi Prefecture near Tokyo, Japan [5]. SC electromagnets provide both field excitation for LSM and EDL force. There are two types of coils in the side beams of the track: three-phase coreless winding forming the long primary unit of LSMs and shorted coils (null-flux coils), which provide levitation and guidance. The air gap between side beams and SC electromagnets at each side of the vehicle is about 150 mm. Climate of Japan requires large air gap.

The seven operational maglev lines in the world

The seven operational maglev lines in the world are briefly characterized in Table 1 [2].

Table 1. Maglev lines in the world operating so far.

Commercial Maglev Train	Location	Running since	Top speed	Track length
Daejeon Expo Maglev	South Korea	1993	100 km/h	1 km
Shanghai Maglev Train	China	2004	431 km/h	30.5 km
Linimo	Japan	2005	100 km/h	8.9 km
Incheon Airport Maglev	South Korea	2016	110 km/h	6.1 km
Changsha Maglev Express	China	2016	100 km/h	18.55 km
Beijing S1 Line	China	2017	110 km/h	8.25 km
Fenghuang Maglev	China	2022	100 km/h	9.12 km

A. Daejon Expo Maglev

Korea Institute of Materials and Machinery (KIMM), Daejeon and Hyundai built a 1 km (0.62 miles) maglev track for the Daejeon Expo in 1993 to demonstrate the electromagnetic suspension to the public [2]. The maglev train runs today on a short track between the Expo Park and the National Science Museum with top speed of 100 km/h (Fig. 8). The Expo Park today attracts over one million visitors annually. The further developed prototype of the HML-series maglev trains, called the UTM-series, are now being used at the Incheon Airport.

Levitation: electromagnet with controlled air gap about 8 mm (Fig. 4). *Propulsion*: single-sided LIM. *Lateral stabilization*: No active control of lateral position is necessary because of double saliency (electromagnet and guiderail).

Fig. 8. Daejeon Expo Maglev. Public domain photo.

B. Transrapid in Shanghai

Pudong International Airport is connected with Longyang Road station in Shanghai with *Transrapid* high-speed maglev line (Fig. 9) [1,4]. This maglev line became instantly famous when introduced in April 2004, as it was the first in the world high-speed maglev line open to public. The most important specifications are:

- It cost US$1.2 billion to build;
- It covers a distance of 30.5 kilometres (19 miles) in 7 min and 26 s;
- Acceleration: 350 km in 2 min;
- It reaches 431 km/h (268 mph) top speed during the ride
- The average section length of each LSM primary winding along the track is about 1.2 km. The maximum current of LSM is 1200 A;
- There are 115 trains per day in both directions.

Levitation: Field excitation system of LSM, i.e., electromagnet with controlled air gap (Figs 6 and 10). Mechanical clearance between vehicle and track is always 10 mm. *Propulsion:* Single-sided LSM. *Lateral stabilization*: Lateral guidance electromagnets with controlled air gap (Fig.10).

Fig. 6 explains the principle of operation. The power supply system consists of two 110 kV substations, one in Longyang Road and one in Pudong Airport. Both 110 kV substations use 110 kV/20 kV-step-down transformers and two 20 kV/1.2 kV rectifier transformers. There are currently three different types of solid-state water-cooled PWM converters (4 kA GTOs) available in order to adapt the converters' output to the vehicle acceleration and velocity demands: (a) high power converter 15.6 MVA; (b) medium power converter 7.5 MVA; (c) low power converter 1,2 MVA in the maintenance area.

The three-phase inverter output voltage is from 0 to 2027 V and frequency from 0 to 300 Hz. The speed of the train is controlled by changing the input frequency of LSMs. At higher frequencies the output transformers (behind inverters) can increase the voltage to maximum 7800 V.

Fig. 9. Transrapid in Shanghai. Photo taken by the author.

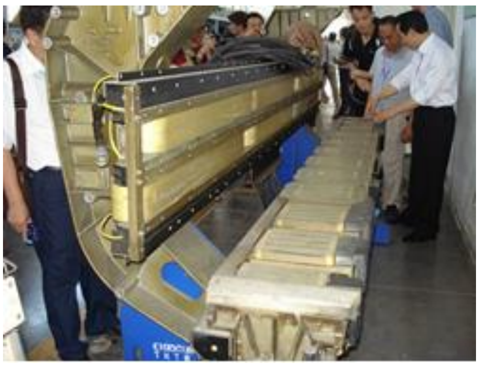

Fig. 10. Support and stabilizing electromagnets. Photo taken by the author.

The power supply of every train section is composed of 4 electrically isolated battery-buffered 440 V circuits. Each circuit is supplied by autonomous 5-phase linear transformer called linear generator. The secondary windings of linear transformers are placed in pole shoes of support electromagnets, The on board power is 400 kW. Most power is consumed by electromagnets, Boost converters adopt frequencies and voltages as the speed fluctuates.

Support electromagnets (36 kAturn) shown in Fig. 10 are fed from two-quadrant transistor choppers of 48 kW maximum power and a sampling frequency of 100 kHz.

At 431 km/h maximum speed and travel time 7 min 26 s the train consumes 1600 kWh electrical energy.

C. Linimo Maglev, Japan

Linimo is Japan's first commercial maglev line. It was built to serve the Expo 2005 fair site. It is now operating on the Aichi High-Speed Transit Tobu Kyuryo Line, Aichi Prefecture, near the city of Nagoya, serving 9 stations (Fig. 11) [2]. While Japan is on track to have the first long distance ultra-high speed maglev (Chuo Shinkansen), the *Linimo* has historical importance: it was the world's first unmanned commercial urban maglev.

Fig. 11. Linimo maglev line near the city of Nagoya, Japan. Public domain photo.

The *Linimo* runs on 8.9 km track. The minimum operating radius is 75 m and maximum gradient of 6%. The top speed is 100 km/h (62 mph). It transports 16,500 passengers per day.

Levitation: electromagnet with controlled airgap (Fig. 4). The nominal levitation air gap is 8 mm. *Propulsion*: single-sided LIMs. The mechanical clearance between primary and secondary of the LIM is 11 mm. *Lateral stabilization*: No active control of lateral position is required.

D. Incheon Airport Maglev Line (IAML), South-Korea

The Incheon Airport Maglev is an unmanned commercial maglev train offering a free ride between Incheon International Airport and Yongyu Station (Fig. 12). It runs on a 6.1 km (3.8 miles) track every 15 minutes between 9 am and 6 pm with six stations and a 110 km/h (68 mph) operating speed []6].

Levitation: electromagnet with controlled airgap g = 8 mm (Fig. 4). *Propulsion*: single-sided LSM. *Lateral stabilization*: No active control of lateral position is required.

Fig. 12. Incheon Airport Maglev. Public domain photo.

The IAML is a completely passive system with attraction electromagnets and primary units of the single-sided LIMs installed in vehicles, while reaction rails (guiderails) for electromagnets and LIMs are installed in the track.

Levitation: electromagnet with controlled airgap (Fig. 4). The nominal air gap between the electromagnets poles and steel reaction rail is 8 mm. *Propulsion*: single-sided vehicle-mounted LIMs. *Lateral stabilization*: No active control of lateral position is required.

The IAML is electrified at 1500 V DC. The electric power is fed to the vehicle with the aid of two contact rails mounted at each side of the concrete elevation. There are two sliding contacts per vehicle.

The construction cost of 1 km of double-track line was US$ 37.8 million in 2009, i.e., 9.5% less than the construction of 1 km of traditional light railway. The author does not agree with this statement.

E. Changsha Maglev Express Line

The Changsha Maglev Express Line was opened in 2016 and connects Changsha South Railway Station with Changsha Huanghua International Airport (Fig. 13) [7]. It is the first Chinese developed and built maglev train. Operating speed is 100 km/h (62 mph). The Changsha Maglev operates on a 18.55 km (11.53 miles) long line connecting 3 stations between 7 am and 9 pm running every 15 min. The travel time is 19 min 30 s.

Fig. 13. Changsha Maglev train. Photo taken by the author.

Fig. 14. Changsha Maglev train depot. Guiderail with aluminum plate at the top and two contact rails. Photo taken by the author.

Levitation: electromagnet with controlled airgap g = 8 mm (Fig. 4). *Propulsion*: single-sided LIMs. *Lateral stabilization*: No active control of lateral position is required.

Two contact rails provide electric power to the vehicle. The attractive force of single suspension electromagnet is up to 33 kN. The average current of electromagnet is 28.21 A. There are 10 LIMs per car. The maximum thrust of a LIM is 3.3 kN. The nominal current of a LIM is 340 A. There is stable slip frequency control.

F. Beijing S1 Metro Line

Beijing S1 Metro Maglev Line is the China's third commercial maglev train in operation. It was opened at the very end of 2017, and it now joins Beijing's extensive subway network (Fig. 15) [2]. The S1 rapid transit line has seven stops, runs on a 8.25 km (5.13 miles) long track at 110 km/h (68 mph) speed.

The construction of suspension electromagnets and LIMs is similar to Changsha Maglev Express Line.

Fig. 15. Beijing S1 Metro Maglev train. Public domain photo.

G. Fenghuang Maglev Sightseeing Express

Fenghuang ancient town is located in Xiangxi Tujia and Miao Autonomous Prefecture, Hunan Province, Central China [8]. Fenghuang Maglev (Phoenix Maglev) is a low speed maglev transit line (Fig. 16). The line can operate at speeds up to 100 km/h. Its first phase 9,15 km long with 4 stations was put into the test operation in May 2022.

The suspension electromagnets and LIMs are similar to those of Changsha Maglev Express Line.

This line predominantly is used as a link connecting the high-speed railway station with the ancient town and nearby scenic areas.

The line was built by China Railway Engineering Corp for Hunan Maglev Group Corp in two years at a cost of 237 billion RMB.(about 350 million US dollars).

Fig. 16. Fenghuang Maglev Sightseeing Express train. Public domain photo.

Maglev Lines Under Construction

A. Qingyuan Maglev

Qinguyan Maglev is under construction in Guangdong Province, China [9]. This is a tourist line, 8.1 km (first phase), total length 38 km, 3 stations, top speed 120 km/h.

Fig. 17. Qingyuan Maglev, Guangdong Province, China. Public domain photo.

The first phase 8.1 km will connect the Yinzhan railway station on Guangzhou–Qingyuan intercity railway with the Qingyuan Chimelong Theme Park.

Levitation: electromagnet with controlled airgap (Fig. 4).. *Propulsion*: single-sided LIMs. *Lateral stabilization*: No active control of lateral position is necessary..

B. Tokyo-Nagoya Chuo Shinkansen. Japan,

The Chuo Shinkansen (Fig. 18) is a Japanese maglev line under construction between Tokyo and Nagoya, with plans for extension to Osaka [10]. Its initial section is between Shinagawa Station in Tokyo and Nagoya Station in Nagoya, with stations in Sagamihara, Kōfu, Lida City and Nakatsugawa. The travel time from Tokyo to Nagoya is expected to be 40 min, and from Tokyo to Osaka about 67 min. The maximum speed is predicted 505 km/h (314 mph). About 90% of the 286-kilometer (178 miles) line to Nagoya will be tunnels [10].

Fig. 18. Chuo Shinkansen maglev train on a test run in Yamanashi Prefecture. Public domain photo.

Electrification of the Chuo Shinkansen line is designed at 33 kV AC, 50 Hz. The line probably will be opened in

2034 or later. The estimated cost to be over 9 trillion yen (approximately 80 billion USD).

The SC maglev project is not just a transportation initiative; it is also seen as a strategic investment in Japan's future. By drastically reducing travel times between major cities, the Maglev line is expected to spur economic growth, enhance regional connectivity, and reduce carbon emissions by offering a faster and more efficient alternative to air and road travel.

Maglev Test Lines

A. Yamanashi Maglev Test Line

The Yamanashi Maglev Test Line (Yamanashi Prefecture, west from Tokyo) is a part of the future Chuo Shinkansen line between Tokyo and Osaka (Fig. 19) [5,11]. It is a joint project of the Central Japan Railway Company (JR Central), Railway Technical Research Insitute (RTRI) and Japan Railway Construction Public Corporation, which was approved by the Ministry of Transport in 1990. Construction has started with an 18.4 km Katsunuma-budokyo–Ohtsuki priority section. Then, the test line was extended to 42.8 km between Sakaigawa village, Higashi–Yatsushiro district, and Akiyama village, Minami–Tsuru district. The maximum planned speed is 550 km/h (operation speed 500 km/h), minimum curve radius is 8 km, maximum gradient is 4%, and distance between the centers of adjacent parallel guideways is 5.8 m. A 12.8 km section is a double-track line where the dynamics of two trains passing each other at a relative speed of about 1000 km/h will be studied. Other specifications are given in Table 2.

Fig. 19. Yamanashi Maglev Test Line: Ogatayama Bridge over the Chuo Expressway. Public domain photo.

Table 2. Yamanashi Maglev Test Line: data specifications [1].

Specifications	Total	Priority section
Length, km	42.8	18.4 (12.8 km double track)
Length of tunnel section, km	34.6	16.0
Elevated section, km	8.2	2.4
Curve radius, km	8 to 20	
Maximum gradient	4%	
Number of control centers	1	1
Number of substations	2	1
Number of train depots	1	1

Levitation, propulsion and lateral stabilization is explained in Fig. 7. The arrangement of ground and vehicle windings is shown in Fig. 20. Both propulsion coils and levitation–guidance coils are attached to the concrete side walls of the guideway (Fig. 7). All ground coils are made of aluminum conductors insulated with polyester (epoxy) resin. Propulsion coils have dimensions approximately 1.42 × 0.6 m. The 8-shaped levitation and guidance coils (null flux) have dimensions approximately 0.9 × 0.9 m and are attached to the surface of the three-phase two-layer propulsion winding. The levitation and guidance coils consist of two sections: for levitation and for lateral stabilization (guidance) of the vehicle (Fig. 7). The guidance sections facing each other at two opposite sides are electrically connected under the track, constituting a null-flux connection. If the train deviates from the center of the guideway, the deviation is reversed by the attractive forces of the SC electromagnet on the distant side of the guideway and repulsive forces on the opposite (near) side. To save energy, a group of propulsion coils are connected in series and create a winding section. Only those sections carrying the train are powered through the feeding section switchgears [11].

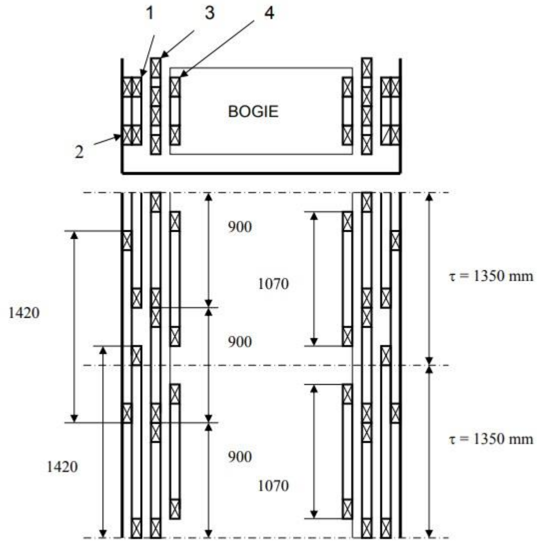

Fig. 20. Arrangement of propulsion, levitation-guidance and field excitation coils: 1 — propulsion, front side, 2 — propulsion, reverse side, 3 — 8-shaped levitation and guidance coils, 4 — field excitation coil (on-board SC electromagnet) [1].

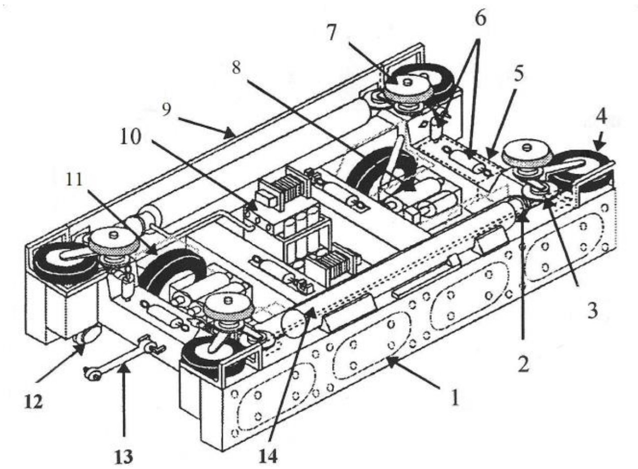

Fig. 21. Bogie of Yamanashi Maglev Test Line Vehicle: 1 — SC magnet, 2 — helium refrigerator, 3 — guiding stopper wheel, 4 — guiding gear, 5 — oil reservoir tank, 6 — dampers, 7 — air spring, 8 — hydraulic pressure unit, 9 — side cover, 10 — helium compressor, 11 — landing gear wheel, 12 — emergency landing wheel, 13 — longitudinal anchor (to car body), 14 — liquid helium and nitrogen tanks [1].

The bogie, on which the SC electromagnets are mounted, serves to transmit the propulsion and levitation forces to the vehicles (Fig. 21). A refrigeration system for freezing the helium is also mounted on the bogie. To improve traveling comfort, pneumatic springs for car body suspension and vibration control devices are incorporated in some bogies. The bogie is fitted with landing and guide gear wheels that are necessary when traveling at low speeds. Side guide gear wheels of smaller diameter than landing gear wheels secure the train to follow the track center at low speeds. Hydraulic apparatus are used for raising and lowering these wheels.

Landing gears have been developed taking durability and mass reduction into consideration. Disk brakes and rubber tires are now capable of use at speeds over 500 km/h.

One leaky coaxial cable (LCX) per track has been installed for the train radio communication system. The train radio system uses millimeter waves from 30 to 300 GHz.

In 2005 two vehicles MLX01 with 3 cars achieved passing speed of 1026 km/h (575 + 451). The speed record of 603 km/h on the Yamanashi Maglev Test Line was achieved in 2015 (manned vehicle) [1,11].

B. General Atomics Maglev, San Diego, CA, USA

A 120 m maglev track for testing an urban maglev vehicle was built by General Atomics in 2004 in San Diego (Sorrento Valley), CA, USA [12]. The test vehicle (Fig. 22) consists of a single 5-m long chassis unit (Fig. 22) [1].

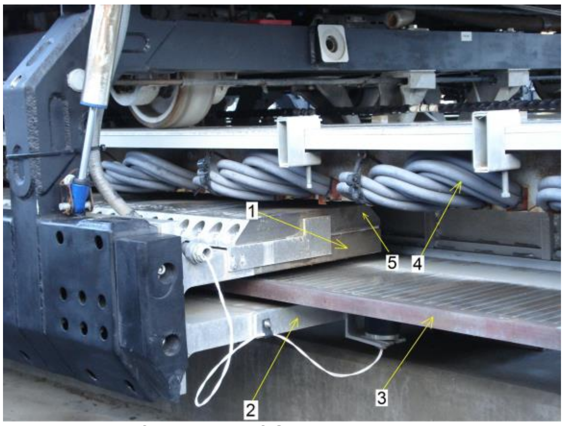

Fig. 22. Principle of operation of General Atomics' maglev vehicle. 1 — upper Mallinson-Halbach array levitation PMs, 2 — lower Mallinson-Halbach array levitation PMs, 3 — Litz wire guideway, 4 — LSM armature winding, 5 — propulsion PMs. Photo taken by the author.

An EDL system with a flat PM LSM is used for levitation and propulsion. NdFeB PMs arranged into a Mallinson-Halbach array [13,14] are mounted on the vehicle (Fig. 23). Coreless levitation coils are installed in the guideway between the upper and lower Mallinson-Halbach arrays. When the vehicle moves, currents induced in shorted levitation coils interact with PMs to produce suspension forces. The nominal air gap between PMs and levitation coil guideway is 25 mm [1.12].

Upper levitation PMs and currents induced in short-circuited coils installed in the guideway produce attraction forces, while lower levitation PMs and currents induced in coils produce repulsive forces (inductrack system). As long as the vehicle keeps moving, these forces keep it airborne. When the vehicle slows down or comes to a stop, it settles back down onto its wheels, which are permanently deployed. The thrust is provided by propulsion PMs (on the vehicle) that interact with the armature winding of a long laminated core LSM embedded in the guideway. Owing to large air gap, an LSM is fundamentally better suited to the needs of an EDS suspension system than an LIM. The LSM three-phase armature winding is simply made of copper cables. Levitation and propulsion components are shown in Fig. 23.

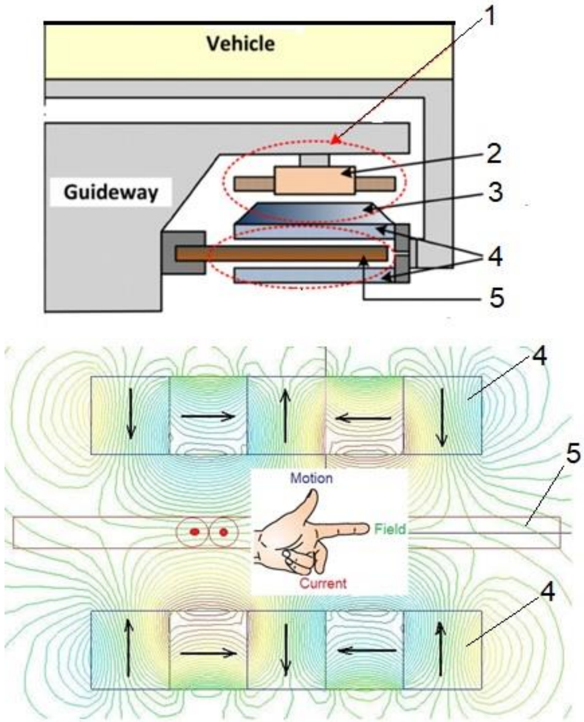

Fig. 23. Principle of operation of General Atomics' maglev vehicle. 1 – PM LSM, 2 – primary of LSM, 3 – propulsion PMs, 4 – levitation PMs (Mallinson-Halbach array), 5 – Litz wire guideway. Author's simulation using the FEM.

C. *Transport System Bögl, Sengenthal, Germany*

The Transport System Bögl (TSB) is EML system with electromagnets integrated with the vehicle and rails installed in the track [15]. This allows the vehicle to maintain a constant air gap of 7 mm between an electromagnet and guiderail. The steel guiderail serves both as electromagnet's armature and steel reaction rail for the LIM (Fig. 24). The guiderail above the primary core of the LIM is covered with aluminum plate to reduce its impedance and increase the trust. To keep the air gap as precise as possible, the TSB relies on an intelligent control system that processes real-time data from gap sensors and readjusts the electromagnetic levitation system in real time.

For propulsion, the TSB uses a short primary LIM mounted on the vehicle. The propulsion and levitation systems, in comparison with those used in China, Japan and Korea, are improved since the normal attraction force produced by the LIM is added to, not subtracted from the levitation force (Fig. 24).

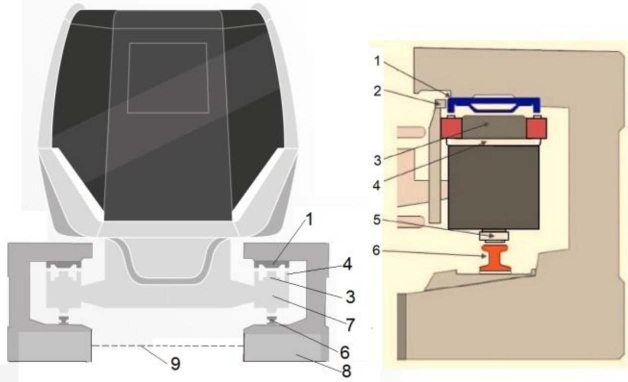

Fig. 24. Levitation, propulsion and lateral stabilization systems of TSB maglev vehicle. 1 – reaction rail, 2 – mechanical lateral stabilization, 3 – primary of LIM, 4 – levitation electromagnet, 5 – support skid and electric contact, 6 – current/slide rail, 7 – housing, 8 – guideway girder, 9 – emergency walkway [15].

The contact rails are installed on the floor of the guideway girder on both sides and also serve as sliding rails on which the vehicle settles when the levitation system is turned off.

Fig. 25. TSB maglev, Sengenthal, Northern Bavaria, Germany. Public domain photo.

Basic characteristics of the TSB system (Fig. 24) are as follows [16]:

- automatic driverless passenger transport system with short stator single-sided LIM;
- electromagnetic levitation system with combined carrying and guiding function;
- vehicle made up of two to six powered sections;
- up to 127 persons per vehicle sections;
- vehicle dimensions: section length 12 m, width 2.85 m, unloaded weight 18 t, payload 9.5 t;
- cruising speed of up to 150 km/h;
- acceleration 1.0 m/s², deceleration 1.0 m/s², maximum gradient 10%, minimum curve radius 45 m
- side passenger entry, front and rear emergency exit

The TSM maglev was built in 2012 by Max Bögl in Sengenthal, Northern Bavaria, Germany.

Abandoned Maglev lines and test facilities

A. Birmingham Airport Maglev, UK

The Birmingham Airport Maglev shuttle (Fig. 26) was opened in 1984. It was the world's first commercial low-speed maglev line [16]. E-shaped levitation electromagnets are located on both sides of vehicle. Every second electromagnet there is a distance *d* (Fig. 27) necessary to obtain lateral stabilization of the vehicle. The air gap between electromagnet pole and guiderail is 15 mm. The long secondary (reaction rail) of LIMs is placed in the middle of the track. Short primary LIMs are mounted underneath of the vehicle.

Fig. 26. Birmingham Airport Maglev. Public domain photo.

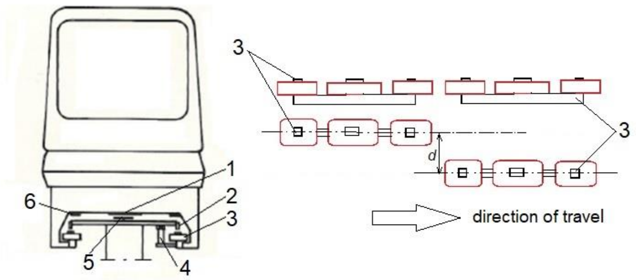

Fig. 27. Levitation propulsion and lateral stabilization of Birmingham Airport Maglev. 1 – short primary LIM, 2- suspension guiderail, 3 – E-core electromagnet, 4 – current collectors, 5 – track mounted long reaction rail for LIM, 6 – skid. The distance *d* between electromagnets is necessary for lateral stabilization.

The length of the track was 623 m and speed up to 54 km/h [16]. The line operated successfully for nearly eleven years, but obsolescence problems with the electronic systems, and a lack of spare parts, made it unreliable in its later years. The system closed in July 1995.

After closure, the original guideway lay dormant and a temporary shuttle bus service was operated until development of a suitable replacement was found. The guideway was reused in 2003 when the replacement cable-hauled SkyRail people mover was opened.

B. Emsland test facility, Germany

Emsland *Transrapid* test facility (TVE), construction work started in 1979 in Lower Saxony, Germany (Fig. 28). In 1984, the first 21.5 km section (North Loop) was opened. Transrapid 06 vehicle achieved the speed of 302 km/h. The test line was completed in 1987 (South Loop). About 20 km of TVE was erected as an elevated concrete guideway, about 5 km as an elevated steel guideway, and the rest as a ground guideway. The total length of test line including two loops is 31.5 km. In 1993 *Transrapid* 07 achieved the speed of 450 km/h [4].

Since 1995 until 2006 *Transrapids* 07 and 08 were available for passengers, and regularly ran at up to 420 km/h. In 2006 *Transrapid* 08 collided with maintenance vehicle at 170 km/h on elevated track in Lathen. The accident was caused by human error. There were 23 fatalities and 10 severe injuries.

Fig. 28. Transrapid 08 at Emsland test line. Public domain photo.

At the end of 2011, the operation license expired and the test track was closed. In early 2012, the demolition and reconversion of all the Emsland site, including the tracks and factory, was approved. Demolition work began around 2016, largely focused on stripping out the electrical equipment.

C Maglev Cobra, Rio de Janeiro, Brazil

The Maglev-Cobra project (2014-2020) developed at the Federal University of Rio de Janeiro (UFRJ), Brazil, is an urban maglev of maximum speed 100 km/h. The Cobra proposes a maglev with HTS and rare-earth PMs for the levitation and guidance [17].. A vehicle is made of short modules, 1.5 m long each one. Once the modules are connected, the vehicle resembles a snake, or “cobra” in Portuguese, and can follow curves with just 30 m of radius. Each module offers space for 8 passengers and maximum load of 800 kg.

Fig. 29. Maglev Cobra at UFRJ campus. Public domain photo.

Repulsive forces between bulk HTS (YBCO) refrigerated with LN2 (vehicle) and NDFeB PM guideway (track) are used for levitation (Meissner–Ochsenfeld effect – Fig. 3). Single-sided LIMs in the middle of the vehicle and track provide propulsion. Since the track mounted cage secondary of the LIM is above the vehicle mounted short primary (Fig. 30), the attraction force of LIMs supports the levitation force [17]. No active control of lateral position is needed.

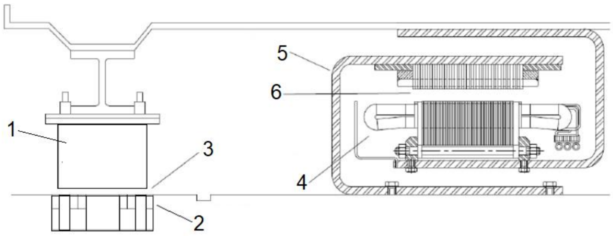

Fig. 30. Cross section of one side of the vehicle undercarriage showing the levitation system (cryostat and PM guideway) and the single-sided LIM. 1 – cryostat, 2 – PM guideway, 3 – levitation gap, 4 – short primary of LIM, 5 – long cage secondary of LIM, 6 – LIM air gap [17].

Conclusions

1. The term “*levitation*” comes from Latin word “*levitas, -atis*”, which means “*lightness*”
2. There are two types of magnetic levitation: electromagnetic levitation (EML) and electrodynamic levitation (EDL).
3. In EML levitation attraction forces between electromagnet and ferromagnetic rail are utilized. The air gap must be controlled.
4. In EDL levitation repulsion forces between currents in electric coils or in an electric coil and non-ferromagnetic plate are utilized.
5. The attraction force in ELM depends on magnetic saturation, in particular, for small air gaps, less than 2 mm. The greater the air gap, the less sensitive the attraction force to the magnetic saturation.
6. The idea of application of magnetic levitation to transportation systems was born in the 1960s of the last century, when the speed of wheel-on-rail trains was maximum 250 km/h.
7. It is claimed that EML levitation vehicles use less energy per passenger per kilometer and generate less acoustic noise than conventional wheel-on-rail high-speed trains. However, from economic point of view, traditional wheel-on-rail trains require less investment and maintenance costs.
8. Linear electric motors in application to traction system consume more electrical energy than their rotary counterparts.
9. EDL vehicles, e.g., Yamanashi Maglev Test Line can operate with greater air gap (about 10 times greater) than ELM vehicles, e.g., *Transrapid*.
10. Yamanashi Maglev vehicles are equipped with landing and guide gear wheels while *Transrapid* and all low-speed maglev vehicles do not have any wheels.
11. There were seven operational maglev lines in 2024. Two lines are now under construction. There are 3 test lines and 3 abandoned lines.
12. Nowadays, wheel-on-rail trains can achieve similar speeds as maglev trains. Speed record for TGV (wheel-on-rail) is 574.8 km/h (2007) and speed record for Yamanashi Maglev Test Line (EDL) is 603 km/h (2015).

Authors*: prof. dr hab. inż. Jacek F. Gieras, IEEE Life Fellow, Politechnika Bydgoska, Zaklad Elektroenergetyki Maszyn i Napedow Elektrycznych, Al.. S. Kaliskiego 7, 85-796 Bydgoszcz, E-mail: jgieras@ieee.org*

REFERENCES

[1] Gieras, J.F., Piech Z. J., Tomczuk B.Z., Linear synchronous motors: transportation and automation systems, 2nd edition, *CRC Press, Taylor and Francis Groups*, Boca Raton – London – New York, 2012.
[2] The six operational maglev lines in 2021, maglev.net, Febr. 16, 2018, https://www.maglev.net/six-operational-maglev-lines-in-2018
[3] Guanchun Li, Zhen Jia, Guang He and Jie Li, Analysis of eddy current induced in track on medium-low speed maglev train, *IOP Conf. Ser.: Earth Environ. Sci.* 69, 2017, 1-9.
[4] *Transrapid Maglev System*, edited by Heinrich K and Kretzschmar R., Hestra-Verlag, Darmstadt, 1989.
[5] Soejima, H., Isoura, K., Development of the maglev system in Japan: past, present and future, *The 15th Int. Conf. Maglev’98*, Mt. Fuji, Japan, 1998, 8-11.
[6] Park, D.Y., Gieras, J.F., Incheon Airport Maglev Line, *Przegląd Elektrotechniczny*, 95 (2019), nr 6, 1-3
[7] Maglev in Changsha, CRRC, https://crrczelc-europe.com/medium-low-speed-maglev-changsha/
[8] Youfang Z., Ruixue Z., Maglev line opens to tourists in Fenghuang, *China Daily*, 08.09.2022, https://www.chinadaily.com.cn/a/202208/09/WS62f1c36aa310fd2b29e71203.html
[9] Chang, J., Qingyuan Maglev tourism dedicated line launch imminent, *GD Today*, Aug. 11 2024, https://www.newsgd.com/node_99363c4f3b/70a8d7affa.shtml
[10] Chuo Shinkansen: Tokyo to Osaka by Maglev, *Japan Railpass*, April 24, 2023, https://www.jrailpass.com/blog/chuo-shinkansen-maglev
[11] Osada, Y., Gotou, H., Sawada, K., Okumura, F., Outline of Yamanashi Maglev Test Line and Test Schedule, The 15th Int. Conf. Maglev’98, Mt. Fuji, Japan, 1998, 50-55.
[12] Gurol, S., Baldi, R., Post, R., General Atomics urban program status, *20th Int. Conf. Maglev’2008*, San Diego, CA, USA, 2008, paper nr 99, available on CD,
[13] Mallinson, J.C., One-sided fluxes – a magnetic curiosity?, *IEEE Trans*. on MAG, 9 (1973), nr 4, 678-682.
[14] Halbach, K., Design of permanent magnets in accelerators and electron storage rings, *Nuclear Instruments and Methods*, 169 (1980), 1-10.
[15] The TSB system as alternative in public transport, Urban Transport Magazine, May 13,.2024, https://www.urban-transport-magazine.com/en/the-tsb-system-as-alternative-in-public-transport/
[16] Worlds’ first commercial maglev system, *Railway Matters on Track*, https://railwaymatters.wordpress.com/traction-technology/worlds-first-commercial-maglev-system/
[17] Stephan R., Costa F., Superconducting magnetic levitation (SML): a new generation of urban maglev vehicles, *Int. Conf. Maglev 2024,* Blekinge Institute of Technology, Malmö, Sweden, Proceedings 2, 2024, 693-702.