INVITED PAPER

Linear Motor-Powered Transportation: History, Present Status, and Future Outlook

This review explains the operation of various types of linear motors used in maglev systems, discusses and compares their suitability, and describes the scope of worldwide maglev developments.

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ABSTRACT | An outline of the different fields of application for linear motors in transportation is given. The different types of linear motors are described and compared. The current status of the different linear motors used in the transportation sector is analyzed. Finally, a look at worldwide activities and future prospects is presented.

KEYWORDS | Electrodynamic levitation; electromagnetic levitation; linear induction motor; linear motor; linear synchronous motor; long stator; short stator; transportation sector

I. HISTORY

The history of the linear motor can be traced back at least as far as the early 1840s, to the work of Charles Wheatstone in Great Britain. In 1889, the Americans Schuyler S. Wheeler and Charles S. Bradley filed an application for a patent for synchronous and asynchronous linear motors to power railway systems. Early U.S. patents for a linear motor-driven train were granted to the German inventor Alfred Zehden in 1902 and 1907. A series of German patents for magnetic levitation trains propelled by linear motors were issued to Hermann Kemper between 1935 and 1941. In the late 1940s, Professor Eric Laithwaite of Imperial College in London developed the first full-size working model.

Manuscript received June 13, 2008; revised December 18, 2008. First published October 6, 2009; current version published October 28, 2009.
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Digital Object Identifier: 10.1109/JPROC.2009.2030249

II. REASONS FOR LINEAR MOTOR APPLICATION IN TRANSPORTATION SYSTEMS

Fresh impetus for worldwide research into linear motor-powered transportation systems came from high-speed maglev systems, on account of the need to develop not only a contactless levitation system but also a contact-free propulsion system [1]. Linear motors have the capability to produce a direct thrust without any conversion of rotational energy into translational energy. This is a major advantage for transportation systems, because the thrust is independent of the adhesion factor between wheel and rail. On the other hand, linear motors excite a normal (orthogonal) force (Fy or Fz), which can be used to support a vehicle. Thus, the two main fields of application are high-speed maglev transportation systems with high acceleration and braking forces and high-gradient railway systems, mainly in the mass transit sector.

III. LINEAR MOTOR TYPES FOR TRANSPORTATION SYSTEMS

As customary for rotating machines, a distinction is made between dc and multiphase ac linear-driven types (Fig. 1). The three-phase ac linear variety is in turn classified into induction and synchronous machines.

A. Short-Stator and Long-Stator Motors

The length of the stator (active part) compared to the reactive part defines the long-stator and the short-stator linear motor (Fig. 2).

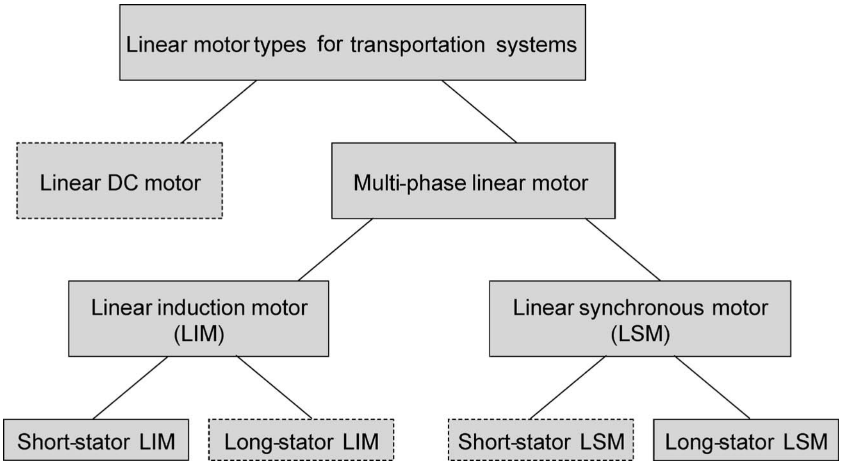

Fig. 1. ***Linear motor types for transportation systems.***

In short-stator linear propulsion systems, the stator and the frequency converter are installed on board the vehicle and the reactive part is fitted along the track. Thus, the weight of the vehicle increases with the design speed, while the outlay for the passive part of the machine remains constant. In addition, a power transmission system for feeding traction energy to the vehicle is necessary.

For the long-stator linear propulsion system, a multiphase traveling-field winding is installed along the track. This winding is fed section by section by stationary power converters.

Thus, the vehicle is the passive part of the motor and it is not necessary to transmit traction energy to the vehicle. This is a major advantage of the long-stator linear motor, permitting speeds of up to more than 500 km/h (over 300 mi/h) [2].

B. Linear DC Machines

Linear dc machines are not suitable for railway systems. Due to the alternating polarity in the active part, the brushes between the active and passive part of the motor cause arcing. The firing of the collector results in a very high maintenance requirement and reliability is low [1], [3], [4].

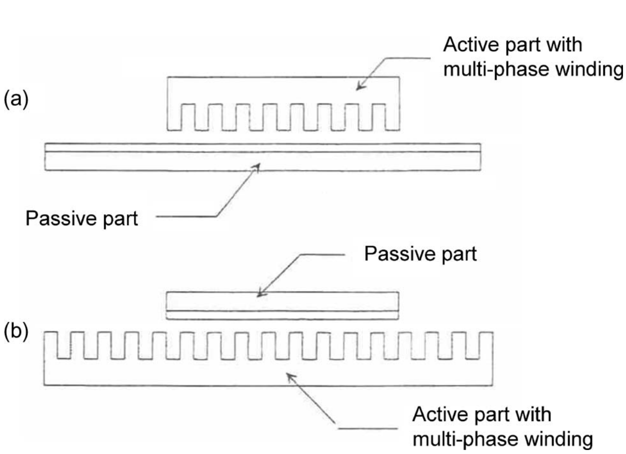

Fig. 2. ***(a) Short-stator motor; (b) long-stator motor.***

C. Linear Synchronous Motors

Linear synchronous motors (LSMs) can be classified into heteropolar and homopolar types. Although the principle of operation is the same for both rotary and linear synchronous motors, there are some differences. For economic reasons, only two topologies are implemented in practice: the active-guideway LSM, with conventional electromagnetic exciting magnets or a superconducting field winding on board the movable part (the vehicle), and the passive-guideway LSM [5].

The passive-guideway LSM is a short-stator LSM. The multiphase winding and field winding are integrated into a single unit. The overall investment costs are lower than those of an active-guideway LSM. The passive part consists of back-to-back poles.

Only part of the field can be used to produce a thrust due to the amplitude modulation of the dc field caused by the reaction poles generated by the field winding. This type of machine is also very heavy, which is why the short-stator LSM is not used for transportation systems (Fig. 3).

The active-guideway LSM is a heteropolar motor and may have either an iron core or an air core. The iron-core type can have electromagnets or permanent magnets. A normal attractive force occurs between the active and passive parts of the iron-core LSM (Fig. 4).

D. Double-Fed Linear Motor With Energy Transfer [7]

The primary field of the linear motor is installed in the track and the secondary field is fitted in the vehicle. If power is supplied to the primary and secondary independently implying independent alignment of the current vectors, the vehicles can be operated in asynchronous mode.

This operating mode allows a relative motion between several vehicles running on the same long-stator section

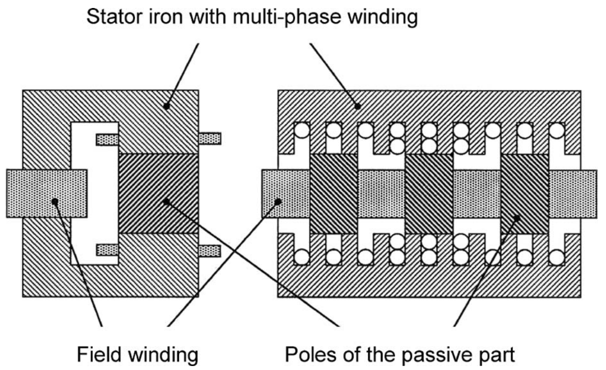

Fig. 3. ***Short-stator linear synchronous homopolar motor [6].***

(Fig. 5). For this purpose, a transfer of energy into the vehicles is necessary.

E. Linear Induction Machines

The operating principle of a linear induction maching (LIM) is identical to that of the rotational induction motor. The design principle is the same as that of the cage rotor motor and thus very simple. The passive part consists of a conductive sheet on solid iron. The multiphase winding of the active side produces a traveling electromagnetic field. This field induces currents in the passive part, which in turn develops a thrust due to the interaction of the traveling field and induces currents.

With the short-stator LIM, energy must be transmitted to the vehicle and efficiency is lower due to the large air gap caused by the tolerances for driving dynamics. On the other hand, the guideway equipment is very simple and inexpensive.

In transportation systems, normally short-stator LIMs are therefore used for low-speed systems (Fig. 6).

F. Advantages and Disadvantages

The advantages of linear motor-driven transportation systems over rotating motor-driven ones are:

1) Usable and controllable normal forces, especially for magnetic levitation systems.
2) Capability to produce a direct thrust, without any conversion of rotational into translational energy, independent of the adhesion factor between wheel and rail. This allows flexible alignments with higher gradients and lower losses, defined accelerations and hence a high stopping accuracy.
3) Low maintenance requirement of wheelsets and rails on account of the contact-free propulsion force.

An additional advantage of synchronous long-stator machines is

4) Installation of the propulsion power system in the track, not on board the vehicles. This reduces the vehicle weight and enables the power to be matched to the track sections. More power is necessary for sections with a high gradient or

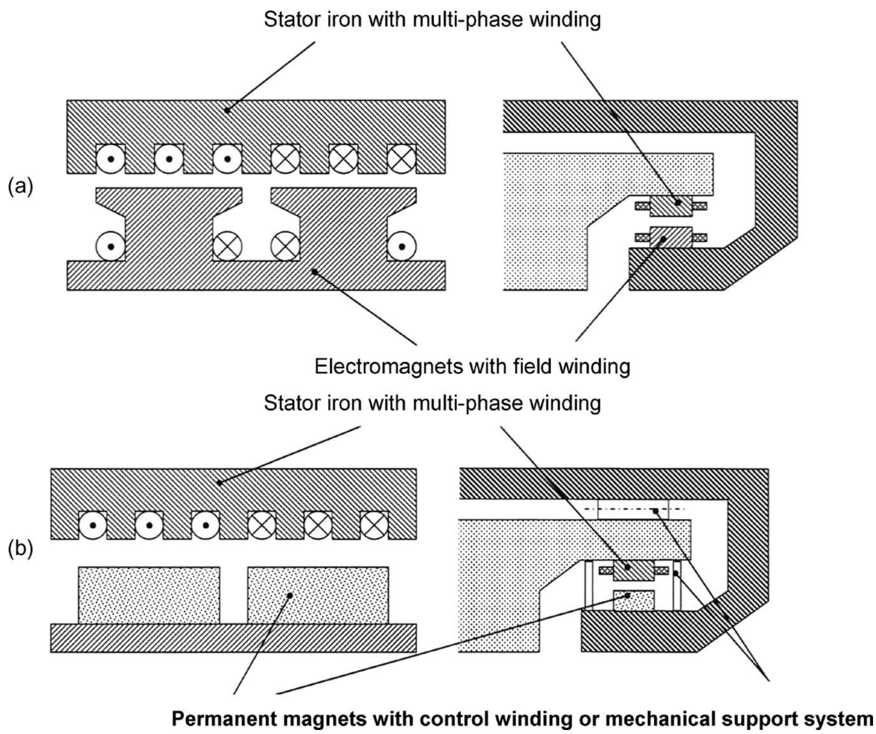

Fig. 4. ***Iron-core long-stator linear synchronous motor. (a) Controllable electromagnetic system. (b) Controllable permanent magnetic system with mechanical support system [6].***

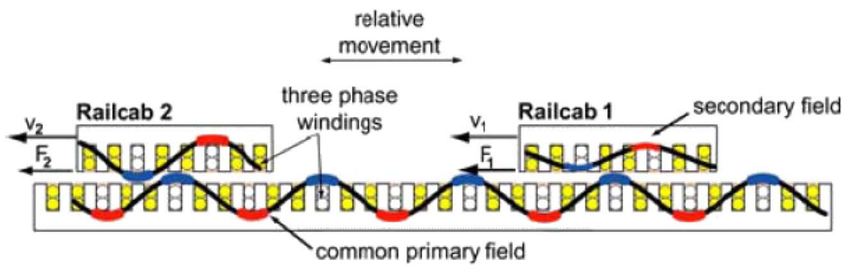

Fig. 5. ***Working principle of doubly-fed linear motor.***

requiring a high acceleration and less for shunting or sections where a constant speed applies.

Disadvantages of linear motors include:

1) Air gaps of 10 mm and more required for vehicles for driving dynamics and safety reasons. In rotating machines, the air gap between the stator and rotor is constant and can easily be only 1 mm. This means the magnetic resistance is higher (low permeability) and efficiency is lower.
2) Much higher losses than for rotating machines. The LIM has a lower efficiency due to its end effects. The lower efficiency of the long-stator LSM is due to the fact that the vehicle (passive part) is shorter than the active motor section.

IV. MAIN CHARACTERISTICS OF LINEAR MOTORS FOR TRANSPORTATION SYSTEMS

The main characteristics of linear motors with electromagnetic excitation in transportation systems are:

- thrust F_x
- velocity v
- normal force F_z
- efficiency η and power factor $\cos\varphi$
- stator current coverage A
- air-gap flux density B_δ
- magnetic air gap δ_m and mechanical air gap δ_0.

The synchronous traveling-field velocity is defined by

$$v_s = 2 \cdot f_1 \cdot \tau_p$$

where f_1 is the frequency of the traveling field and τ_p the pole pitch.

The synchronous speed varies with the frequency and pole pitch (frequency converter, pole switch). In addition, in LIMs, the operational speed is dependent on the slip s in accordance with

$$v = v_s \cdot (1 - s).$$

The thrust F_x of a linear motor is given by

$$F_x(x,t) = \int_0^{w_{Fe}} \int_0^{2p\tau_p} A(x,t) \cdot B\delta(x,t)\, dx\, dy$$

where w_{Fe} is the width of the iron core and $2p$ the number of poles.

It is proportional to the induced cross-section A_δ, the fundamental waves of the active current distribution A_1 and the air-gap flux density $B_{\delta 1}$:

$$F_x = c_1 \cdot A_\delta \cdot A_1 \cdot B_{\delta 1}.$$

The air-gap flux density of the LIM is defined by

$$B_{\delta 1} = c_2 \cdot A_1 \cdot \frac{\tau_p}{\delta_m}.$$

Thus, the thrust of the LIM is

$$F_x = c \cdot A_\delta \cdot A_1^2 \cdot \frac{\tau_p}{\delta_m}.$$

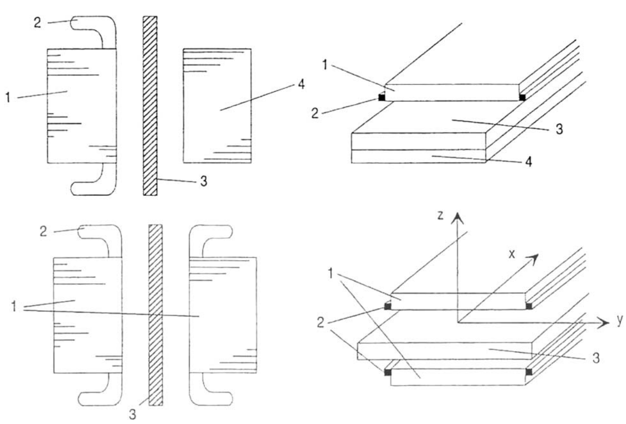

Fig. 6. ***Short-stator linear induction motor: single- and double-stator. 1: Stator iron; 2: multiphase winding; 3: passive part (conductive sheet); 4: solid iron [8].***

The constants c_1, c_2, and c take account of the material properties and geometry of the motor.

The normal force F_z of the LIM is

$$F_z(x,t) = \int_0^{w_{Fe}} \int_0^{2p\tau_p} B^2(x,t)\,dx\,dy$$

This means that $F_x \sim (1/\delta_m)$ and $F_z \sim (1/\delta_m^2)$.

The power of the machine is defined by

$$P = F_x \cdot v.$$

The air gap is the relevant value for the thrust of a vehicle and efficiency of the motor. Due to the driving dynamics and the necessary tolerances, e.g., wheel wear in railway systems, the air gap is bigger than on rotatory machines.

Typical values are

for railway systems: short-stator linear induction motor with wheel sets $\delta_0 \geq 12$ mm

for maglev systems: short-stator linear induction motor with EMS $\delta_0 = 12$ mm [9]

iron-core long-stator synchronous motor with EMS $\delta_0 = 8$–12 mm

air-core long-stator synchronous motor with EDS $\delta_0 = 10$–25 cm

EMS systems with higher air-gap values of up to 20 to 25 mm and a feasible efficiency could be realized by permanent magnetic or superconducting excitation. The higher air gap, however, is only related to the higher magnetic fields produced by the permanent magnets or superconducting system. The physical context is the same.

V. CURRENT STATUS OF LINEAR MOTOR-POWERED RAILWAY AND MAGLEV TECHNOLOGIES

A. Railway Systems

Linear motor-driven railway systems are typically adopted in mass transit systems for metro lines, usually with a low capacity and small structure gauge, for alignments with high gradients in the existing infrastructure in megacity centers. Short-stator linear induction motors are therefore used (Fig. 7).

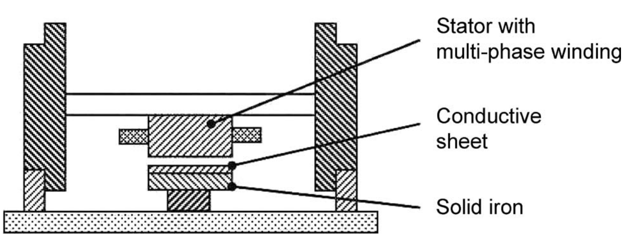

Fig. 7. ***Principle of a short-stator LIM under the bogie of a railway vehicle [6].***

One example of such a system is the Yokohama municipal subway (Fig. 8).

Fig. 8. ***Yokohama municipal subway with a short-stator linear induction motor [10].***

B. Maglev Systems

There are four different development lines of maglev systems (Fig. 9):

- electrodynamic levitation systems with air-core long-stator linear synchronous motors;
- electromagnetic levitation systems with short-stator linear induction motors;
- electromagnetic levitation systems with iron-core long-stator linear synchronous motors;
- (controlled) permanent magnetic levitation system with iron-core long-stator linear synchronous motors.

In the 1960s, Great Britain was leading in maglev research. Eric R. Laithwaite, professor of heavy electrical engineering at Imperial College London, researched in the field of the linear induction motor and developed a functional maglev vehicle.

In 1969, the U.S. inventors James Powell and Gordon Danby, both researchers at the Brookhaven National Laboratory, were awarded a patent for the superconductivity maglev concept using static magnets to induce electrodynamic levitation forces.

In the early 1970s, the United States, Germany, and Japan concentrated their research and development activities on the electrodynamic principle, using superconducting magnets. The United States started the Magplane project and developed, under the lead of Henry Kolm and Richard Thornton, the first superconducting magnetically

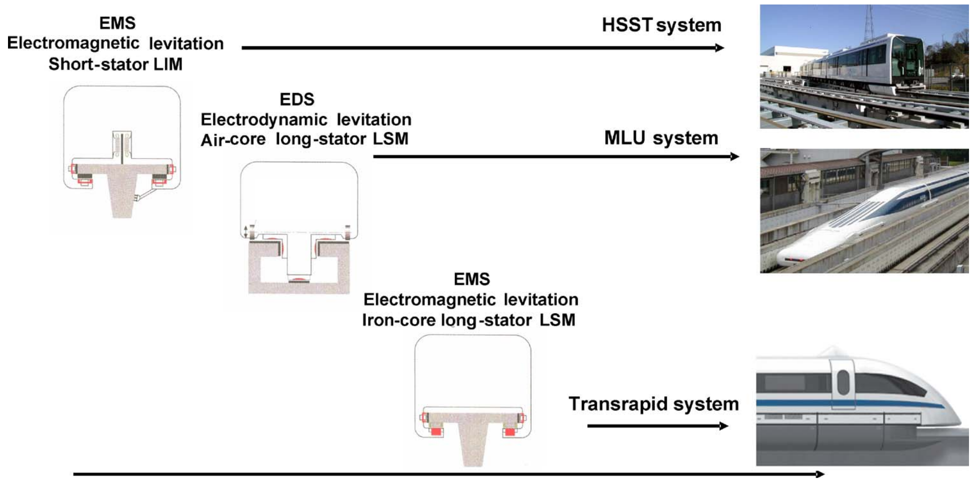

Fig. 9. *System development in Germany and current systems in Japan and Germany.*

levitated high-speed ground transportation prototype, designed and built at the Massachusetts Institute of Technology (MIT).

In Japan, JR's Railway Technical Research Institute (RTRI) developed the superconducting electrodynamic system. The development of the magnetic levitation U-shape (MLU) system started in 1969 and was tested at the Miyazaki test track. In 1979, the world record of 517 km/h was achieved.

In parallel, the Chubu HSST Development Corporation developed in 1974 the High-Speed Surface Transportation HSST01 vehicle, levitated by electromagnets and propelled by a short-stator linear induction motor.

In Germany, AEG-Telefunken, Brown Boveri Cie AG (BBC) und Siemens favored the electrodynamic levitation principle and, in 1972, developed together with Maschinen- und Anlagenfabrik Nürnberg (MAN) the "Erlangen Test Track" and the "EET 01" vehicle, levitated by superconducting magnets and propelled by a short-stator LIM.

Messerschmidt-Bölkow-Blohm preferred the electromagnetic principle and, in 1971, developed the Transrapid 01, based on electromagnets for levitation. In 1975, the Technical University of Brunswick developed the M-Bahn system together with Götz Heidelberg. The M-Bahn was an electromagnetic system based on permanent magnets with a mechanical open-loop control system. A long-stator linear motor was used for propulsion.

In 1977, Germany decided to focus on the iron-core long-stator motor for an electromagnetic levitation system (type Transrapid).

The world's first commercial automated system was a low-speed maglev shuttle that ran from the airport terminal at Birmingham International Airport to the nearby Birmingham International railway station between 1984 and 1995. Components of this system can be seen at the National Railway Museum in York, U.K.

In the 1990s, Japan and Germany in particular were very active in the development of maglev systems, followed by the United States, South Korea, and China.

The HSST system has been tested at the Chubu test line in Nagoya. The first commercial line of the HSST system, called Linimo, started revenue service on the Tobu Kyuryo Line in the suburbs of Nagoya in Japan in March 2005 (Figs. 10 and 11). This line is 9.0 km long and has nine stations. Its capacity is 3500 passengers per hour. The end-to-end trip time is 15 min, with 6-min headways (frequencies) in the peak period and 10-min headways during the off-peak period. Its maximum speed is about 100 km/h.

In 1997, the elaborate test track in Yamanashi was opened. In that year, the Japanese achieved 550 km/h (unmanned) and 531 km/h (manned). The maximum speed so far is 581.7 km/h (2003) (Fig. 12).

In Germany, the Transrapid test track was modernized and the Transrapid 08 together with an improved propulsion and operation control system was tested.

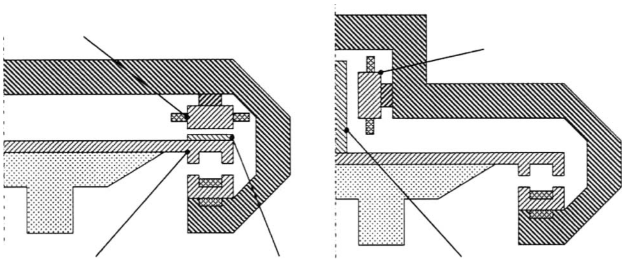

Fig. 10. *Principle of the short-stator LIM (single- and double-stator) for low-speed maglev [6].*

Fig. 11. ***Linimo short-stator LIM EMS system (Japan) [11].***

Fig. 12. ***Magnetic levitation U-shape synchronous long-stator EDS system (Japan) [12].***

Fig. 13. ***Transrapid synchronous long-stator EMS system (Germany).***

In April 2004, the first fully automated high-speed maglev system went into operation in Shanghai (Fig. 13). For the 30-km track, the Transrapid system needs a trip time of 7.5 min, at a maximum speed of 430 km/h and with a headway of 10 min in the peak period.

In the United States, the Federal Transit Administration has the lead for development of the MagneMotion Urban Maglev system. The MagneMotion Urban Maglev uses permanent magnets in conjunction with control coils for the electromagnetic levitation principle. This allows magnetic gaps of up to 20 mm [13], this being a major advantage for driving dynamics. The vehicle is propelled by a synchronous long-stator motor. This design has been demonstrated in a prototype and will soon be operational at Old Dominion University in Norfolk, VA.

General Atomics is developing the Urban Maglev system using the electrodynamic levitation principle. Permanent magnets are mounted on the vehicle based on the Halbach principle and a linear long-stator synchronous machine is used for propulsion. The electrodynamic system is self-stabilizing and allows magnetic gaps of up to 25 mm.

To date, in the mass transit sector, we usually find short-stator linear induction motors, because they are low-cost and easy to install. In the intercity transportation sector where high speed is typically required, synchronous long-stator motors are used to avoid the transfer of traction energy to the vehicles.

VI. CONCLUSION AND FUTURE OUTLOOK

The map below (Fig. 14) shows that linear motor-powered transportation systems are being developed all over the world.

So far, railway systems with short-stator linear induction motors have gone into service in Canada and Japan (metro systems and Linimo) and systems with long-stator motors in China (the German Transrapid).

The Canadian Advanced Rapid Transit (ART) system is used in Vancouver, Toronto, Detroit, New York, Beijing, Yongin, and Kuala Lumpur. The first line was opened in the early 1980s. The latest ART systems to be inaugurated are the Everline in South Korea and the airport connector in Beijing.

The Japanese LIM metro systems have been in operation since the early 1990s. The Osaka subway Line 7 went into service in 1990, the Tokyo subway Line 12 (Oedo line) followed in 1991 [14]. The Nanakuma subway line in Fukuoka opened in 2005.

Table 1 shows current maglev activities around the world.

The Japanese Linimo system entered service in Nagoya in March 2005 and, during its first seven months of operation, carried about 20 million passengers [15].

Germany's Transrapid in Shanghai has been in operation since 2004 and has meanwhile carried more than 18 million passengers with a punctuality of 99.95%.

In 2004, the German Government funded the Maglev Development Program to guarantee the state of the art and to optimize the Transrapid system with regard to total investment and operational costs of the overall system [16].

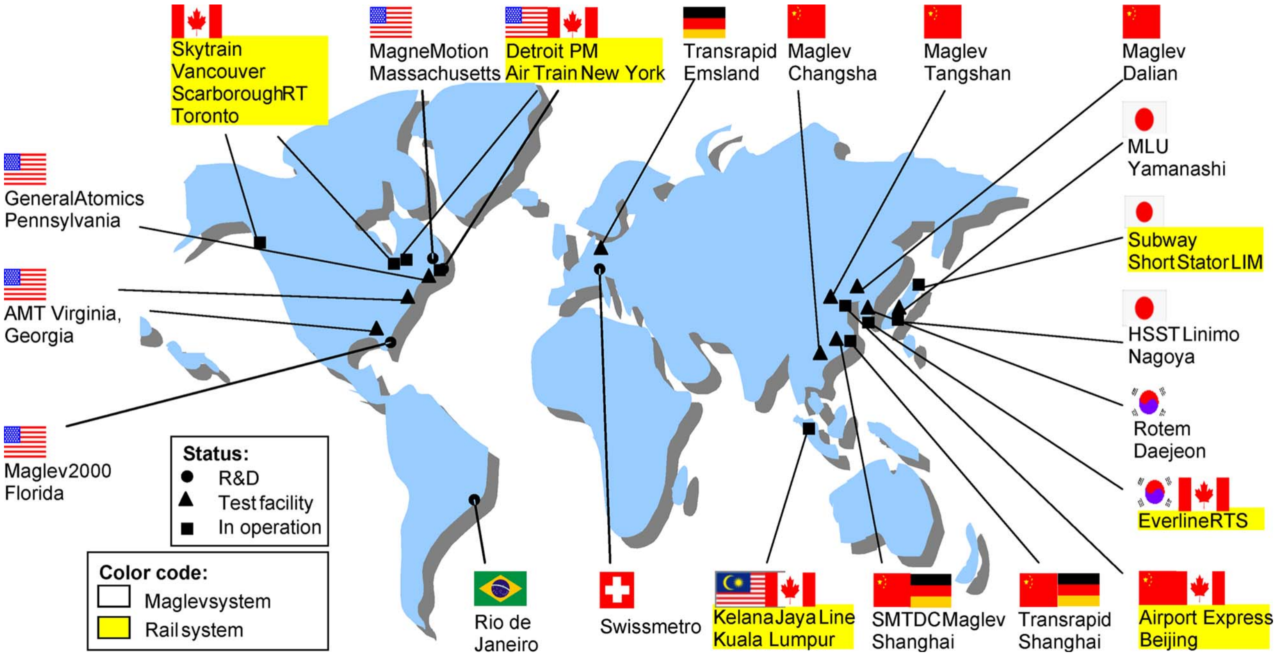

Fig. 14. *Linear motor-powered transportation systems worldwide.*

The Japanese MLU system has been further developed, too, especially from the point of view of investment and operating costs. The core technologies, such as superconduction, have been optimized [17].

In addition, much R&D work is going on throughout the world, especially in the United States, China, and South Korea [18].

At present, there are a lot of new ideas, for example the use of long-stator linear motors in personal rapid transit systems [19] or contactless inductive power supply along the track for auxiliary power supply of the vehicles by linear transformers [20].

The environmental concerns for the rapidly growing transportation demand of the future require high-speed, high-capacity, and eco-friendly transportation systems. Maglev technology can be an auspicious solution for the upcoming traffic and ecological challenges, because the main advantages of maglev technology are obvious:

1) short trip times due to high speed and/or high acceleration;
2) safe and comfortable due to magnetic guidance and levitation systems;
3) low operating costs due to low maintenance effort (contactless) and high efficiency;
4) flexible alignment due to high gradients because there is no need for any functional grip between the wheel and the rail;

Table 1 Current Maglev Activities

System	Location	Country	Motor type	Suspension type	Operation / test velocity	Status
Transrapid	Emsland	Germany	Long-stator LSM	EMS	400 / 451 km/h	Test facility
Transrapid	Shanghai	China	Long-stator LSM	EMS	430 / 501 km/h	In operation
MLU	Yamanashi	Japan	Air-core long-stator LSM	EDS	n/a / 581 km/h	Test facility
HSST	Nagoya	Japan	Short-stator LIM	EMS	n/a / 80 km/h	Test facility
Linimo	Nagoya	Japan	Short-stator LIM	EMS	100 km/h / n/a	In operation
Korean Maglev	Daejeon	South Korea	Short-stator LIM	EMS	n/a / 110 km/h	Test facility
	Changsha	China	Short-stator LIM	EMS	n/a / 150 km/h	Test facility
	Tangshan	China	Short-stator LIM	EMS	Planned up to 150 km/h	Test facility under construction
	Dalian	China	Wheels and PM	EDS with PM	Planned up to 320 km/h	Test facility under construction
Magplane	Shanghai	China	Long-stator LSM	EDS	Planned up to 550 km/h	Abandoned
MagneMotion M3	Massachusetts	USA	Long-stator LSM	EMS with PM, control coils		Test facility
General Atomics	Pennsylvania	USA	Long-stator LSM	EDS with PM	n/a / 160 km/h	Test facility
American Maglev	Virginia, Georgia	USA	Short-stator LIM	EMS	n/a / 60-70 km/h	Test facility
Maglev 2000	Florida	USA	Long-stator LSM	EDS	Planned up to 500 km/h	In research
Swissmetro		Switzerland	Short-stator LIM or long-stator LSM	EMS	Planned up to 500 km/h	Abandoned

5) eco-friendly due to high-efficiency, emission-free system, flexible alignment, low noise, and independence of energy mode.

In particular, countries with large territories or megacities are interested in this technology.

In September 2006, at the International Conference on Magnetically Levitated Systems in Dresden, China announced that it would be extending the existing Transrapid line in Shanghai to Honqiao Domestic Airport and further on to Hangzhou [21].

In April 2007, Central Japan Railway Company announced its plan to start a commercial maglev service between Tokyo and Nagoya in 2025.

Today, there are a large number of pending projects all over the world, e.g., in Asia and North and South America. The coming years will show whether or not maglev or at least linear motor-powered transportation systems will establish themselves. ■

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