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Ultra high-speed ground transportation systems: Current Status and a vision for the future

***Abstract**. Latest achievements in three technologies of ultra high-speed ground transportation (UHSGT) have been presented: high-speed rail (steel wheel-on-rail); magnetic levitation (maglev) and Hyperloop. Selection of linear motors and major problems in construction of Hyperloop have been discussed. China is the world leader in UHSGT.*

***Streszczenie.** Przedstawiono najnowsze osiągnięcia w trzech systemach transportu naziemnego o wysokiej predkosci: kolej szynowa; kolej lewitacji magnetycznej (maglev) oraz Hyperloop. Omówiono dobór silników liniowych i główne problemy w konstrukcji transportu Hyperloop. Chiny są światowym liderem w transporcie naziemnym o bardzo wysokiej predkosci (**Transportu naziemny o bardzo wysokiej prędkości: stan obecny oraz wizja na przyszlosc**).*

Keywords: ultra high-speed, ground transportation, railway, magnetic levitation, hyperloop, linear motors.
Słowa kluczowe: bardzo wysoka predkosc, transport naziemny, kolej szynowa, lewitacja magnetyczna, hyperloop, silniki liniowe.

Introduction

According to Washington State Department of Transportation, USA, ultra high-speed is defined as a maximum operating speed of >402 km/h (250 mph) [1]. The introduction of ultra-high-speed ground transportation (UHSGT) shortens the commute between the largest cities, improves mobility, and boosts economic growth. It also improves the environment with millions metric tons of carbon emissions reduced as travellers opt for the UHSGT rather than private vehicles or planes. Many construction jobs, operating and service jobs can be created.

Technologies that can meet UHSGT requirements

Three technologies could potentially meet the operating speed requirement for UHSGT [1]:

a) High-speed rail (steel wheel-on-rail);
b) Magnetic levitation (maglev);
c) Hyperloop.

High-speed rail (HSR) is a major technology advancement, which is based on the same basic principles as the early railways, namely steel wheel on the trains running railroad tracks (Table 1).

Table 1. Basic specifications of high-speed rail

Current maximum speed	380 km/h (236 mph)
Speed record	TGV (2007) 574.8 km/h (357.2 mph)
Maximum design speed	402 km/h (250 mph)
Maximum seating capacity	1500
Minimum horizontal curve	7.6 km (4.7 miles)
Maximum gradient	4%
Technology maturity	mature

In the *maglev technology* the trains levitate above the guideway using magnetic fields (Table 2). There is no contact between the vehicle and the guideway. The trains are propelled by linear electric motors.

Hyperloop is a proposed passenger and/or freight transportation using electromagnetic propulsion to carry vehicles through highly evacuated tubes with very high speed (Table 3). The main goal is to reduce the air resistance and therefore to enable very high speeds at moderate energy consumption.

Table 2. Basic specifications of maglev system

Current maximum speed	431 km/h (270 mph)
Speed record	YMTL[1] (2015) 603 km/h (375 mph),
Maximum design speed	604 km/h (375 mph)
Maximum seating capacity	824
Minimum horizontal curve	9.1 km (5.7 miles)
Maximum gradient	not applicable
Technology maturity	almost mature

Table 3. Basic specifications of Hyperloop

Current maximum speed	387 km/h (240 mph) Virgin Hyperloop One
Maximum design speed	1,223 km/h (760 mph)
Maximum seating capacity	28 per capsule
Minimum horizontal curve	4.8 km (3.0 miles)
Maximum gradient	not applicable
Technology maturity	infant

High-speed rail

At present time the maximum speed of the HSR trains is 380 km/h (236 mph). Table 4 shows the speed of the ten fastest trains in the world. The country with the largest HSR network is China [2]. In 2019 the length of HSR network was over 35 000 km. In December 2012 the world's longest HSR line, China's Beijing – Guangzhou (Hong Kong), with a total length of 2298km was completed.

The most modern trainset is CRH380A consisting of 8 cars (6M2T) or CRH380AL consisting of 16 cars (14M2T). The original CRH380A 8-car trainset 203-m long recorded a top speed of 416.6 km/h during a trial run. The CRH380AL 16-car trainset 401.4-m long reached a top speed of 486.1 km/h. The ouput power of CRH380A trainset is 9.6 MW (12,900 hp) and the output power of CRH380AL train is

[1] Yamanashi Maglev Test Line in Yamanashi Prefecture near Tokyo, Japan. This system uses superconducting electromagnets mounted on the vehicle, coreless LSM and shorted levitation coils in the guideway.

20.44 MW (27 410 hp). The power supply is from overhead catenary (pantograph) 25 kV AC, 50 Hz. Three-phase YQ-365 cage induction motors rated at 365 kW or YQ-420 induction motors rated at 420 kW are used as traction motors. Motors are fed from single-phase ATM9 shell-type oil-cooled traction transformers. There is IGBT VVVF inverter control. There are two types of braking systems: regenerative braking and electronically controlled pneumatic brakes.

Table 4. Ten fastest wheel-on-rail trains in the world

Name of the train	Speed km/h	Route	Country
Harmony CRH 380A	380	Shangai-Nanjing	China
AGV Italo	360	Rome - Naples	Italy
Siemens Velaro E/AVS 103	350	Madrid-Barcelona	Spain
Talgo 350	350	Madrid-Barcelona	Spain
Shinkansen E5 Hayabusa	320	Tokyo - Aomori	Japan
Alstom Euroduplex TGV	320	International network	France
SNCF TGV Duplex	320	All main cities in France	France
ETR 500 Frecciarossa	300	Milan – Rome - Naples	Italy
Suseo–Pyeongtaek SRT	300	Suseo near Soeul - Dongtan	South Korea
THSR 700T	300	Taipei City - Kaohsiung	Taiwan

Fig. 1. CRH380A trainset

Maglev

Maglev ground transportation systems can be classified according to speed:

- Low speed maglev trains – up to 120 km/h
- Medium speed maglev trains – around 200 km/h
- High speed maglev trains – over 400 km/h

There are six operational maglev lines in the world (Table 5). Only one maglev line, i.e., *Shanghai Transrapid Maglev* meets the requirements of UHSGT (Fig. 2).

Connecting Pudong International Airport (PVA) with Longyang Road station in Pudong, Shanghai, this Maglev line became instantly famous when introduced in April 2004, as it was the first high-speed maglev line open to public [3,4,5]. The most important numbers are:

- It costs US$1.2 billion to build;
- It covers a distance of 30.5 km in 7 min and 26 s;
- It reaches 431 km/h (268 mph) top speed;
- At this speed and travel time the single maglev train consumes 1600 kWh electrical energy;
- Acceleration 350 km/h in 2 min;
- Input frequency of linear synchronous motor (LSM) from 0 to 300 Hz;
- Current ranges from 1200 to 2000 A during acceleration.

Principle of operation of *Transrapid* maglev system is shown in Fig. 3. For electromagnetic levitation (EML) the field excitation system of LSM, i.e., electromagnet with controlled air gap is used. The air gap between levitation electromagnets and stationary ferromagnetic core of the three-phase winding is 10 mm. These field excitation and levitation electromagnets (36 kAturn) are fed from two-quadrant transistor choppers of 48 kW maximum power and sampling frequency of 100 kHz.

Table 5. The six operational maglev lines in the world

Commercial Maglev Train	**Running since**	**Top speed** km/h	**Track length m**
Daejeon Expo Maglev South Korea	1993	100	1 km
Shanghai *Transrapid* Maglev Train, China	2004	43	30.5 km
Linimo, Japan	2005	100	8.9 km
Incheon Airport Maglev South Korea	2016	110	6.1 km
Changsha Maglev Express China	2016	100	18.55 km
Beijing S1 Line China	2017	110	8.25 km

Rys. 2. Transrapid at Pudong International Airport station

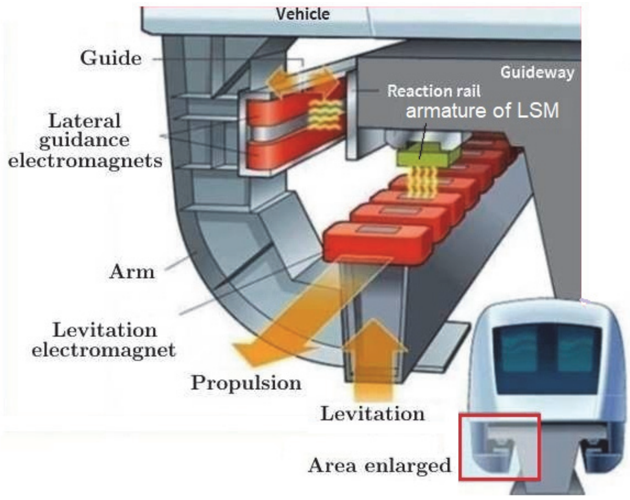

Fig. 3. Principle of operation of Transrapid maglev system.

Single-sided LSM with track-mounted three-phase armature winding provides propulsion and braking. Lateral stabilization is provided with the aid of lateral guidance electromagnets with controlled air gap.

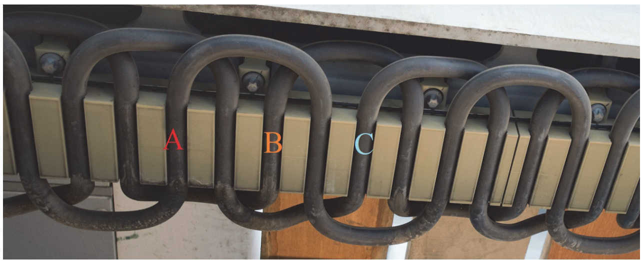

Fig. 4. Track-mounted armature winding of LSM made of aluminum power cable. There are single-turn coils with full-pitch coil span.

The three-phase armature winding of a LSM is placed in slots of a laminated core fixed to both sides of the concrete track. There are single-turn coils made of aluminum power cable (Fig. 4). The pole pitch is 258 mm. The track (armature winding) is divided into sections (Fig. 5). The average length of each section along the track is about 1.2 km. Only the section with train is fed from power supply. The maximum current of LSM is 1200 A at cruising.

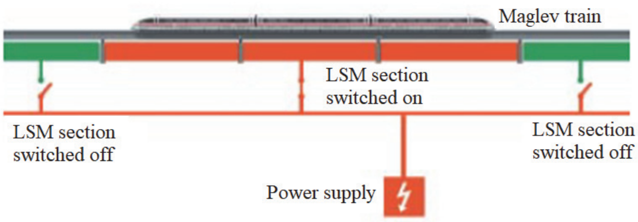

Fig. 5. The track (armature winding) is divided into sections. Only the section with train is fed with electric power.

Fig. 6. Levitation (suspension) and lateral stabilization electromagnets. Five-phase winding of a linear generator is placed in pole shoes of levitation electromagnets.

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-transformer 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 215 Hz. At higher frequencies the output transformers (behind inverters) can increase the voltage to maximum 7800 V.

Levitation and lateral stabilization units are shown in Fig. 6. There are slots in the pole shoes of suspension electromagnets with five-phase winding. This winding forms the so-called linear generator (linear transformer) to pick up the electrical energy from the stationary armature winding and deliver to the vehicle.

The power supply of every vehicle section is composed of 4 electrically isolated battery-buffered 440 V circuits. Each circuit is supplied by autonomous five-phase linear generator. The on-board power is about 400 kW. Boost converter adopt frequencies and voltages as the speed fluctuates.

For many years, National Maglev Transportation Engineering R&D Center at Tongji University, Shanghai has been doing research in high-speed maglev ground transportation. Tongji University has built on its Jiading campus a 2-km full-scale track for *Transrapid* system (Fig. 7). Tongji University wants to implement hybrid field excitation and levitation system: permanent magnets (PMs) and field winding. PMs are the primary source of the magnetic flux. Winding is necessary to control the air gap. The hybrid field excitation system reduces the electric power consumption by the vehicle.

Fig. 7. High-speed Maglev at Tongji University.

According to Tongji University, the most important R&D in the next 10 years is to implement a 600 km/h (373 mph) surface maglev train network (Fig. 8) [5]. The ground transportation in evacuated tube exceeding 1000 km/h may become a hot issue in the next decades.

Fig. 8. Vision of high-speed 600 km/h Maglev in China.

The provincial government in Zhejiang Province announced new plans on April 17, 2020 for the construction of a magnetic levitation train to connect Shanghai via Hangzhou with Ningbo in the South. The maglev line will be about 400 km long and cost about 100 billion yuan (US$14.1 billion). The speed will be 600 km/h. The government in Zhejiang intends to revitalize the local economy through this and other investments in transport infrastructure. It is planned to put the new line into operation around 2035.

Hyperloop

Hyperloop, a new form of ground transport currently in development by a number of companies, has a long history:
1799. George Medhurst of London conceived of and patented an atmospheric railway that could convey people or cargo through pressurized or evacuated tubes.
1888. Michel Verne, son of Jules Verne, imagined a submarine pneumatic tube transport system that could propel a passenger capsule at speeds up to 1800 km/h under the Atlantic Ocean (a transatlantic tunnel) in a short story called "An Express of the Future“.
1906. The *vactrain* (vacuum train), a vessel magnetically levitated and propelled in reduced-air-pressure tunnel was proposed by rocket pioneer Robert Goddard, as a freshman at Worcester Polytechnic Institute in the United States. Goddard subsequently refined the idea in a 1906 short story called "The High-Speed Bet", which was summarized and published in a *Scientific American* editorial in 1909 called "The Limit of Rapid Transit“.
1909. Boris Weinberg, Russian professor at Tomsk Polytechnic University prototyped an early version of ultra high-speed ground transportation publishing the concept in “Motion without friction (airless electric way)” in 1914.
1970s and early **1980s**. The *Swissmetro* was proposed to leverage the invention of the experimental German Transrapid maglev train, and operate in large tunnels with reduced pressure to 10 kPa [3].
2013. Elon Musk, CEO of *Tesla* and *SpaceX*, called this system *Hyperloop* and he predicted it would achieve the speed over 1200 km/h under reduced pressure to 100 Pa [6].

At present time, there are 8 Companies (USA, China, Canada, the Netherlands, Spain, Poland), over 50 University teams and over 1000 people involved in the R&D in *Hyperloop*. Some of the best known *Hyperloop* companies or *Hyperloop* projects are:
1) *Virgin Hyperloop One*, Los Angeles, CA, USA [7]. It has a full-scale test track 488-m long in the Nevada desert (Fig. 9) where an empty pod reached speeds of 387 km/h in December 2017. Levitation: air cushion 0.5–1.3 mm. Propulsion: double-sided linear induction motor (LIM)

Fig. 9. Full-scale *Hyperloop* test track 488-m long in the Nevada desert built by *Virgin Hyperloop One* [7]

2) *Hyperloop TT*, Los Angeles, CA, USA [8]. Recently completed a 320 m test track in Toulouse, France. Levitation: Inductrack [9,10]. Propulsion: PM LSM.
3) *TransPod*, Ontario M5G1L7, Canada [11,12,13]. Building a 3 km test track (with a half size scale prototype) in Limoges, France. Levitation: electrodynamic levitation (EDL) repulsive forces. Propulsion: LIM.
4) *Delft Hyperloop*, Delft, The Netherlands [14]. Levitation: EDL repulsive forces between PMs and conductive rail. Propulsion: unknown.
5) *Hardt Hyperloop*, Delft, The Netherlands [15]. Opened a 30-m long test track in 2017, the first one in Europe. Levitation: EML, PMs positioned and stabilized by the electromagnets. Propulsion: LSM similar to *Transrapid*.
6) *Zeleros*, Valencia, Spain [16]. Built a *Hyperloop* prototype and a 12-m research test-track in Spain. Levitation: probably EDL. Propulsion: unknown.

The *Hyperloop Consortium* [17], a collaboration between leading *Hyperloop* companies, i.e., *TransPod*, Canada, *Hardt Hyperloop*, the Netherlands, *Hyperpoland,* Warsaw, Poland [18,19] and EIT Climate-KIC supported *Zeleros*, Spain have announced the first-ever international partnership to establish standardized methodologies and frameworks to regulate vacuum-based *Hyperloop* transport systems.

In the *Hyperloop One* system, the primary units are mounted to the tube and the secondary aluminum rail is mounted to the capsule (pod). E. Musk proposed reaction rail about 15-m long, 0.45-m high and 50-mm thick aluminum blades integrated into the capsules (Fig. 10). Because the eddy-currents will mainly flow in the outer 10 mm surface of the blade, it could be made hollow to cut its weight and costs. The gap between the reaction rail and the primary core-mounted on the bottom of the tube would be 20 mm on each side [6].

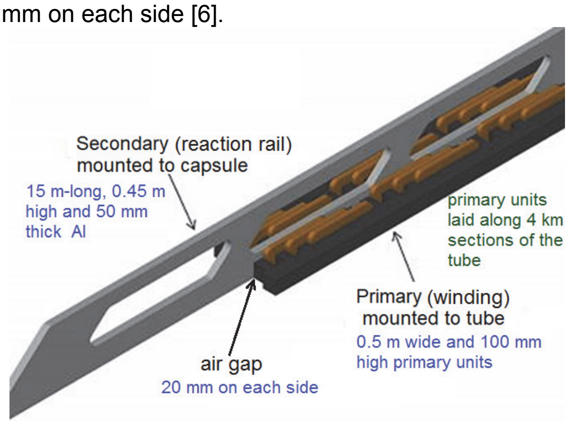

Fig. 10. Double-sided LIM for propulsion according to E. Musk [6]

The 0.5-m wide and 100-mm high primary units will be laid along 4 km sections of the tube – long enough to accelerate at 1*g* and decelerate the capsule between 480 and 1,220 km/h. Each section of primary unit will need two 65 MVA inverters [6].

The capsules would be supported by an array of 28 air bearing “skis” producing an air cushion 0.5–1.3 mm between the pod and the tube walls. According to Musk’s calculations, the aerodynamic power requirements at 1,130 km/h would be about 100 kW. He estimates that the total drag generated by the air cushion at 1220 km/h will be 140 N, resulting in a 48 kW power loss [6].

The 3.5-ton, 1.35 m-wide capsules, spaced about 30 s apart, would carry on-board axial compressors to create an air cushion to suspend the pod (Fig. 11). The compressors would also help to prevent the build-up of air in front of the pod and provide part of the propulsion. Each compressor would be driven by a 325-kW motor powered by a 1.5 ton battery that could keep it running for 45 min. Up to 28 passengers would travel in capsules whisked along inside steel tubes containing air at a low pressure of 100 Pa (10 kPa in *Swissmetro* [3]) to minimize air resistance [6].

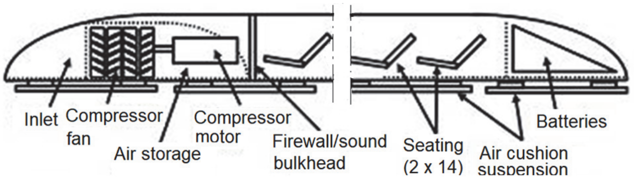

Fig. 11. *Hyperloop* capsule as envisaged by E. Musk [6]

The State Key Laboratory and Traction Power at Southwest Jiaotong University, Chengdu, China (Prof. Deng Zigang) has built a 45-long elliptical tube (two arcs 6-m radius and two 3.8-m straight lines) for testing small-scale vehicle under reduced pressure (Fig. 12). Repulsive forces between high temperature superconductors (HTS) refrigerated with LN2 (vehicle) and Mallinson-Halbach PM rail (track) are used for levitation (Meissner effect), as shown in Fig. 13. The levitation height is from 10 to 20 mm and the levitation capability is 1000 kg per one meter of guideway length. Single-sided LIM is used as a propulsion motor. No active control of lateral position is required.

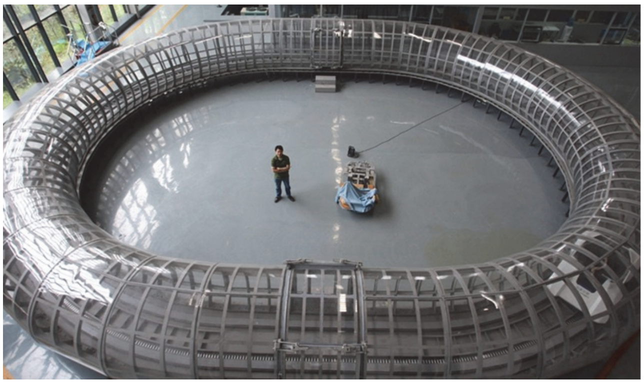

Fig.12. Elliptical tube 45-m long built at State Key Laboratory and Traction Power, Southwest Jiaotong University, Chengdu, China for testing a small-scale magnetically levitated vehicle.

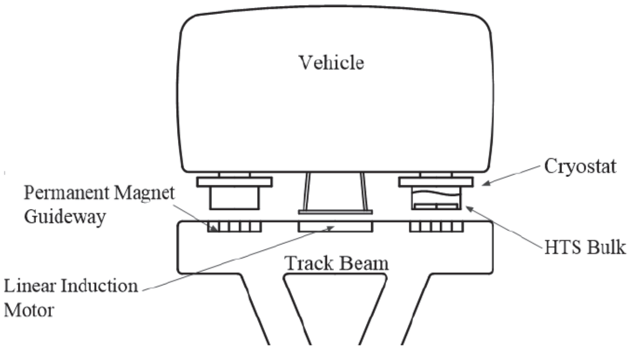

Fig. 13. Principle of operation of maglev vehicle built at State Key Laboratory and Traction Power, Southwest Jiaotong University

The State Key Laboratory at Southwest Jiaotong University also has built a full-scale 140-m long HTS Hyperloop high-speed test platform (Fig. 14). The diameter of the evacuated tube is 4.2 m.

Linear motor propulsion

Both flat single-sided and double side LSMs and LIMs can be used for propulsion of *Hyperloop* capsules. Table 6 shows comparison between LSMs and LIMs in application to ground transportation systems [20,21]. The family of LSMs is larger than that of LIMs. LSMs may have PM, wound-field, HTS or hybrid, i.e., PMs and wound-field excitation systems. The armature system can be either with ferromagnetic core, i.e., winding distributed in slots or without ferromagnetic core, i.e., coreless slotless windings.

Fig. 14. Full-scale 140-m long evacuated tube at State Key Laboratory and Traction Power, Southwest Jiaotong University

Table 6. Comparison of linear synchronous motors (LSM) and linear induction motors (LIM) [20,21]

Linear Synchronous Motor LSM	Linear Induction Motor LIM
$v = v_s = f/p = const$ independent of load	$v = v_s\,(1 - s) = f/p\,(1 - s) = var$ depends on load f = frequency, p = number of pole pairs, s = slip
Possibility of controlling the $\cos\varphi$ by changing the field excitation current.	No such possibility, $\cos\varphi$ depends on the air gap and load
More complex, needs more maintenance, less reliable	Simple construction, minimal maintenance, very reliable
Thrust F proportional to terminal voltage U ($F \sim U$)	Thrust F proportional to terminal voltage U square ($F \sim U^2$)
Must be inverter-fed	Self-starting (without inverter)
Large air gap, good overload capacity factor. Magnetizing current depends on the input terminal voltage	Air gap must be as small as possible to reduce the magnetizing current and do not deteriorate the power factor $\cos\varphi$.
Expensive motor	Cost effective motor

Taking into account the following aspects:

- low cost;
- simple construction;
- good performance at high speed;
- minimization of losses;
- high efficiency;
- no normal attractive force between primary and secondary units;
- no detent force;

in opinion of the author, the best linear motors for *Hyperloop* are double-sided linear motors, in which at least one part (either primary or secondary) does not have ferromagnetic core. These will be:

(a) double-side LIM with aluminum secondary (Fig. 15)

(b) double-sided PM LSM with coreless primary, i.e., coreless armature winding (Fig. 16).

However, double-sided motors of vertical configuration need large radius of horizontal curve of the guidance.

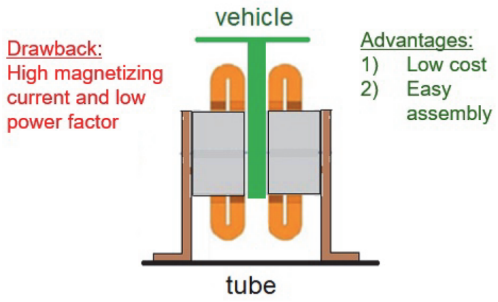

Fig. 15. Double-side LIM with aluminum secondary (reaction rail)

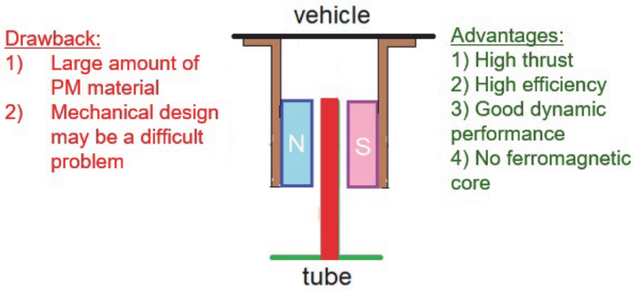

Fig. 16. Double-sided PM LSM with coreless primary (armature)

Major problems in construction of Hyperloop system

1) A 600 km/h surface maglev and all electric aircraft (AEA) are competitors to *Hyperloop* and may delay implementation of this system. On the other hand, *Hyperloop* provides transportation independent of the weather conditions .
2) Electromagnetic problems (levitation, linear motor propulsion) for *Hyperloop* have been partially solved. The maglev technology can be leveraged to *Hyperloop* technology. However, the following problems have no solution so far:

- How to maintain partial vacuum in large vacuum vessels?
- How to prevent accidental loss of vacuum (failure of seals, punctures or holes in the tube, etc.?
- How to take out the heat from the inside of the tube? The thermal conductivity of air under low pressure is almost zero (Fig. 17). For comparison, the thermal conductivity of the air at atmospheric pressure (101,325 kPa) is about 0.03 W/(K $\times$m).

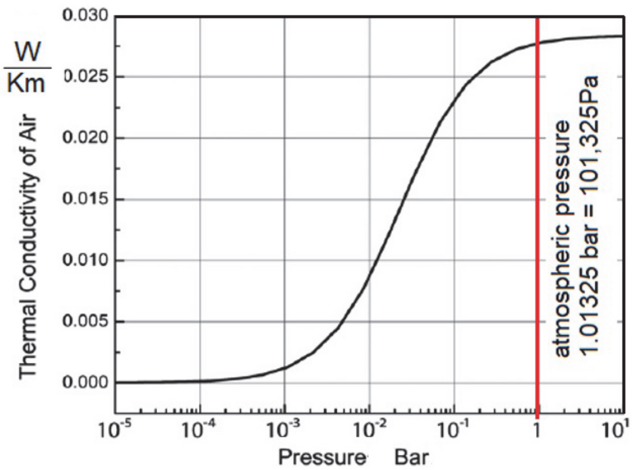

Fig. 17. Thermal conductivity of air as a function of pressure.

3) How to protect long-distance *Hyperloop* line against terrorism?
4) There are more other difficult problems, e.g.,

- Large energy consumption of vacuum pumps. *Hyperloop* will be the largest vacuum vessel in the world.
- Large air resistance due to partial vacuum and small gap between capsule and tube
- Division of tube into sections.
- Maintaining vacuum at stations.
- Low capacity of capsules (28 passengers according to E. Musk white paper)
- Dispatching.
- Evacuation of passengers from the tube in the case technical problems or emergency

University teams participating in *Hyperloop* projects and competitions (*SpaceX Hyperloop Pod Competition* [22]) consist of young people, who are very enthusiastic and optimistic. However, thorough solutions to multidisciplinary problems constitute a big challenge to researchers and engineers and are distant in time, not to mention enormous costs of development and implementation. Some experts are sceptical if *Hyperloop* system will be feasible and economically justified.

Conclusions

1) There are tree technologies that potentially can meet the operating speed of 402 km/h (250 mph) required for UHSGT, i.e., high-speed rail, maglev and *Hyperloop*.
2) The fastest wheel-on-rail train in the world CRH 380A reaches the speed of 380 km/h on Shangai-Nanjing route in China (Table 4).
3) The country with the largest HSR network is China. In 2019 the length of HSR network was over 35 000 km.
4) There are six operational maglev lines in the world (Table 5). Only one maglev line, i.e., *Shanghai Trasrapid Maglev* (top speed 431 km/h) meets the requirements of UHSGT.
5) China is planning to implement in the next 10 years a 600 km/h (373 mph) surface maglev network (Fig. 8).
6) At present time, there are 8 Companies (USA, China, Canada, the Netherlands, Spain, Poland), over 50 University teams and over 1000 people involved in the R&D in *Hyperloop*. Some of the best known *Hyperloop* companies or projects are: *Virgin Hyperloop One*, *Hyperloop TT*, *TransPod*, *Delft Hyperloop*, *Hardt Hyperloop*, *Zeleros*.
7) The best linear motors for UHSGT are double-sided linear motors, in which at least one part (either primary or secondary) does not have ferromagnetic core. These are double-side LIM with aluminum secondary (Fig. 15) and double-sided PM LSM with coreless primary (Fig.16).
8) For future *Hyperloop* system the electromagnetic problems (levitation, linear motor propulsion) have been practically solved. Most difficult problems are vacuum maintenance, sealing, heat transfer, low passenger capacity capsules, evacuation of passengers from the tube in the case of technical problems or emergency.
9) China is the world leader in research, development and implementation of UHSGT systems.

Acknowledgments The author would like to thank Dr. Fei Ni and Prof. Guobin Li for organizing his trip to several Universities, Research Centers and factories in China and for organizing a workshop at Tongji University. He would also like to thank Prof. Deng Zigang for organizing visit to the State Key Laboratory and Traction Power at Southwest Jiaotong University, Chengdu, Sichuan Province, China.

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