Technical Overview and Improvement Analysis for Magnetic Levitation Transportation

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Abstract
As a major invention in the history of transportation technology, magnetic levitation (maglev) is showing great potential both in academia and industry. Due to this reason, this paper systematically conducted a technical overview and improvement analysis for maglev transportation. Firstly, the definition, principle of maglev, and the concept of maglev-based rail transportation are introduced in general. And the four major types of maglev and the present status of maglev research and development in different countries are briefly described. Subsequently, using literature research, case studies and other methods to analyse the key technologies for each principle of maglev. This paper proposes three aspects for the improvement direction of maglev in terms of full speed domain, operation & maintenance management system and noise control. Further, the differences in technical, economic, and social benefits between maglev and wheeled track are compared. And a Chinese road network planning proposal integrated with maglev development is proposed. The research has shown that at speeds of 600km/h and above, high-speed and ultra-high-speed maglev are the best choices and have better benefits for technology, the economy and society.

Keywords
Magnetic levitation transportation; key technology analysis; Chinese development prospect

Introduction

From a thousand years ago to the present, humanity has never stopped the pursuit of speed. Thus, transportation means have experienced dramatic innovations due to technical development. Before the industrial civilization (in the agricultural civilization), the workforce and the carriage were the most common transportation means for supporting long-distance travel. Until the first industrial revolution, it was the milestone of the transportation industry that Watt invented the steam engine in 1698 and the train also arose at an opportune time to support massive commodity delivery in 1825. Later, during the second industrial revolution, Karl Benz and Daimler invented the earliest automobile (internal combustion engine) in 1885. Then, Ford created the first car in America in 1894. And in the third industrial revolution, people focused on scientific and technological breakthroughs. After entering the 21st century, the fourth industrial revolution rapidly boosted

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the global economy, society, physics, engineering, materials science, and various other disciplines. So the demand for faster and more efficient transportation means rapidly growing, driving the huge development of the rail transportation field. Therefore, the maglev stands out in rail transportation as a very competitive green ground transportation (Thornton, 200) (Wang, 2014) due to the advantages of the wide speed range, intense climbing, low noise, good smoothness, high safety, environmental protection, energy savings, low maintenance cost and strong adaptability. For the first time, it has achieved contactless operation between the track and the train, enriched and improved the transportation network and changed the world's transportation landscape. Furthermore, through continuous theoretical innovations and application research to promote long-term development from designing to manufacturing, maglev will have a broader prospect in the future.

Maglev is regarded as a major invention in the history of transportation technology, which can be used for urban commuters and cargo freight. Maglev transportation serves as a new mode of rail transportation with a completely different operating principle from the traditional wheel. As the mainstream model of the current world rail transportation technology, wheeled track operating speed is always constrained by air resistance, wheel-rail adhesion, serpentine instability and bow network relationship. Meanwhile, energy consumption and mechanical frictions rise with the increased speed. The present maximum technical speed is about 400 km/h within the economical limitations (Fu, 201) (Wang & Wen, 2020). While the maglev train is a new type of contactless levitation, guiding and driving rail trains on land without wheels, its operation relies on magnetic propulsion (magnetic suction or magnetic repulsion). By alleviating the friction, vibration, and high-speed flow of the railroad, it has better performance in its speed, capacity, power, load, comfort and safety (Li & Xu, 2001). And it has become the only ground transportation that exceeds 500 km/h nowadays (Yan, 2002). According to the differences between the three systems of the maglev train (levitation system, drive system, guidance system), the following four types are being studied currently: Electromagnetic Suspension (EMS), Superconducting Pinning Levitation (SPL)/High-Temperature Superconducting Magnetic Levitation (HTS Maglev), Permanent Magnet Electrodynamic Suspension (PMEDS) and Low-Temperature Superconducting Electrodynamic Suspension (LTSEDS).

As a new cutting-edge rail transportation technology, maglev is receiving worldwide attention and becoming a hot spot. At present, Japan, Germany, America and China lead the direction. Japan mainly develops Electrodynamic Suspension (EDS) which has reached quasi-commercial operation. Germany mainly develops EMS and the related technology is applied in Shanghai Maglev special line in China. The U.S. mainly develops low-evacuated tube maglev technology, which is in the test and verification stage. China has researched different high-speed maglev technologies, with the highest level of industrial EMS applications and HTS Maglev prototypes. In addition, building a low-evacuated operating environment to reduce air resistance and noise is another important development area for higher-speed rail technology.

There are various studies on maglev systems. However, there is a lack of articles that completely sort them out. In order to facilitate readers who first contacted maglev technology can understand more completely and efficiently the current situation and to avoid the lack of information caused by the insufficiency of information search, this article will make a systematic arrangement to fill this gap. In this way, a more integrated description of the overall technology and the current state of development in the world of maglev will be presented, as key technologies and subsequent improvement directions for each type, and the potential for future development of maglev in China will be enriched more comprehensively. At the same time, the author can also gain a deeper understanding of the sectors such as physics, engineering, materials, economics, and society.

The remainder of this paper is organized as follows. Overall introduction, classification of the four types of technologies, and present status of research and development in different countries are presented in the Literature Review. The Discussion illustrates the bottlenecks technologies of the three technology principles, three improvement directions, and the proposal for Chinese road network planning integrated with maglev development. Then, the author concludes this paper in the Conclusion and a self-assessment of this study was conducted in the Review

Literature Review

Overall Introduction of the Magnetic Levitation Transportation Technology

Definition and Principle of the Magnetic Levitation

Maglev technology refers to the use of magnetic force to overcome gravity and make objects be levitated. Its working principle is based on the magnetic flux of the coil in the electromagnet. By changing the supplied alternating current to the electromagnet, the magnetic field around the electromagnet will be enforced or alleviated correspondingly. And through the controller, the magnetic force on the levitating body is equal to its gravity so that the levitating body can be suspended in the air.

Moreover, the suspension may have a small disturbance and deviates from the equilibrium position. At this time, the position sensor detects the displacement size of the levitated body deviation, and the data is converted into a control signal through the microprocessor of the controller. And then, the control signals are converted into the control currents through the power amplifier. The size of the control current is thus determined according to the direction and size of the displacement. After several iterations of fine-tuning, the levitated body will be forced to return to its original equilibrium position. From this principle, it can be seen that whether the direction of disturbance displacement of the suspended body is facing downward or upward, it can be in equilibrium (Zhang, 2003). It is a typical mechatronics technology that integrates power electronics, electromagnetics, mechanics, dynamics, control engineering, signal processing and other technologies, and applies them to maglev trains.

Magnetic Levitation Rail Transportation

Maglev trains consist of three main systems: levitation system, drive system and guidance system (Wang, 2019). For the levitation system, the basic principle of suspension motion is using electromagnetic suction or repulsion to make the train suspended in the air. The drive and guidance system can be guided and driven by the traction force generated by the linear motor. When the maglev train operates, it only receives the resistance from the air, without receiving the friction between the train and the ground track. So, the problems of wheel-rail adhesion, friction, vibration, high-speed flow, and other problems of the wheel-rail railroad are solved ingeniously and have a higher speed-up potential (Zhu, 2016).

Classification of the Magnetic Levitation Transportation

According to the different principles and methods of train levitation, maglev is divided into three forms: Electromagnetic Suspension (EMS), Electrodynamic Suspension (EDS) and Superconducting Pinning Levitation (SPL). Particularly, EDS can be classified again as Permanent Magnet Electrodynamic Suspension (PMEDS) and Low-Temperature Superconducting Electrodynamic Suspension (LTSEDS). SPL is also called High-Temperature Superconducting Magnetic Levitation (HTS Maglev).

Electromagnetic Suspension

EMS is also divided into two categories: high-speed maglev and low and medium-speed maglev. As shown in Fig. 1, EMS generally uses the rail holding form in which the train is wrapped around both sides of the track. Based on the principle of ferromagnetism, the train body can be levitated by relying on the on-board electric magnetic attraction between the magnet and the ferromagnetic track to balance the gravity. The conventional electromagnets mounted on the train are not only used for levitation and guidance but also as excitation windings for synchronous linear motors. The long stator cores and guide rails mounted on T-rails (track beams) interact with the electromagnets to generate the levitation and guidance forces. Generally, the suspension height is set from 8mm-12mm.

The power supply uses 10,000 kilowatts of power electronic variable frequency power supply, which will be switched to the section where the train is located in real time and adjusted according to the speed of the train with variable frequency. The train's position and speed information shall be transmitted to the control room in real time and the most advanced ground control systems are also used. It can be concluded that the standing maglev systems have very high requirements for control, relying on the suction force generated by the on-board DC (direct circuit) magnets to attract the magnetic circuits below the track. Thus, the main body of the maglev can be levitated adaptively.

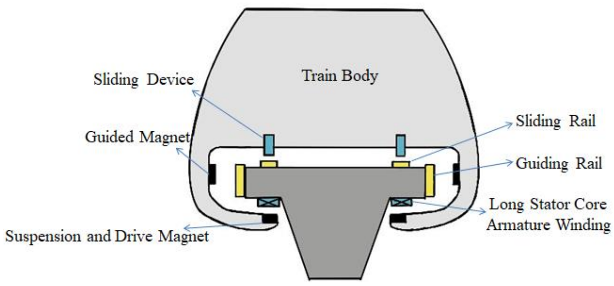

Figure 1. Schematic of principle for EMS

Permanent Magnet Electrodynamic Suspension

PMEDS uses the principle that permanent magnets are repulsive to each other to levitate the train. As shown in Fig. 2, permanent magnets made of NdFeB are installed at the bottom of the traveling section of the train, while electrical conductors (conductor plates) are installed above the track.

When the train levitation permanent magnets (levitation Halbach array) are moving relative to the conductive track, the magnetic fields distributed in the conductor plate track change relative to the conductor plates. According to the law of electromagnetic induction, the induced electric potentials are generated in the conductor plates and the circuits are formed between each part of the conductor plates. Then, the mirror vortexes are generated with the magnets in motion which means the vortex magnetic field and the train magnet will repel each other to generate levitation force. As long as the levitation force is large enough, the train will be levitated. However, a certain speed (such as 20km/h) will be required to have sufficient levitation force to lift the train, that is the train cannot be levitated at a standstill or low speed.

PMEDS is driven by a long stator linear motor, where the stator is continuously distributed along the track. The rotor is mounted in the centre of the train body using on-board propulsion permanent magnets (driving Halbach array) (Xiong & Deng, 2021, p. 180). And the thrust is generated by high-frequency AC (alternating circuit) current from the stator winding (driving winding) on the track. The train suspension height can always reach 20mm-30mm, and the speed can reach about 550km/h.

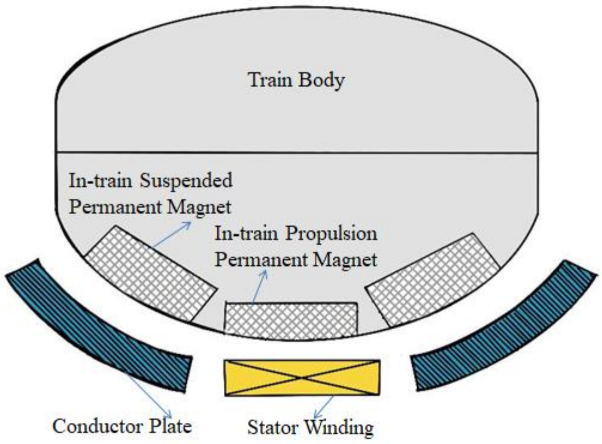

Figure 2. Schematic of principle for PMEDS

Low-temperature Superconducting Electrodynamic Suspension

LTSEDS reduces the temperature of low-temperature superconducting materials to extremely low (-269℃) to a superconducting state for obtaining zero resistance. The train suspension height can reach 80mm-150mm. LTSEDS generally adopts the form of track wrapped around the train, using the magnetic repulsion between the train and the track to levitate, to realize the train above 500km/h speed operation.

It is based on the principle of dynamic electric potential, relying on the magnetic repulsion between the on-board magnets and the orbital coils to balance the gravity for levitating the train. LTSEDS used a low-temperature superconducting coil, in which the Nb-Ti wire low-temperature superconducting coil was immersed in liquid helium at a temperature of 4.2 K to achieve a superconducting state through cooling. As shown in Fig. 3, currents are passed in the superconducting coils to form strong magnetic field superconducting magnets. And the ‘8’-shape coils are continuously arranged on the sidewall of the U-shaped track beam. When the train's low-temperature superconducting magnet moves horizontally along the track, the induction currents will be generated in the coil on the side wall. And the magnetic field between the lower part of the ‘8’-coil and the train superconducting magnet will repel each other, while the upper part of the magnetic field and the train superconducting magnet will attract each other to realize the levitation (Fujiwara & Fujimoto, 1989). Since the induction currents are small at low speed, the train needs to reach a certain operating speed (no smaller than 120km/h) to be suspended.

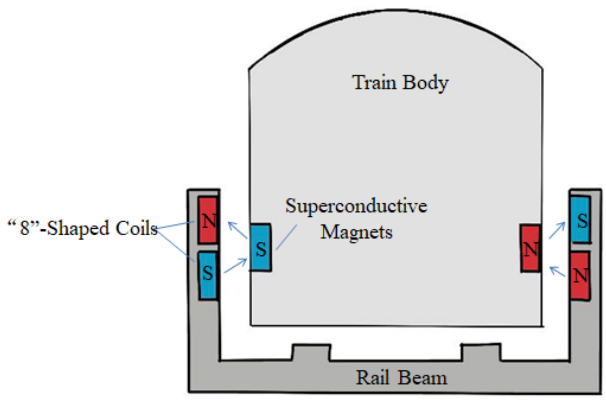

Figure 3. Schematic of principle for LTSEDS

Superconducting Pinning Levitation (High-temperature Superconducting Magnetic Levitation)

High-temperature superconductivity is relative to low-temperature superconductivity, with the former having a cooling temperature of -196 °C and the latter -269 °C, indicating that the operating temperature has been greatly increased (Deng & Zhang, 2016). HTS Maglev is based on the principle of induction, relying on the induced magnetic repulsion between the train’s high-temperature superconductor and the permanent magnetic track to balance the gravity and levitate the train. The train suspension height is within 10mm-30mm.

In an external magnetic field, the strong pegging force unique to high-temperature superconductors (non-ideal type II superconductors) makes it difficult to escape from the pegging centres (already captured lines of force) or to penetrate into the superconductor (uncaptured free lines of force) (Xiong & Deng, 2021). This unique pegging property allows the variation of superconductors with the external magnetic field to induce strong superconducting currents that impede such changes. Furtherly, it interacts electromagnetically with the external magnetic field to produce a levitational force in balance with the levitating body’s own gravity. And the required guiding force is provided for lateral stability. The whole system of HTS Maglev is mainly composed of three key parts: the on-board superconducting block & its low-temperature system, the ground permanent magnetic track system, and the linear drive system (Deng & Li, 2017). As shown in Fig. 4, the on-board superconductor is a cylindrical or square high-temperature superconducting YbaCuO block prepared by the melt-weaving method. The track is assembled by NdFeB permanent magnets and poly magnet yoke in a certain structure and the linear drive is done by induction linear motor or synchronous linear motor.

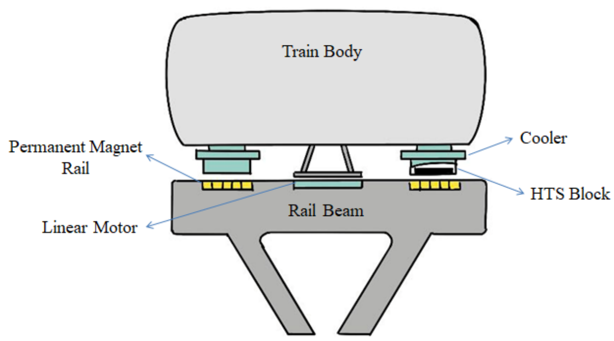

Figure 4. Schematic of principle for HTS Maglev

The Present Status of High-speed Magnetic Levitation Research and Development in Different

Countries

The research and development of the high-speed maglev is a continuous persistent and long-term process. There are still many construction and operation challenges to be solved and no real industrialization yet. Compared with the high-speed rail trains that have been built and operated for more than 50 years, the high investment, long cycle, relatively complex technology, the development of the maglev are subject to many technical and economic constraints and also have to face competition from the traditional wheeled track, aviation and other transportation modes. So the gap is obvious in terms of technical maturity, construction and operation experience, and industrialization.

Table 1 shows a comparison of the present status of high-speed maglev research and development in different countries. Since the 1960s, Japan, Germany, America, China and other countries have carried out research on maglev with different development strategies, development models and technical routes.

Table 1. Table of comparison of the present status of high-speed magnetic levitation research and development in different countries

Main countries	Japan	Germany	America
Type of suspension	LTEDS	EMS, HTS Maglev	PMEDS (Hyperloop)
Start time	1970	1960s	1999
Test speed (km/h)	603	550	463
Technical maturity	Quasi-commercial operation	Commercial operation	Experimental studies
Application	MLU, MLX, L0 Series	TR01-TR09, Supra-Trans Series	Hyperloop One, HTT, Space X Companies

Japan

Japan has chosen LTSEDS by using low-temperature superconducting materials in maglev trains, which belongs to superconducting electrodynamic suspension technology. As one of the most representative countries in the world for the promotion of EDS, Japan is committed to making EDS a national business card. It has been clear in its development strategy for maglev, continuing to invest in research and testing. ("The Ministry of Land, Infrastructure, Transport and Tourism", 2018). At the same time, Japan treats maglev as an important part of high-speed rail expansion overseas and targets the American market to actively promote technology exports. Table. 2 shows the present status of the research.

Table 2. Table of the present status of high-speed magnetic levitation research in Japan

Time	Model	Main role	Test speed (km/h)	Reference
1979	ML500	---	517	Saijo et al., 1981, pp. 533-543
1980-1987	MLU002	Manned operation	---	---
1994	MLU002N	Fire protection	---	---
1995	MLX01	Quasi-commercial operation	---	---
2003	MLX01-901	---	581	Kusada et al., 2007, pp. 2111-2116
2012	L0 Series	Configured for the Central Shinkansen	603	---

Since May 2014, the construction of the first phase (Tokyo-Nagoya) of the Central Shinkansen (438 km long, 86% of which are mountain tunnel intervals, with a maximum design speed of 505 km/h), Japan's first maglev line in commercial operation, began and scheduled to open in 2027. The second phase was originally planned to be completed and opened in 2045, but the Japanese government plans to open it eight years earlier, i.e., in 2037.

Germany

Germany has researched on high-capacity fast tracks containing high-speed maglev, starting the engineering process and concentrating on the development of high-speed EMS systems since the late 1960s. At present, a complete set of EMS has been formed and a number of experiments have been carried out to verify it. The relevant technology has been commercially applied in Shanghai, China. Table. 3 shows the present status of the research. Besides, two generations of HTS Maglev trains, named SupraTrans-I (completed in 2004) (Schultz et al., 2005) (Beyer et al., 2006) and SupraTrans-II (completed in 2011, with a maximum operating speed of 20km/h) (Kuehn et al., 2012), has been developed by the German Institute of Solid State and Materials Physics in Burnitz.

Table 3. Table of the present status of high-speed magnetic levitation research in Germany

Time	Model	Main role	Test speed (km/h)	Reference
1971	TR01 & TR02	Principle train & manned train	---	---
1973	TR04	---	---	---
1975	HMB & Komet	Laid the foundation for the TR series	---	(Sanchez, 2000, pp. 1-9)
1976-1989	TR06, TR07	---	---	---
2009	TR09	---	550	---

There are currently no commercially operated maglev lines in Germany. Since the 1990s, Germany has proposed three maglev track construction plans, including Berlin-Hamburg, Dortmund-Dusseldorf and Munich Airport-Munich Central Station. But they were shelved due to high budget costs, dim future profit prospects, project financing failure and their own national conditions.

America

The American government's research and development support for the development of high-speed maglev have always been intermittent. But with the help of private capital, America has conducted a lot of forward-looking technology exploration and made some progress. America had the intention to introduce Japan's superconducting maglev and the two sides have set up a joint venture company to jointly carry out environmental and technical assessments ("Northeast Maglev", 2020) ("Baltimore-Washington SC Maglev Project", 2020) ("Washington SC Maglev Project", 2018). American maglev technology development direction is relatively flexible, except the government, private research and development enthusiasm is very high.

The American company ET3 (incorporated in 1999 by Oster) was the first to elaborate on the concept of the Evacuated Tube Transport (ETT) system. Since 2003, to realize the idea of building an evacuated tube maglev subway system in America, the American company Magplane has respectively proposed high-speed and quasi-high-speed solutions using PMEDS and linear synchronous motor drives.

After its initial proposal by Musk in 2013 (Musk, 2019), Hyperloop One plans to build an evacuated tube capsule train with a speed of over 1,200km/h, achieving an acceleration of 1s to 96km/h, a test result that brought the evacuated tube high-speed maglev concept back to global attention. In 2017, Hyperloop One fully tested its Hyperloop technology for the first time in an evacuated environment, achieving a top speed of 310km/h.

In 2018, HTT demonstrated the first full-size Hyperloop passenger capsule in Spain, it was deployed on the first commercial Hyperloop tracks after the additional assembly.

The Present Status and History of Magnetic Levitation Research and Development in China

High-speed Magnetic Levitation

The development of high-speed maglev in China already has a solid technical foundation and engineering application experience. In 2003, through the introduction of German technology in Shanghai, the world's first and so far the only commercially operated high-speed maglev track was built. At present, several companies are actively carrying out research on high-speed maglev, covering different systems such as EMS, EDS and HTS Maglev. Also, they actively explore technologies related to ultra-high-speed maglev in low evacuated tubes. After decades years development, the research for high-speed maglev mainly owes to two institutions.

China Railway Rolling Stock Corporation Limited (CRRC) mainly carries out research related to the EMS system. In October 2016, CRRC officially launched the project of developing a 600km/h maglev engineering, which integrates many high technologies like laminar flow and low resistance aerodynamics for special research and development (Lin, 2017). A full set of high-speed magnetic technology and engineering capabilities will be formed in 2021 and it is planned to be put into operation by 2025.

China Aerospace Science & Industry Corp (CASIC) announced in August 2017 that it is carrying out research and demonstration of the 1,000 km/h "high-speed flying train" project. It is a transportation system that uses a low evacuated environment and supersonic profile to reduce air resistance and reduces frictional resistance through maglev to achieve supersonic operation with a maximum speed of 4,000km/h. At present, CASIC has joined hands with more than 20 research institutions at home and abroad to carry out related research, mainly based on the electrodynamic system.

Low and Medium-speed Magnetic Levitation

Nowadays, the development of low-speed maglev has also made a breakthrough in China. Its research companies and universities have mastered a series of key technologies such as levitation guidance control, bogies, vehicle-track coupling resonance, and overall system design.

The core technology and application routes are the same in the two completed low and medium-speed maglev commercial operation lines in China. Their development history is as follows.

In 1992, Southwest Jiaotong University and the National University of Defense Technology led the project of “key technology research of maglev train”. In 2008, Beijing Maglev Transportation Development Corporation Limited undertook the key project of the National Support Program “Low and Medium-Speed Maglev Transportation Technology and Engineering Application Research”. And in May, they independently mastered the core technologies of low and medium-speed maglev and established the engineering research &development and production system.

From 2011 to 2017, Changsha Maglev Express Line achieved official passenger operation, becoming Chinese first commercial operation line of low and medium-speed maglev with fully independent intellectual property rights and realized localization. Beijing S1 line which was solely responded by Beijing Maglev Transportation Development Company Limited opened for operation and became the second maglev line in China and the first one in Beijing. Also, Beijing Maglev Transportation Development Corporation Limited became the first low and medium-speed maglev industrialization enterprise in China, integrating independent intellectual property rights, localized technology research and development, engineering application, train manufacturing, and service system.

Discussion

Based on the literature review, the discussion will unfold along the lines shown in the figure below:

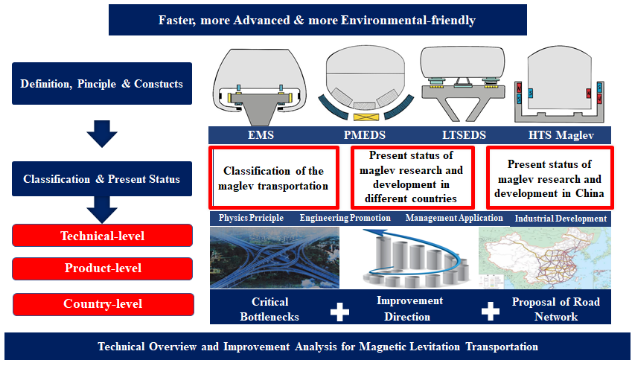

Figure 5. The overview of the discussion of this paper

Analysis of Key Technologies for Each Principle of Magnetic Levitation

Electromagnetic Suspension

The key technologies of EMS are the train-line coupling vibration suppression and levitation redundancy realization.

In terms of train-line coupling vibration, application practice shows that train suspension is very sensitive to its own structure, overhead lines and control systems. Especially in static suspension or low-speed operation in the light turnout beam, turnout coupling vibration is very prominent and very easy to lead to suspension failure. The main measure to suppress the train-line coupling vibration is still to control the deflection-to-span ratio of the track beam. And the high-speed maglev line also requires the first-order vertical bending frequency of the beam to be increased as much as possible (Xu et al., 2019, p. 44). The Shanghai high-speed maglev track beam requires Vc<0.9, it is a requirement that significantly increases the line construction cost.

Optimal suspension control also has the potential to improve coupling vibration, but the effectiveness of optimal suspension control in suppressing coupling vibration is not promising under the specific line structure and train constraints.

The suspension frame structure and suspension design also have significant effects on the coupling vibration.

In terms of levitation redundancy, the Shanghai TR high-speed maglev train has achieved mechanical redundancy by means of an electromagnet lap structure, so that the train can remain levitated when individual levitation points fail. The low and medium-speed maglevs have not yet solved this problem well.

Electrodynamic Suspension

EDS is passively supported and can be stabilized suspension with a small amount of damping control. The track requirements are much lower than those of the EMS. The key technologies are twofold.

One is to obtain a strong on-board magnetic field. With the development of permanent magnet material science, the existing permanent magnets can meet the requirements of rail transportation applications. Thus, various EDS solutions for on-board permanent magnets have been proposed. However, since the magnetic field strength of early-year permanent magnets is weak, it is difficult to meet the practical needs of rail transportation projects. Japan has adopted on-board superconducting magnets.

And another is the clever use of magnets on-board and the magnetic force of the induction magnetic field to achieve the vehicle guidance under the high-speed suspension state.

Existing industrial technology capabilities can meet these challenges without significant technical barriers.

High-Temperature Superconducting Magnetic Levitation

HTS Maglev is a passive support method. The mass of the train is about 1/2 of the light rail body with lower infrastructure cost. The liquid nitrogen required for cooling comes from the air and is discharged back into the air, so there is no pollution to the environment. The energy consumption for operation is only 1/20 of that of an airplane. And the permanent magnetic track produces static magnetic fields, which are lower than the static magnetic field exposure standard recommended by the International Commission on Non-Ionizing Radiation Protection (not more than 40mT). It is an efficient, energy-saving, environmental-friendly, safe, and comfortable future rail transportation.

Its key technologies are: (1) Furtherly enhance the suspension carrying capacity. (2) Need a reasonable field cooling height to achieve a compromise between guiding and suspension forces which are relatively contradictory (Zheng et al., 2007). (3) The rational design and manufacture of the low-temperature cage.

Research on the Improvement Direction of Magnetic Levitation Technology

Improvement Direction of Full Speed Domain

For scholars who want to get started in the field of maglev, most of the literature they come across is about the analysis of maglev technology. And to engineer the technology the society and manage it, the full-speed domain is going to be a good breakthrough. Therefore, the improvement direction of the full-speed domain is also a focus of the discussion of this paper. In fact, maglev methods have a promising future feasible in the full speed domain from low and medium-speed to astronautically speed.

The first range of full-speed domains discussed is low and medium-speed

Advantages and disadvantages

Low and medium-speed domain maglev has the advantages of a small turning radius, strong climbing ability, low vibration noise and so on. The shortcomings are limited carrying capacity, which is suitable for rail transportation in the medium sized city.

Possible technology routes

Both EMS and HTS Maglev can be used in this speed domain. EMS has been put into commercial use, which is the mainstream of low and medium-speed maglev trains. HTS Maglev has the advantage of using bridges with a large deflection-to-span ratio. Commercially operated low and medium-speed maglev trains use essentially the same suspension frame structure. The maximum operating speed is 110km/h.

The second range of full-speed domain discussed is the medium-speed (200km/h-400km/h)

Advantages and disadvantages

The advantages of using maglev transportation in the medium-speed domain are the strong ramp and bending capacity, and the smaller vibration impact of trains on the line and trains. Thus, the system operation and maintenance costs are lower. And the disadvantages are that the system technology has not been sufficiently verified, and the special nature of the track structure leads to the higher construction cost of one-time investment.

Possible technology routes

Both EMS and HTS Maglev can be used as methods of the medium-speed domain maglev. And currently, in principle, HTS Maglev is applicable to the medium-speed domain as the basic solution in the medium-speed domain.

The third range of full-speed domain discussed is the high-speed (400km/h-1000km/h)

Possible application area

This range of speed is regarded as an extension of wheeled track high-speed rail to the higher speed. It can not only fill the speed gap between wheeled track high-speed rail and air transportation, strengthen the existing advantages and economic aggregation effect of wheeled track high-speed rail, but also further transfer air passenger flow, and is conducive to emission reduction.

Possible technology routes

The three suspension principles are applicable to this speed domain. EMS has achieved commercial applications, and commercial lines of LTSEDS are under construction.

In this speed domain, the combination of train and evacuated tube technology has not formed a definite speed limit. The key technology research of high-speed maglev of 600km/h is being carried out without the combination with evacuated tube technology.

The fourth range of full-speed domain discussed is the ultra-high-speed (from subsonic to supersonic)

Possible application area

The minimum requirement for ultra-high-speed is to be able to be comparable to aviation to divert air traffic. And next, to meet public expectations for higher speeds in the future. For public transportation, the speed range of 1,000km/h-2,000km/h is the goal of ultra-high speed domain efforts.

Possible technology routes

Currently, the ETT technology route is feasible. As an infrastructure, it is necessary to solve a series of technical problems such as the construction of over-length evacuated pipelines, disaster prevention, emergency rescue, applicable vehicles, station transition, and so on.

HTS Maglev and EDS have been proven that can reach speeds of more than 1000km/h in principle. Therefore, “ETT+HTS Maglev” or “ETT+EDS” are both feasible. The former has the characteristics of a permanent magnetic track, static suspension, and zero magnetic resistance. The latter has the characteristics of a simple track.

The fifth range of full speed domain discussed is space speed (space launches)

Possible technology routes

The most suitable technological route for this task is the “ETT + superconducting electrodynamic suspension system”. It uses superconductivity to obtain a very strong moving magnetic field. And uses the evacuated tube to obtain speed as fast as possible and reduce the requirements of the length of the infrastructure. It also uses EDS to significantly reduce the requirements for track accuracy.

Improvement Direction of Operation and Maintenance Management System

As a high-tech rail transportation with cutting-edge engineering, maglev has very strict requirements for safety, reliability, and redundancy. Its maintenance management must have the characteristics of scientific planning, condition monitoring, process control, history traceability and information sharing. However, traditional maintenance management often uses a large number of personnel for information collection, processing, and transmission. This results in overly large and complex management departments and difficulties in timely forecasting and handling of system failures. Thus, delaying the maintenance and normal operation of trains. It is obviously difficult to meet the above requirements.

According to the actual operation needs, the maglev train operation and maintenance management system should, on the one hand, be able to timely reflect the train operation condition, automatically generate planned maintenance work, and improve the response speed of fault prediction and maintenance. On the other hand, it should realize the integrated management of the maintenance plan and shorten the maintenance occupation time through the rapid sharing of maintenance management information.

Thus, the design of the system should reflect the following aspects: (1) Networked structure. An information network connecting various units or departments is formed. Different departments and individuals access work-related information according to their access rights. (2) Modular design. Maintenance Management System (MMS) (Dan & Zhao, 2006) should have strong flexibility and scalability. With the change in information management needs, administrators can adjust the structure of the information system and user rights by themselves. (3) Automatic transmission of information. The transmission of information, reports, etc. should be done automatically by the system. The relevant departments only need to perform simple click operations to complete the work to be done and fully grasp the status of each business. This relieves the complicated process of printing, tabulation, signing, transmission and other processes. (4) Timely transmission of information. This allows maintenance managers to communicate and collaborate more easily and quickly through the MMS. And eliminating barriers in time and space. (5) Shared information resources. All kinds of information resources related to the operation of maglev trains such as documents, reports and data, and other information resources related to people, money and materials can be unfriendlily managed through MMS to improve maintenance efficiency and facilitate comprehensive inquiries.

Improvement Direction of Noise Control

Noise is the key to the service performance of the trains. The noise not only affects the surrounding residents, but also affects the comfort of the passengers inside the train, and even causes fatigue damage to certain components of the maglev train.

The noises of the maglev train are mainly from two aspects. The main aspect is aerodynamic noise, which has a clear link between this noise and speed. The secondary aspect is electromagnetic noise, the motor long stator variable frequency and variable voltage current may make the long stator winding produce this noise. The pass-by noise of maglev trains can peak and drop in a very short period. For low and medium-speed maglev trains, the noise generated during the climbing section is significantly higher than that generated during the flat section. And the lower the speed, the more obvious this phenomenon is.

The noise inside the maglev train includes not only the basic maglev noise but also covers the equipment operation and other noises. Usually, the noise can be divided into two categories: air sound and solid sound. If the two types of noise in the interior of the car through multiple reflections, it will cause the noise level to increase (An et al., 2017).

In order to reduce the adverse effects of maglev trains on the passengers inside the cars, the control of the noise inside the maglev trains needs to be carried out in various ways. Specific control measures are as follows:

Simplify the composite body plate. The body structure of the maglev train mainly chooses sandwich boards as the main material. According to the location difference, set different thicknesses of the damping layer. (Liu et al., 2017).

Double-layer sound insulation wall. It can be used to reduce the noise hazard by adding argon to the middle layer of the window and setting the tilt angle of the outer glass, thus, realizing the double-layer sound insulation.

Floating floor. The human ear can feel the sound vibration frequency of 30-50 Hz but the resonance frequency of a floating floor is lower than 15-20 Hz, so it can be effectively applied to the sound insulation and noise control in the maglev train.

After the internal noise control for the train is completed, the noise can be controlled comprehensively by combining the basic situation of the maglev train line. First of all, the maglev line should be selected as far away as possible from the intercity line, avoid the residential concentration area, and plan to control the new sensitive buildings. In addition, it is also necessary to reasonably control the running speed of maglev trains (⩽250km/h), ensure the speed of travel as well as effectively control the maglev noise.

Comparison Study of Technical, Economic and Social Benefits with Wheeled Track

This is also the count argument of this paper: the advantages of the maglev are the missing benefits of using only wheeled tracks instead of a maglev.

Technology Advantages and Corresponding Economical Effects

Maglev and wheeled track each have their own characteristics and limitations that can complement each other:

Firstly, is no commonality. Wheeled track after more than 200 years of development follows the same basic principle: the use of rolling contact with the wheeled track to achieve support, guidance, traction, or braking. This shows that the basic line structure of the train and the maglev lacks versatility.

Secondly is the non-adhesive operation. Conventional railroads rely on wheel-rail rolling friction operation, known as cohesive operation. The degree of friction utilization determines and limits the traction capacity of the system. In order to achieve higher speeds, it must use as much of the train's mass as possible to generate friction. Ultimately the entire mass of the train is used to generate friction, with all axles being dynamic.

Regardless of the principle used, maglev does not have mechanical contact friction and breaks through the friction limit, which is called non-adhesive operation. So the maglev can adapt to much higher speeds than high-speed rail.

Thirdly is the non-vehicle power. For a wheeled track, the traction motor of a non-vehicle-powered high-speed wheeled track train is installed on the body, and the traction power will be transmitted from the ground to the train through the sliding contact. The maximum speed of the train should not exceed 70% of the contact line wave speed, the maximum speed of the train is therefore limited.

While medium and above-speed maglev are used track-side long stator linear synchronous motors, traction power does not need to be transmitted from the ground to the maglev train so that the traction and ramp capacity for higher speed is no longer subject to flow restrictions.

Finally, the suspension distribution load. Most of the Chinese high-speed rail lines use the viaduct. The train belongs to the passive support mode, which can use a larger bridge deflection-to-span ratio. This is conducive to reducing construction costs. However, the high speed always leads to a large dynamic response component, which increases the maintenance cost of the line and wheeled track train.

Maglev belongs to active support and keeps the levitation gap at the rated value through active control between the train and the track. And according to the practical experience of Shanghai high-speed maglev, the maintenance cost of maglev lines is about 50% of that of conventional high-speed rail.

As the example of the suspension distribution load shows, the technological advantages will be transformed into economic advantages. The economic value of maglev is not only reflected in the maglev itself such as the high speed brings more business needs, the traction method makes the motor spend less and built in such a way that maintenance costs are lower, but also in the development of basic industries and technologies through the development of maglev technology. Like maglev involves rare earth materials, permanent magnetic materials, composite materials and other basic materials that are the basis of industrial development. In order to drive the development of other basic industries, the high ground of this technology should be occupied.

Social Benefits

Quantifiable social benefits.

Benefits of time-saving in transit. Maglev trains in service can reach a maximum speed of 505km/h, while the bus speed is only 45km/h due to the performance of the transport and road traffic restrictions. Based on the same 30 km ride distance, each ride can save 33 minutes.

Benefits of replacing ground buses. Maglev trains have a large capacity, according to the grouping of 5 cars/column, with a rated occupancy of up to 500 people. While bus capacity is generally 45 people/standard, only 1/11 is weak for the maglev train. If the bus utilization rate is 10 trips/day standard, according to the maglev train forecast 3.24 two-way, 10,000 daily passenger flow, the number of new buses needs to increase by 72 standards. Suppose each standard vehicle purchase price is ￥350,000, the vehicle purchase cost savings of ￥25.2 million. In addition, consider if there are no maglev trains, but only ground buses, it also needs to invest in bus-supporting facilities. If each standard bus-supporting facility for ￥100,000 one time, the bus-supporting facility can save ￥7.2 million. Also, road maintenance costs￥1 million per year. Bus operating costs, at ￥1.5 per passenger, annual savings of ￥14.58 million.

Benefits of reducing traffic accidents. The use of maglev trains can greatly reduce the loss of traffic accidents. If the traffic loss per person is ￥0.2, the recent annual traffic accident loss reduction is ￥1,944,000.

Benefits of land value appreciation. The completion of the maglev train operation line will make it another landmark in the region and rapidly drive the value of land in the surrounding area.

Potential social benefits.

Improve transportation structure and reduce energy consumption and urban pollution. The completion of the maglev train operation line can greatly reduce the energy consumption caused by vehicles. This reduces emissions and noise interference, which is conducive to the improvement and enhancement of the urban living environment. At the same time, it will improve road passing capacity and save transit time.

Promote further development of the city. The completion of the maglev train operation line will promote the further development of the city’s economy and, in particular, play a positive and effective role in improving the investment environment of the region.

Proposal of Chinese Road Network Planning Integrated with Magnetic Levitation Development

China High-Speed Railway is an important type of transportation infrastructure in contemporary China.

China’s high-speed track network of “four longitudinal and four horizontal” trunk lines has been completed ahead of schedule. And is advancing towards the “eight longitudinal and eight horizontal" network and will achieve a 1h-4h traffic circle between neighbouring large and medium-sized cities. The most modern and developed high-speed track network in the world has been built. Moreover, there are 206 civil airports in China's civil aviation industry, which can achieve 4h of access between long-distance cities in China.

However, in this context, the development of high-speed maglev is still had its necessary. In 2021, China issued a transportation network planning proposal: "Study the layout and test line construction of high-speed maglev channels between mega-cities". The plan also puts forward the "123" hour requirement: 3h arrival between major cities is required. So high-speed maglev should be integrated into the systematic planning of network planning.

However, the high-speed maglev is more controversial. First, what is the maximum and approximate technical speed of wheeled track trains? The second is what maglev technology to replace the wheeled track technology at higher speeds? This section will conclude credible conclusions and give feasible suggestions.

Regarding the maximum speed of the wheeled track, the successful operation of the "Fuxing" CR400 has resulted in a maximum theoretical speed of over 600km/h, with a commercial operation speed of 350km/h. If the intelligent "Fuxing" CR500 and CR600 are successfully developed and can adapt to line conditions, it is possible to speed up to 450km/h and 500km/h in straight sections. But the facts show that it's difficult to break through the speed higher, due to the operation environment, materials of the train, body size, operation and maintenance capabilities, and other practical limitations.

By analysing the research and industrial applications, operating speed between 200km/h-500km/h, should also belong to the rail world. Any maglev is not enough to compare with the wheeled track. For example, if the intelligent "Fuxing" CR500 can be developed successfully, its intelligent autopilot will be able to memorize the state parameters throughout the whole line. To run on the low-standard high-speed track network, it is only to precisely adjust the operating speed according to the line conditions in real time.

As for the operation speed of 600km/h and above, high-speed and ultra-high-speed maglev are the best choice. And China's original HTS Maglev train can reach a speed of 620km/h at the starting point. The speed can even reach more than 800km/h, up to several thousand kilometres per hour if it is equipped with a vacuum tube. Even if open operation, it can cover 400km/h-600km/h, which can not only fill the speed gap of the wheeled track but also accommodate the whole course of ultra-high-speed. So at present, the future of maglev high-speed or ultra-high-speed trains preferably use HTS Maglev.

Conclusion

In summary, this paper analyses the technical status and Chinese development prospects of maglev transportation from physical principles and technical details to product realization, engineering promotion, management application, and industrial development.

Physical principles: The definition and principle of maglev technology are understood to conclude that this principle can be applied to rail transportation.

Technical details: The principles and modes of operation of levitation, drive and guidance system of the EMS, PMEDS, LTSEDS and HTS Maglev modes are analysed separately.

Product realization & engineering promotion: According to the present status of high-speed maglev research and development in Japan, Germany, America and China, and the history of low and medium-speed maglev research and development in China, there is an obvious gap between maglev and wheeled track. But there has been a good development trend with the active efforts of each country.

Management applications: By analysing the key technologies of each maglev mode, it is found that they can be applied to the full-speed domain to fill the speed gap of wheeled tracks. In addition, it is possible to improve operation and maintenance management by optimizing computer systems and controlling noise by three methods of changing the body structure such as simplifying composite body panels.

Industrial development: By comparing with the wheeled track in terms of technology, economic and social benefits, it can be concluded that the wheeled track is more versatile while the maglev can reach speeds far beyond that of the wheeled track and is more economical and environmental-friendly, which can promote social development. Thus, the two transportation modes have their own characteristics and limitations and can complement each other. So in this case, the Chinese road network also has a new plan, that is, the low and medium and medium-speed domain should belong to the wheeled track world, while maglev is the best choice in the high-speed and above-speed domain.

This paper completely sorts the research on maglev out. However, it also has a limitation. Only aspects related to technology were written in the proposal for the Chinese road network, while the economic aspects were not mentioned much. So in the future, this project can do a further study to combine economic factors with the proposal for the Chinese road network.

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