Equinox Issue

SCHOLARLY REVIEW

An overview of maglev trains

By Dhairya Sheth

Author Biography

Dhairya Sheth is a senior at Navrachana International School Vadodara. He has always been interested in knowing how things work and applying physics concepts to real life. One area he is highly passionate about is electromagnetic levitation and he keeps expanding his knowledge about the subject by continuously researching and attending courses. He is interested in pursuing Engineering and continuing research in university.

Abstract

This paper provides a detailed review of maglev (magnetic levitation) trains, explaining the technology and underlying principles behind it. It also covers the history of this evolving mode of transport. Moreover, it addresses and analyzes the advantages and challenges of maglev trains compared to the traditional rail system: technical, infrastructural, and economic factors have been taken into consideration. Further, it explores the potential improvements to the technology to make it more efficient and cost-effective. The paper will focus slightly more on the Japanese maglev trains as they are the most developed.

This paper aims to become a one-place resource for readers to gain knowledge about maglev trains. The author was motivated by the fact that this field, despite being so heavily researched, has a lack of research papers or articles published for readers and inquirers to easily learn about the whole concept; the majority of papers found were published in the early 2000s. Therefore, this paper also intends to include the latest advancements. It is an overview, written after going through multiple past research papers, websites, informative videos and videos of interviews from reliable and credible sources.

Keywords: maglev trains, Magnetic levitation, Electromagnetism, High-speed trains, Propulsion, Electromagnetic suspension (EMS), Electrodynamic suspension (EDS), Japanese maglev

Maglev technology

Electromagnetism and magnetic levitation

A magnetic field is an invisible force that forms around a magnet due to moving electric charge. This is what makes magnets what they are; they can repel and attract other magnets according to their magnetic fields. Magnets can be classified into a number of types: permanent, temporary magnets, electromagnets, diamagnets, paramagnets and ferromagnets, according to the element it is made of.

Electromagnetism is an interaction of electric currents and magnetic fields. When charge flows through an electric conductor (wire), a magnetic field is created around it, and an electromagnet is formed. It is a form of magnet that, unlike other forms, can be switched on and off because the flow of current can be controlled.

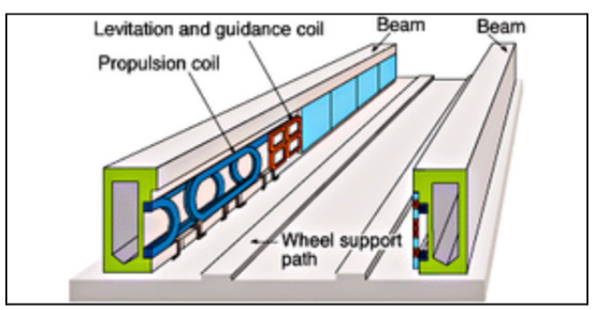
Magnetic levitation is a phenomenon where an object is suspended mid-air without any direct physical contact. It mainly occurs due to repulsion of opposite poles of the magnets. Any system that uses magnetic fields needs to take in consideration multiple factors such as strength of magnetic field, weight of object, and distance between the magnet and object. Moreover, the stability of the levitating object is the most important feature that needs to be achieved for a maglev system to be proved successful. Electromagnets have achieved it; however, the type of materials and other features depend on the extent of power and stability needed ("What is Electromagnetism?," n.d.).

There are two ways to levitate objects: Electromagnetic suspension (EMS) involves use of magnets to both lift and propel the object; magnets have complete control of all directions. Electrodynamic suspension (EDS) uses magnets to lift the object, but it is the electricity created by the motion of the object that helps it move forward. Most of the current maglev trains use EDS systems as they have been proved to be more beneficial.

Material and technology behind maglev trains

Like most maglev applications, maglev trains also require the magnetic field to be switched on and off. Hence, only electromagnets can be used. However, ordinary electromagnets are not capable enough to produce the required power with precision needed to propel the heavy train; strong and stable magnetic fields are needed that can counteract the train's weight and levitate it.
Therefore, superconducting materials are used as they allow flow of charge with zero resistance when cooled to very low temperatures, making them the perfect material for maglev trains. The magnetic field is very strong and there is no energy loss in any form like heat or light.
Specifically, the alloy niobium-titanium (NbTi) is the most commonly used material. To cool NbTi to a superconducting state, liquid helium (He) is used as it can attain a temperature around -269 °C (TokyoTechX, 2023).
Maglev trains function using three concepts:
Levitation—train is lifted off the track.
Propulsion—train is moved forward by magnetic forces.
Guidance—train is kept on the track by magnetic forces.

Figure 1
Structure of guideway

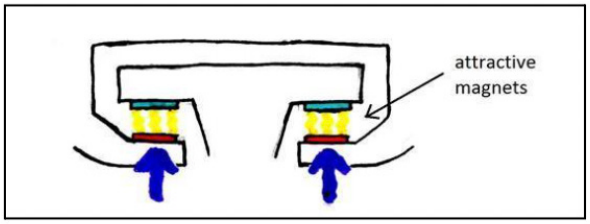


Note: HowStuffWorks. (n.d.). [Image of Maglev Track]. Retrieved August 3, 2024

Levitation

When current is supplied, it uses attractive forces of electromagnets installed along the guideway and underneath the train to achieve levitation.

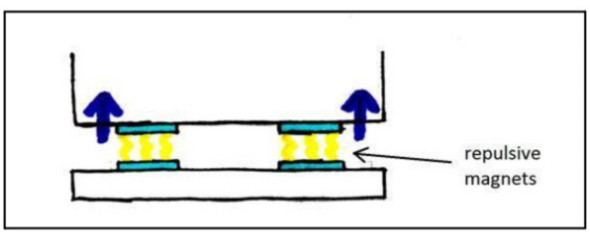
Figure 2
Electromagnetic suspension (EMS)



Note: Wilson, C. (2015). ECE_SHP_Figure05_v1 [Image]. Tufts University. Retrieved August 3, 2024

The main benefit of EMS is its uncomplicatedness and its ability to levitate the train even when it is stationary. However, EMS systems would result in unstable levitation of the train, and would require elaborate feedback control systems to make sure that the train maintains the desired distance from the guideway (Wilson, 2015).

Figure 3
Electrodynamic suspension (EDS)



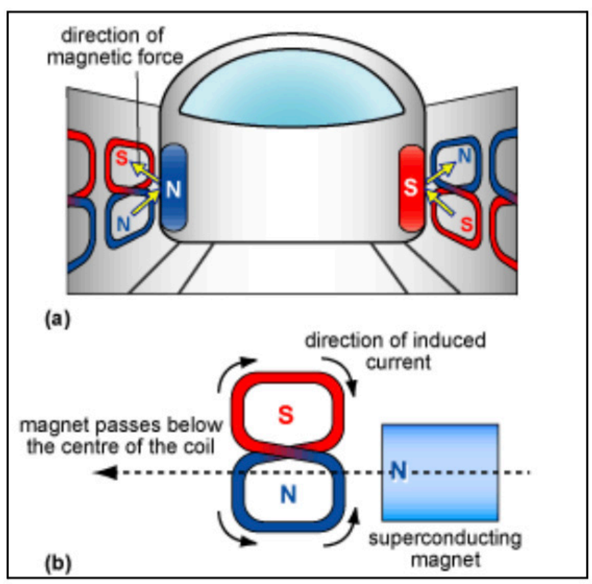
Note: Wilson, C. (2015). ECE_SHP_Figure06_v1 [Image]. Tufts University. Retrieved August 3, 2024

EDS systems work due to the repulsion of the superconducting magnets on the guideway and the train. Stable repulsive force will be produced when the train's magnets pass the magnets of the guideway at high speeds.

As suggested by their name, EDS systems are 'dynamically' stable. Therefore, any variations in the distance between the train and guideway will result in strong forces being generated that automatically correct the position. Hence, feedback control systems are not needed. However, the only drawback is that EDS systems require the train to travel at a particular speed before it can levitate. This makes it a bit complex, and wheels are needed to begin and end the motion of the train. Specifically, the Japanese EDS trains need to reach a speed of approximately 93 mph (150km/h) (Wilson, 2015).

Japanese engineers have developed a version of EDS that uses cooled superconducting electromagnets. The special feature of these is that they can conduct electricity even when power is not supplied, preventing any mishaps due to a power cut and saving energy. The systems required to cool these magnets are called cryogenic systems, which are very expensive. These trains levitate approximately 4 inches (10 centimeters) above the guideway.

Figures 4a, 4b
Levitation, Japanese levitation-guidance coil



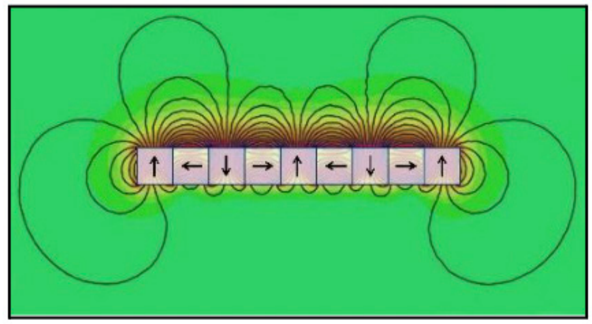
Note: Physics and Radio Electronics. (2017, December). [Technology of EDS]. Retrieved August 3, 2024

The levitation in maglev with superconducting magnets is achieved with electromagnetic induction. That is the reason why it does not require external power for levitation. The levitation-guidance coil that interacts with the superconducting magnets has a structure like the digit “8” and is made of common wires. When the superconducting magnets on the train are not centered, oppositely induced voltages in the coil cancel each other and so there is no flow of current. However, as soon as the magnet moves, an imbalance in the magnetic field induces a current in the coil, producing a force that pushes the magnet back to the center. This repeated cycle results in stable levitation that becomes more stable with speed (Tandan et al., 2015).

Inductrack

Inductrack is a novel version of EDS that utilizes permanent magnets at room temperature to generate magnetic fields required for levitation. It uses an array of permanent magnets arranged in a configuration known as the Halbach array. This array configuration is a substitute of powered electromagnets or the cooled superconducting magnets. The magnetic field is concentrated above the magnets, resulting in a stronger levitating force. There are different variations of the inductrack system according to the function of the train, for example, high and slow speeds, or carrying cargo.

Figure 5
Array of permanent magnets



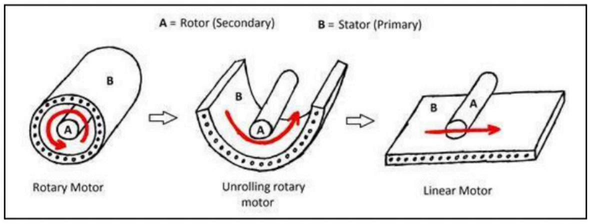
Note: Wikipedia. (n.d.). Hallbach array field. In Wikipedia, The Free Encyclopedia. Retrieved August 3, 2024.

The main advantage of Inductrack is that it levitates the train even at lower speeds, so control systems are not needed. Additionally, in case of a power cut, the train can decrease the speed gradually and stop on wheels. Moreover, the Inductrack system is cost effective compared to superconducting EDS systems as permanent magnets are significantly cheaper than superconducting materials.

Propulsion

Propulsion is the force that causes the train to move forward. Electric linear motors are used in maglev trains to achieve propulsion. A commonly-used electric rotary motor uses magnetism to generate torque and spin an axle. It also has a stator, a stationary piece, which surrounds the rotor, the rotating part. A linear motor can be said to be an unrolled version of this rotary motor: the stator is put flat, and the rotor is placed above it. Therefore, instead of a rotating magnetic field, the stator produces a magnetic field that goes down its length. Similarly, instead of experiencing a rotational force, the rotor experiences a linear force that pulls it down the stator, producing motion in a straight line. However, the motor only generates a force when the rotor is above the stator; when the rotor reaches the end, it does not experience force any more and stops moving.

Figure 6
Rotary motor and linear motor



Note: Wilson, C. (2015). ECE_SHP_Figure07_v1 [Image]. Tufts University. Retrieved August 3, 2024.

When talking about linear motors, the "stator" is actually called the "primary" and the "rotor" is termed "secondary". Therefore, in the case of maglev trains, the primary is in the guideway and secondary is at the bottom of the maglev train. So the magnetic field goes down the guideway, pulling the train along.

The system described above is known as Linear Induction Motor (LIM). This is because the magnetic field in the primary induces the magnetic field in the secondary and their interaction causes the secondary field (train) to be pulled along. However, in this structure, the secondary layer lags behind the moving magnetic field in the primary, and this fact generates some energy.

Linear Synchronous Motor (LSM)

In LSM the energy loss problem is solved. This is done by placing permanent magnets on the secondary. Now the secondary generates its own stationary magnetic field and travels in sync with the moving magnetic field of the primary, making it faster and more efficient. Therefore, LSM is used instead of LLM in high-speed maglev trains.

Superconducting maglev propulsion

As in levitation, superconducting materials are used for propulsion. Either LLM or LSM is used. The train is propelled by regularly altering the electric current. The speed of the train is proportional to the rate of change of the direction of the current. An electric supply with variable frequency is used to control the speed.

The propulsion coils are placed on the sidewalls of the guideways. Position sensors track the train's position and speed as it moves forward. The propulsion control system compares measured data with the reference values and determines the current that is required to be supplied to the propulsion coil: the current produced by the inverter follows the reference value from the control system. The measured data by the sensors is sent to the drive control system. For smooth and efficient propulsion, this feedback system calculates the required current and its phase angle. The propulsion control system does not actually have a driver on board. It is controlled by ground staff. The train schedule stored in the database serves as the reference values and the traffic control system gives instructions regarding the running of the maglev according to the set run-curve reference (Wilson, 2015).

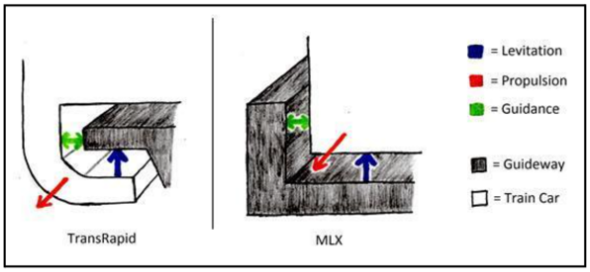
Guidance: Track and Guideway

The guideway structure is comprised of two main elements:

- The traveling track- it is the bottom part of the guideway. The train starts and stops on this.
- Sidewalls- these are walls on the sides of the traveling track. They consist of the levitation-guidance and propulsion coils.

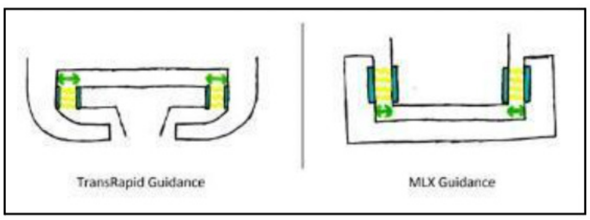
Guidance mechanisms are methods to ensure that the train is in its correct positions:

Figure 7
German guidance mechanism: TransRapid



Note: Wilson, C. (2015). ECE_SHP_Figure04_v1 [Image]. Tufts University. Retrieved August 3, 2024.

Figure 8
Japanese guidance mechanism: MLX



Note: Wilson, C. (2015). ECE_SHP_Figure08_v1 [Image]. Tufts University. Retrieved August 3, 2024.

TransRapid (Germany): this system uses EMS where two electromagnetic rails are placed on the train, facing either side of the guideway. These rails keep the train in the correct position with the help of repulsive forces to cancel any lateral movements.

MLX (Japan): the MLX system integrates guidance with levitation. The levitation rails on the sides of the guideway are interconnected. When the train, from center, moves to one side, it is pushed back to center by a restoring force.

The superconducting maglev trains in Japan have a sophisticated levitation guidance mechanism consisting of levitation-guidance coil and horizontal centering, as described previously in the paper under the heading ‘Levitation’ (Bonsor & Chandler, 2024).

Evolution of maglev trains

With the discovery of electromagnetic induction, the foundation of the maglev technology was laid in the 19th century. However, in the mid-20th century maglev started to gain popularity amongst scientists who then began research on the uses and applications of maglev.

It was in the 1960s and 1970s that the idea of maglev trains was conceived and researched upon by the scientists of countries like Japan, Germany, and the United States of America. At that time, the systems were based on EMS, where magnets on the train experienced an attractive force by the conducting rail. These models did form a base for further advancements but there were many problems with them such as energy efficiency and stability. In the late 20th century great advancements in material science led to improvements in the maglev trains. Superconducting materials were used, and Japan and Germany lead the path of developing fully functional and commercial maglev trains.

Japan was at the forefront in the development of maglev trains. The L0 series maglev train of Japan Railway Company (JR Central) has achieved all-time-high speeds. In 2015, they achieved the record-breaking speed of 375 mph (603 km/h). These trains use EDS technology (Northeast Maglev, 2018). China has also shown progress in maglev technology. It has the Shanghai maglev train that uses a German-developed EMS system. Though it has not been commercially operating since 2004 and is not as fast as the Japanese maglev train.

In present times, maglev trains are at an important stage that will decide their future. Developers will have to invest resources into it to achieve its full potential. Japan and China are aiming to make the trains completely available to public trains at the earliest, whereas other countries are still exploring the technology. The United States has shown interest in the trains and plans to execute a number of projects, and many researchers at universities are exploring and experimenting with the technology. Currently, there are six commercial maglev trains located in Japan, South Korea and China. China is also working on making autonomous (driverless) maglev trains that will function on computer sensors and automation for acceleration and braking.

Comparison with the traditional rail system

Advantages

Along with the most desirable feature of maglev—the high speed—multiple other factors make maglev more desirable than the traditional trains.

Longevity and economic viability: components (wheels and rails) of traditional rails experience a lot of stress over time. In maglev, there is no physical contact between the train and guideway, so there is less deterioration. Therefore, parts of maglev last longer.

Energy efficiency: one of the main benefits is that there is no friction between the train and its guideway like it is in traditional trains and its rail. Therefore, maglev trains do not lose any energy and are more efficient. Moreover, less power is needed to operate maglev trains, especially with EDS systems, as only initial power is required to create magnetic fields, but not for the motion. The success of any transport system is mostly decided based on its power consumption and efficiency. Hence, on a long term, maglev trains are better for an economy compared to current rail systems.

Environmental impact: maglev trains can make quicker and sharper turns, which allows guideways to be built in tighter spaces. These guideways occupy less space, reducing deforestation. It is also safer for animals as it might reduce the accidents that are caused due to animals stepping onto the tracks and crashing with the rail-trains; maglev trains might pass above the animal, saving them in such situations. Additionally, maglev trains will cause less noise pollution. These would also be beneficial features for citizens residing near the guideways.

City's perception and tourist attraction: to some extent technological advancements like these build a better image of the city in the minds of the citizens, visitors, and the broader public in general. They perceive the city to be better and modern. Moreover, the citizens would appreciate novel technology being implemented in their city and this would also indirectly create a positive opinion in their minds for the government. Citizens enjoy better facilities that improve their quality of life. Furthermore, this might also attract tourism, which is beneficial for the economy of the city and country.

Safety: maglev trains are virtually impossible to derail. Aside from a problem with the building of the structures, otherwise the technology on its own is safe. Moreover, the weather can not cause much problem, like it can to normal trains. Snow, rain, ice or wind can affect the traditional trains as they use contact and friction for motion, but maglev trains would not be affected. Lastly, it is easier to build guideways on a height as, except the beginning and starting part, the guideway does not have to sustain the weight of the train. Therefore, the height of the guideways prevents objects from interfering with the path of the trains and reducing the probability of any collisions (Wilson, 2015).

Disadvantages

High initial costs: one barrier to completely shift to maglev trains is the high costs to set up the infrastructure. Building the elevated guideways, getting all the materials, building new trains and cooling systems demand high investment that governments are not ready to make. Moreover, rail systems are all over cities in the whole world, and replacing them with maglev will be a large change that can be done gradually. This would take up many resources such as labor, costs, and time. Lot of construction work would have to be done in the city, causing destruction, as the old rail networks will be destroyed and new guideways will be installed.

Technological complexity: it is a completely new concept to the engineering world and needs highly skilled and educated engineers for the making of guideways and trains. If the required expertise is not available then there might be technical failures that in turn can increase maintenance costs.

Public acceptance: people may not find such a large change reasonable. It would be difficult to convince them to trust this new technology as they might doubt its safety and effectiveness (Wilson, 2015).

Future improvements and advancements

Maglev technology holds a lot more potential. Further advancements can lead to even higher speeds being achieved, and technological improvements may make the maglev trains more economically sustainable.

One of the most interesting advancements may be combining maglev with vacuum tube technology. This idea, exemplified by the Hyperloop and ET3 (Evacuated Tube Transport Technologies), can reduce air resistance to a virtual zero, further increasing the speed of maglev trains, making it possible to achieve a speed of more than 621 mph (1000 km/h). Effective ET3 can also make vehicles travel at the speed of 4000 mph (6500 km/h). If this near-vacuum environment is achieved in a tube, maglev trains theoretically would be able to travel at hypersonic velocities. However, though the ET3 technology is a similar concept, it is a bit far from the working of maglev trains. Another way to reduce drag can be building the guideway in tunnels underground and suck the air out.

To improve maglev trains further, improvements in superconducting materials are necessary. Developing superconducting materials that operate at higher temperatures would reduce the need of highly-advanced cooling-systems. This would reduce the costs as funds would have to be invested in cooling-systems. Moreover, it will be more energy efficient as less energy would be needed in operating the cooling-systems.

The whole world is shifting to renewable energy to become more environmentally sustainable, and the same can be done for maglev trains. Using energy sources such as wind, solar, and hydroelectric can reduce the trains' environmental strain. Furthermore, due to renewable energy sources' tendency to produce energy irregularly, effective energy storage solutions would have to be figured out, like suitable batteries or flywheels, to use the energy sources to the fullest (SkedGo, 2014).

However, these advancements will take time, but the current advantages of maglev trains are a lot to ignore. Nevertheless, only time will tell how soon maglev trains will be widely visible in cities around the world.

References

Bonsor, K., & Chandler, N. (2024, March 21). How Maglev Trains Work. HowStuffWorks. https://science.howstuffworks.com/transport/engines-equipment/maglev-train.htm

Northeast Maglev. (2018, December 18). Transportation Innovation: History of Maglev in the World. Northeast Maglev. https://northeastmaglev.com/2018/09/25/transportation-innovation-history-of-maglev-in-the-world/

SkedGo. (2019, May 21). Future of transport :: Maglev trains. SkedGo. https://skedgo.com/the-future-of-transport-maglev-trains/#:~text=Combining%20maglev%20with%20%20vacuum,is%20based%20on%20this%20idea

Tandan, G. K., Sen, P. K., Sahu, G., Sharma, R., & Bohidar, S. (2015). A Review on Development and Analysis of Maglev Train. International Journal of Research in Advent Technology, Vol.3(No.12), 14–16. https://ijrat.org/downloads/Vol-3/dec-2015/paper%20ID-312201504.pdf

TokyoTechX (n.d.). [Course]. edX. https://learning.edx.org/course/course-v1:TokyoTechX+EE101Jx+1T2021/home

What is Electromagnetism? All you need to know - Ferrovial. (2022, November 2). Ferrovial. https://www.ferrovial.com/en/stem/electromagnetism/#:~:text=Electromagnetism%20is%20a%20branch%20of,with%20electric%20and%20magnetic%20fields

Wilson, C. (2015, March 17). Maglev: Magnetic Levitating Trains – Electrical and Computer Engineering Design Handbook. https://sites.tufts.edu/eeseniordesignhandbook/2015/maglev-magnetic-levitating-trains/