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MagLev: The Train of the Future

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Abstract : *As the world continues to grow and as cities continue to become more crowded and congested, our normal modes of transportation will not be able to handle these overpopulated areas. The answer to this transportation problem lies in the world of electro magnetism and superconducting magnets. Electromagnets and superconducting magnets have allowed us to create a magnetic levitating train nicknamed “Maglev” that floats on the track instead of being directly on it. This has a lot of potential to create trains that are super fast with low maintenance requirements. China is the first country in the world to commercially use MagLevs, and has already helped ease the congestion on the six lane highway leading from the Pudong Shanghai International Airport to Shanghai Lujiazui financial district. This new technology has already helped China in a short period of time and can certainly help other cities around the world that are just as congested as Shanghai.*

Key Words : *Maglev, superconducting magnets, magnetic levitation, Transrapid, lateral guidance, linear induction motor, linear synchronous motor, frictionless travel,*

Tomorrow’s Train

Trains have affected our daily lives ever since they were first conceived and built. Trains have been helping us move large amounts of cargo or people at one time. The earliest trains consisted of only wooden tracks and horse drawn wagons. It was easier to move cargo over these wooden tracks than on dirt roads. This was the beginning of modern railroads. By 1776, iron had replaced the wooden wheels and tracks^[1]. The invention of steam engines helped fuel the industrial revolution and helped move tons of supplies over a long distance.

Steam engines were better than other modes of transportation during the mid-1800’s. They were fast, comfortable, and could carry many people at one time. Steam engines have evolved since then. Even though they have evolved, they are slow. Diesel trains and electrical trains could carry people/cargo much faster than steam engines could. Yet in this ever growing world of ours, we need a faster mode of land transportation.

The answer to this problem lies in the world of electro magnetism and superconducting magnets. There is a train that relies on these principles to float above the tracks and achieve speeds that we could have only imagined before. It is a so called flying train. These trains are called magnetically levitated trains or so called “MagLevs.” Maglev uses superconducting magnets to lift, guide, and propel these vehicles.

Maglev has other advantages over conventional rail travel besides speed. It is a safe and reliable form of transportation. It is no wonder that Japan and Germany have been developing Maglev since the 1970s. They have realized the potential for a technology like this. They have come a long way since then and are continuing to invest in Maglev because they have realized that this technology will be necessary for the growth of their cities in the future.

History and Development

Maglev has been a long standing dream of railway engineers for the past century. These engineers envisioned a train that could float above its tracks. They saw the enormous potential for a train like this. The vision of Maglev began in the beginning of the 20th century with two scientists.

Early Dreams

In 1904, Robert Goddard, who was a college freshman at the time, wrote a paper proposing a form of frictionless travel by raising train cars off the rails by using electromagnetic repulsion roadbeds^[2]. He said the train would travel at super fast speeds. In 1910, Emile Bachelet applied for a patent on a rail car which for levitation would use alternating-current electromagnets and for propulsion would use solenoids at intervals along a road-bed^[2]. Bachelet's dreams couldn't be realized because his concept used too much power for conventional magnets^[3].

In the early 1920s, a German scientist named Hermann Kemper pioneered in work in attractive-mode Maglev^[4]. He received a patent for magnetically levitating trains. Kemper continued to research and pursue his concept through the 1930s and 1940s and established the basic design for practical, attractive-mode Maglev in a 1953 paper^[4].

In 1969, two Americans, Gordon Danby and James Powell, were granted a patent on their design of a magnetically levitated train. This was the first patent for a design of this kind of train^[5]. This was around the same time that Germany and Japan were both getting very interested in Maglev technology. In 1970, both countries start investing money into researching maglev. That same year, the United States Federal Railroad Administration studied high-speed ground transportation. Little Maglev research was actually done and in 1986, all Maglev research funding was stopped and the United States officially stepped out of the Maglev race for the time being.

German Development

In 1969, the German government sponsored a research project which built their first full scale model of a Maglev design^[6]. They called their version of the Maglev the TransRapid 01. A few years later, the first passenger Maglev debuted and carried people for a few thousand feet at speeds of only 50 mph. The German company, Munich's KraussMaffei, which built the first TransRapid, continue to build improved versions of the TransRapid in a joint private-public funded research effort. In 1971, they completed the TransRapid 02. They completed the TR 03, TR 04 in 1972 and 1973, respectively. The TR 04 set a new speed record for passenger MagLevs by going 157 mph in December of 1973^[6]. Germany's first large scale demonstration of the TR was in 1979 was at the International Transportation Fair in Hamburg, where the TR 05 carried about fifty thousand visitors between a parking lot and the exhibition hall for six months^[6].

At this time, a test track was erected to test the system in real world conditions. The test track was a nineteen mile figure "8" track that was built between 1979 and 1987 in Northern Germany [6]. The TR 06 was the first to be tested on this track and it reached speeds of 221 mph after the completion of the first 13 miles of the track. The TR 06 eventually reached a speed of 256 mph and was finally retired after traveling 40,000 miles in 1990^[6]. The TransRapid 07 was built by Thyssen Co. in Kassel. The TR 07 reached a record speed of 280 mph.

A TransRapid route was planned from Hamburg to Berlin in 1992. In 1998, a joint company was formed under the system houses Adtranz, Siemens, and Thyssen^[6]. This new joint company was called TransRapid International. In 2000, the government said that the Berlin-Hamburg route will not be realized and TransRapid International proposed 5 alternative routes where the TransRapid can be built. None of the routes were accepted and TransRapid International started looking for outside interest in their project to save a billion dollars and 30 years of investment.

China expressed their interest in the German Maglev technology. After statistical gathering and analyzing, a contract was reached on January 23, 2001 between Shanghai and TransRapid International to build a line between Shanghai and its airport. On December 31, 2002, the first commercially operated Maglev line took its maiden voyage carrying on board Chinese Prime Minister Zhu Rongji, German Chancellor Gerhard Schroder and other high ranking politicians and business people from both countries. One year later, the world's first commercial TransRapid route starts scheduled operation in Shanghai.

Japanese Development

The Tokaido Shinkansen was the early Japanese high speed train line. It opened in 1964 and since then has expanded considerably. Its success also prompted the development of high speed trains in the west. But the Japanese public demanded an even faster form of high speed rail travel. The Shinkansen used a conventional train design, with motors and other equipment mounted on the rolling stock, electric power gathered from overhead wires, and wheels running on rails. It was impossible to increase the speeds much more. Some of the limitations included: Greater size and weight of on board equipment, difficulty in collecting electric power, and reduced adhesion between wheels and rails at higher speeds that may cause wheel slipping^[7]. There had to be some new sort of technology that could create faster trains that were just as safe as or even safer than the trains running on the Shinkansen lines. The answer to this problem lied in electro magnetism.

The former Japanese National Railways (JNR) began conducting Maglev research and development in 1970. The Miyazaki Test Track was built in southern Japan and experiments and test runs were being conducted on the tracks. In 1979, the prototype ML-500 test train reached an unmanned speed of 517 km/h on the 7 km track, which proved that Maglev had a great potential for reaching higher speeds than any other train built before that. The Miyazaki track was later modified into a U shaped to simulate more real world track curves. At this stage of development, the government started funding the project. The MLU001 was the first Maglev developed with government financial aid. Other models were built and continued to be tested and experimented on the Miyazaki test track. But there was a problem with the track. It was too short and only had a single guideway with no tunnels and no inclines or declines. The experimental data gathered on the Miyazaki test track would be too limited to verify trains commercial potential and use.

After the JNR was split and privatized in 1987, the Tokaido Shinkansen experienced an increase in passengers which led to more calls to build a commercial Maglev line as soon as possible^[7]. As a result, the Yamanashi Test Line was constructed in Yamanashi Prefecture, approximately 100 km west of Tokyo.

The Yamanashi test line was 18.4 km long and supported a wide range of tests to determine the commercial feasibility of the Maglev train. The track was made up 16 km of tunnels and an open section that was 1.5 km long in the middle of the track. A substation for power conversion and other facilities were located in the 1.5 km stretch of open section. Part of the line was double tracked to simulate trains going in opposite directions at super high speeds.

Trial runs began on the Yamanashi Test line in April 1997. The cars weren't levitated but instead were driven at low speeds on rubber tires. Once tests confirmed that there were no defects in the vehicles or the guideway itself, levitation runs began at the end of May 1997. The speeds were increased incrementally to monitor car movement and verify braking performance. On December 12 1997, a new world record of 531 km/h was set for manned train travel. A maximum speed of 550 km/h was set for unmanned travel 12 days later. There was only one more problem that remained: air vibration that rattles the windows of buildings near tunnel portals when a Maglev train enters or leaves a tunnel at high speeds. Everything else seemed to be in good shape. There were no environmental problems, ground vibration measurements were well within acceptable limits. Magnetic fields measured at ground level directly under the elevated guideways were also within acceptable limits.

Tests were conducted so that two cars passed each other at high speeds. The vibration of the trains passing each other was so small that it could only be felt by someone actually expecting it. Overall, there were no major problems that occurred during the test runs. More testing will be required before commercial use of Maglev trains in Japan will start. During the next few years, these test runs will be focusing on 3 things:

- Verifying long-term durability
- Finding ways to reduce costs
- Achieving more aerodynamic car designs

But what is the history of maglev without knowing how this magnificent technology works?

How Maglev Works

Understanding how Maglev trains work requires some knowledge in advance topics such as calculus, physics, and chemistry. It is important to know common variables assigned to physics terms and a brief overview of chemistry laws dealing with magnets. Most of the equations used to determine how the MagLev trains move is derived from formulas used to calculate electric current, induced voltage, circuit loops, and many other formulas dealing with electromagnetism.

One of the first concepts that form the basis of how MagLev trains work is understanding magnetism and the use of magnetic propulsion. If you were to have a bar magnet you should know that one end is designated a north pole while the other end is called the south pole. Now suppose you are given a second bar magnet, experimenting with it you will find that opposite poles attract while attractive poles repel. This simple form of attraction and repulsion is the same idea used to move those gigantic MagLev trains. Since the magnets needed required enough strength to move a train, engineers have devised the MagLev train using electromagnets and superconducting magnets. Electromagnets are metals with electric current running through them giving the metals a magnetic field similar to that of the bar magnets and superconducting magnets are able to induce charge, or give charge, to a material causing repulsive forces.

MagLev railway development has since integrated these two types of magnetic systems for propulsion to control how the trains move. These magnetic suspension systems are designed so that the MagLev train can glide through air by levitating it above the actual rail line reducing friction that would normally be created from the metal wheel and rail line used in conventional railway trains. The transrapid system developed by in Germany utilizes regular electromagnets on the undercarriage of the train to levitate the vehicle while an additional set of magnets are used to guide the train. The electrodynamic suspension or EDS system developed in Japan use superconducting electromagnets for their MagLev trains allowing the train to remain aloft for a while even after the electric current is turned off using the property of the metals to easily allow electrons to flow easier. What both systems do though is control the MagLev train's lateral guidance, levitation system, and its propulsion.

Lateral Guidance System

The Lateral guidance systems control the train's ability to actually stay on the track. It stabilized the movement of the train from moving left and right of the train track by using the system of electromagnets found in the undercarriage of the MagLev train. The placement of the electromagnets in conjunction with a computer control system ensures that the train does not deviate more than 10mm from the actual train tracks^[8]. The lateral guidance system used in the Japanese electrodynamic suspension system is able to use one "set of four superconducting magnets" to control lateral guidance from the magnetic propulsion of the null flux coils located on the guideways of the track as shown in Fig. 1. Coils are used frequently in the design of MagLev trains because the magnetic fields created are perpendicular to the electric current, thus making the magnetic fields stronger. The Japanese Lateral Guidance system also uses a semi-active suspension system. This system dampens the effect of the side to side vibrations of the train car and allows for more comfortable train rides. This stable lateral motion caused from the magnetic propulsion is a joint operation from the acceleration sensor, control devive, to the actual air spring that dampens the lateral motion of the train car.

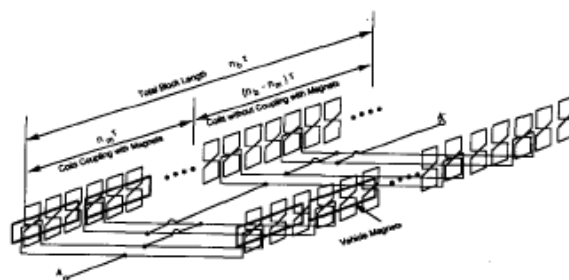


FIGURE 1

A SKETCH OF THE COMBINED LEVITATION, PROPULSION, AND GUIDANCE SYSTEM. [8]

The lateral guidance system found in the German transrapid system is similar to the Japanese model. In a combination of attraction and repulsion, the MagLev train is able to remain centered on the railway. Once again levitation coils are used to control lateral movement in the German MagLev suspension system. The levitation coils are connected on both sides of the guideway and have opposite poles. The opposite poles of the guideway cause a repulsive force on one side of the train while creating an attractive force on the other side of the train. The location of the electromagnets on the Transrapid system is located in a different side of the guideways. To obtain electro magnetic suspension, the Transrapid system uses “the attractive forces between iron-core electromagnets and ferromagnetic rails.” A simplified drawing of the electrodynamic magnetic suspension train and the transrapid suspension train are shown in figure 2.

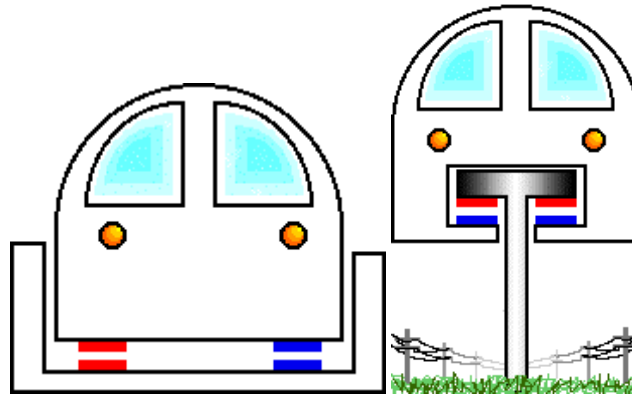


FIGURE 2
 PICTURES OF THE GUIDWAY DESIGN OF THE EDS (LEFT) AND THE TRANSRAPID (RIGHT)

Levitation System

The Levitation systems used in the design of the MagLev railway allow it to glide above the actual track. In electrodynamic suspension systems the actual train can be as high as 80 mm above the track while the Transrapid suspension system allows it to go less than 12 mm from above the track^[10]. In the case of air drift or a turn in the railway course causes the train to lift above the distance needed to stay on track, there is “enhanced current input into the levitation magnets to increase the magnetic force.” Doing this ensures that the train stays on the track with gap sensors on the rail line to detect any change in lateral shift. In order to use magnetic levitation by induction, the team behind EDS had created a system that allowed five degrees of motion. The physics of the actual lift can be described in mathematical terms. The calculated voltage of the magnetically induced coils can be tabulated according to (1) where N is the number of turns.

$$V = -N \frac{\partial \Phi_{\text{coil}}}{\partial t} \quad (1)$$

Once the voltage is found in the coils used in the induction, a formula can be derived for the coil’s current, *i*, as shown in (2) with respect to time. Knowing the *i*, engineers apply Lorentz force equation (3) to calculate the lift force caused by the magnets [11].

$$\frac{\partial i}{\partial t} = \frac{1}{L}(V - Ri) \quad (2)$$

$$d\vec{F} = \vec{i} \times dl\vec{B} \quad (3)$$

Using these equations and additional equations on magnetic flux you can describe the five degrees of motions in the electrodynamic suspension levitation system. These degrees are levitation height,

sideways displacement, yaw, pitch and roll. Each dimension contributes to the torque of the EDS MagLev train^[11].

The electromagnetic suspension system used in the German Transrapid system levitates the train a few millimeters from the actual track. Using a system of electromagnets, the Transrapid system attracts the coils found in the guideway of the MagLev train. The attraction of the magnetic forces occur because the currents found in both the train and the guideway both flow in the same direction. Since this system uses electricity to power the magnetic fields the train is always above the track unless cut from the electric current. To prevent this from happening German engineers have put in a backup battery in the actual MagLev train in case of power failure.

Propulsion System

There are two types of propulsion systems used in current MagLev trains. The Linear Induction Motor (LIM) is used to propel the Japanese EDS system while the Linear Synchronous Motor (LSM) propels the German Transrapid system. Both of the systems are move by the guideways themselves instead of the actual train car. Propulsion occurring in the Linear Induction Motor is caused from the sum of four individual linear motors. The motors induce voltages to the four motors. When these voltages are combined they produce a repulsive force that pushes the train car forward. The speeds for Linear Induction Motors is determined by “the ratio of length of the vehicle magnet system to the length of the energized block, the sum of the coupling coefficients between vehicled magnets and the guideway coils, applied voltage, and the current flowing in the superconducting coils^{[8].”}

The speed of MagLev trains in Linear Synchronous motors are determined by the frequency of the alternating current and the magnetic field directions. Propulsion is created when the current is in ‘synch’ with the frequency allowing for forward propulsion. In order for the train car to brake and slow down, the field simply has to be reversed allowing the train car to brake without the use of friction.

Why Maglev Better

There are several reasons why Maglev is better than conventional rail transportation used today. From being faster, more energy efficient, safer and more environmentally friendly, Maglev surpasses normal trains in almost every way.

Frictionless Travel

Maglev stands for Magnetically Levitated. That means that these trains won't have to touch the tracks in order to move. That will mean they will travel frictionless. That creates the potential for speeds faster than all the conventional rail travel used today. These conventional trains have achieved speeds about 500 km/h in special laboratory tests but their normal operating speeds is below 300 km/h. Maglev vehicles are designed for operating speeds up to 500 km/h. That is a tremendous speed advantage of Maglev trains over conventional rail travel^[5].

Frictionless travel means that the train won't actually touch the rails. Because there is no mechanical contact and wear, Maglev guideways could last up to 50 years or more with very little maintenance at all. Maglev vehicles will have longer lifetimes than conventional rail travel for this reason. They will also have longer lifetimes than automobiles, trucks, and airplanes^[12].

Not only do they have longer lifetimes than these other methods of transportation, but they are also relatively cheaper. Maglev operating costs will be only 3 cents per passenger mile and 7 cents per ton mile, compared to 15 cents per passenger mile for airplanes, and 30 cents per ton mile for intercity trucks [12]. The cost of making the guideway is a high percentage of total investment for a Maglev system. The costs for making these guideways are no higher than those of other high speed rail systems and look even better when the terrain is bad because Maglev rail lines are easily adaptable to the difficult terrain. This combined with the longer lifetimes of the Maglev trains makes it a better investment for our future.

Maglevs have faster acceleration and deceleration than conventional rail travel. They accelerate from 0 to 300 km/h within 5 km as compared to the German ICE high-speed train which requires 30 km to reach the same speed [5]. This makes maglev ideal for short distances, (Short distances meaning 20 or so), medium-distances (intercity connections), and long distance national or international connections.

An advantage of conventional rail travel over other forms of transportation is their ability to operate in almost any weather conditions. Maglevs are even better prepared for icy conditions because they do not require overhead power lines or pantographs (parts that are subject to freezing on conventional railroads). The guidance and propulsion components of the Maglev are under the guideway which protects them from rain and snow. Snow will almost never accumulate on the tracks because of the wind that the Maglev creates when moving at high speeds. Even if snow builds up on the guideway, the train will not actually touch the rails and will continue to operate normally.

Energy Efficient

Maglev does not burn oil but instead uses electricity, which can be produced from coal, nuclear, hydro, wind, or solar power plants. When traveling at 300 mph in the open atmosphere, Maglev consumes only 4 mega joules per passenger mile, compared to 4 mega joules per passenger mile of oil fuel for a 20-miles-per-gallon car that carries 2 people at 60 mph. That is a huge difference in energy consumption when you compare the speeds at which they are traveling at. At 150 mph, Maglev consumes only .1 mega joules per passenger miles, which is just 2% of the energy consumption of a typical 60 mph vehicle.

Safe for Us and the Environment

Maglevs are safer than conventional rail travel, highway vehicles and airplanes. Since the tracks are elevated, there is no risk of any type of collision with automobiles and trucks as compared to conventional trains. There is no possibility of collisions between vehicles on the guideway because the distance between Maglev vehicles on a guideway and the speed of the vehicles are all automatically controlled and maintained by the frequency of the electric power fed to the guideway. There is also no chance for derailment due to the superconducting magnets in the rails.

Also, there won't be much of an effect on the animal life in area. The elevated guideways allow for small animals and microorganisms to pass underneath. This eliminates animal collisions that occur frequently with normal roadways and conventional rail travel.

Since only electric power is being used, Maglev is also safer for the environment than conventional rail travel. There are no fuels being used so air pollution is reduced because there are no emissions of exhaust gasses. Even if they use electricity from coal or natural gas fired power plants, the resulting CO2 emission is much less than that from cars, trucks and airplanes, because of Maglev's high energy efficiency. Maglevs operate at low noise levels because there is no mechanical contact with the rails. Aerodynamic noise is reduced by making the Maglevs more streamlined. Maglevs traveling at 250 km/h results in vibrations that are below the human threshold of perception (KB value of .1).

The German Transrapid releases a very low magnetic field. The magnetic field inside a passenger compartment is much less than that of a hair dryer, toaster, or even an electric sewing machine. It will therefore have no negative influence on cardiac pacemakers, or magnetic cards such as credit cards. The Japanese version emits only about 4 gauss. Hospitals recommend a maximum of 5 gauss as the maximum permissible exposure for a pacemaker wearer.

Quality of Life

The quality of life will improve as a result of the construction of Maglev trains. Airports have been becoming more and more congested ever since the events of September 11, 2001. People have to wait a very long time just to board their planes, due to increased security. This is not comfortable way for people to travel. People should be able to relax and unwind when they travel, not face the frantic lines at the security check points. Although planes are still the fastest way to travel, compared to the other transportation options we have, Maglevs can help ease this problem. With the ability to travel up to 500

km/h, people will be able to travel long distances on land in a relatively short amount of time. They will not have to wait in long lines at the airport. Traveling in Maglevs will be a relatively short and quiet ride, not to mention the very comfortable seats.

Today's Reality

Railways using MagLev technology are on the horizon. They have proven to be faster than traditional railway systems that use metal wheels and rails and are slowed by friction. The low maintenance of the MagLev is an advantage that should not be taken lightly. When you don't have to deal with the wear and tear of contact friction you gain greater longevity of the vehicle. Energy saved by not using motors running on fossil fuels allow more energy efficiency and environmental friendliness.

Maglev will have a positive impact on sustainability. Using superconducting magnets instead of fossil fuels, it will not emit greenhouse gases into the atmosphere. Energy created by magnetic fields can be easily replenished. The track of a Maglev train is small compared to those of a conventional train and are elevated above the ground so the track itself will not have a large effect on the topography of a region. Since a Maglev train levitates above the track, it will experience no mechanical wear and thus will require very little maintenance.

Overall, the sustainability of Maglev is very positive. Although the relative costs of constructing Maglev trains are still expensive, there are many other positive factors that overshadow this. Maglev will contribute more to our society and our planet than it takes away. Considering everything Maglev has to offer, the transportation of our future and our children's future is on very capable tracks.

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