Maglev Trains And The Technology Behind Them

Introduction

Magnets

Magnetism is a phenomenon that occurs when a moving charge exerts a force on other moving charges. The magnetic force caused by these moving charges sets up a field which in turn exerts a force on other moving charges. This magnetic field is found to be perpendicular to the velocity of the current. The force of the field decays with distance from the charge. Most magnets we come across are weak permanent magnets, such as fridge magnets and door catches. A permanent magnet is a material that is naturally magnetic, they set up magnetic fields by electrons circling an atom setting up magnetic fields. They are based on oxides of barium and iron. They have low field strength and would not be strong enough for use in Maglev trains. Lately, developments in magnet research have found rare earth-permanent magnets that have a much stronger magnetic field. These new magnets have become an important part of our everyday life being used in many everyday applications such as computers, CD players and mobile phones. It is these high performance magnets that are used in Maglev trains. The rare earth elements are scandium 21, yttrium 39 and lanthanide's 57-71.

The principle of a Maglev (Magnetic Levitation) train is that it floats on a magnetic field and is propelled by a linear induction motor. They follow guidance tracks with magnets and have been seen to have great potential in the transport world.

An example of a maglev train from http://www.newscientist.com

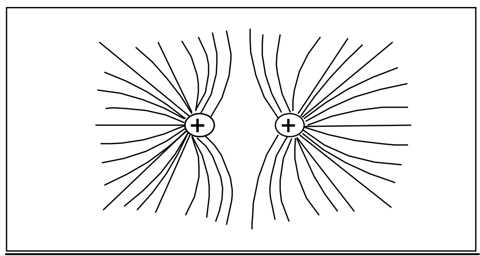
Simple Theory

A maglev train will float about 10mm above the guideway on a magnetic field. It is propelled not by an onboard engine, but by the guideway itself by changing the magnetic field of the electromagnets along the length of the guideway. Once the train is pulled into the next section the magnetism switches so that the train is pulled on again.

The repulsive force between magnets with like poles facing explains how permanent magnets can be used to provide a levitating and thrust force to the train.

Magnet Strength

We know that magnets have a north and south pole and if we bring them together they will repel each other. We can see this effect in the picture below with the area between the two magnets having the iron filings being repelled away from the area in between the two magnets.



We can use this theory to determine the strength of repulsion. We use the following formulas.
The magnetic flux density is another word for the strength of the magnetic field. Lines of magnetic force of flux are used to describe the shape of a magnetic field near a magnet or solenoid (a long coil through which current is flowing, establishing a magnetic field). The density of the lines of force increase in proportion to the field strength. It can be calculated by using the equation

$$B=O/A$$

where B is the flux density O is the flux and A is the cross sectional area of the material.
Magnet flux in o is produced by current-turns *NI.* The formula for this is given to be

$$O = \quad NI$$

where = the permeance of the magnetic circuit. Permeance is a quantity which says how much flux there is in the material for a given number of current turns round the material. The permeance is bigger for larger cross sections and smaller for long sections of material. Also to find the strength of the Flux density in a straight conductor when can use the Equation

$$F=BIl$$

In this equation F = the force in Newtons on a straight conductor of length l which carries current I. By using these equations we can come up with an equation that tells us the attractive force between two magnets from which we would be able to calculate the strengths of the distance apart they are from each other.

$$F=\frac{M1*M2}{u*d^2}$$

In this formula F is the force, M1 and M2 are the flux strengths of the two magnets, d is the distance between the magnets and u is the relative permeability of the medium between the magnets. By using some figures from a Physics World magazine is possible to see why magnetic levitation is possible. By using them we can find the size of the magnet that is needed to levitate two people at 20mm. First to find the force we multiply the weight of two people at 70N each by the gravitational constant 9.8 and then multiply this figure by a safety factor of two we get 2744N. And is using the figures for a possible levitation magnet Nd Fe B we can find that the magnet flux strength M=1.2 x 10 Wb. Given this we find that the circular pole face to give this figure is 94mm. This is not very big and proves that levitation is possible with the right conditions.

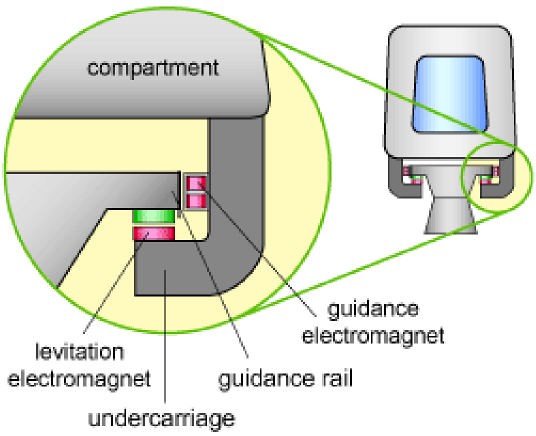
But according to a theorem by Earnshaw it is not possible to achieve static levitation using any combination of fixed magnets and electric charges. Static levitation means stable suspension of an object against gravity. It was found that there are several exceptions to this theory. They are Quantum effects, as Earnshaw’s theorem only takes classic physical laws into account, this is not used in Maglev trains. Feedback is another exception to the theory and one which is used in Maglev trains, if you can detect the position of an object then use it in a control system in which you can vary the strength of electromagnets which are acting on the object it is possible to keep it levitated. The system must be programmed to weaken the strength of the magnet whenever the object approaches it and strengthen as it moves away. This is an exception as Earnshaw’s theorem only takes into account that the magnets are fixed. This is the type of Maglev that was used in Birmingham airport. The other exception is diamagnetism. A diamagnetic material is one that expels a magnetic field. It is possible to levitate superconductors and other diamagnetic materials which magnetise in the opposite sense to a magnetic field in which they are placed. This system can only be used with the strongest magnetic fields that technology has produced. This system has been used to levitate water droplets and even frogs. A superconductor is a material that below a certain temperature has zero resistance. Resistance is undesirable because it cause the loss of energy. In theory once set in motion the electricity will flow forever in a closed loop. It is referred to as a “Macroscopic Quantum Phenomenon”.

Different Types of Maglev Technology

There are essentially two types of Maglev trains depending on the different ways they levitate. One is the electromagnetic suspension or EMS uses electromagnets on the train which are attracted to an iron rail. The vehicle magnets wrap around the iron guideway, and the attractive force in the +z direction lifts the train. The electrodynamic suspension, or EDS is levitated by forces caused by induced circulating currents in a passive conductive guideway. In either case, the levitating magnets are mounted to a number of “bogies” which in most Maglev systems are connected to the main train body by a secondary suspension consisting of springs and dampers. EDS is commonly know as "Repulsive Levitation," and EMS is commonly known as "Attractive Levitation”.

The EMS System

The EMS or Electromagnetic Suspension system is currently the most used of the two systems as it is probably the most practical and easy to implement of the two. EMS maglev attracts to the guideway above, balancing attractive forces with gravity. Permanent magnet based levitation has very low power requirements. Electromagnetic suspension (EMS) is an attractive force levitation system whereby electromagnets on the vehicle interact with and are attracted to ferromagnetic rails on the guideway. The orientation of the magnetic fields in a ferromagnet of the domains is random, giving rise to no net magnetic field. A useful property of Ferromagnets is that when an external magnetic field is applied to them, the magnetic fields of the individual domains line up in the direction of this external field due to the nature of the magnetic forces, this causes the external magnetic field to be enhanced. This is why they are used as the core of the electromagnet. The picture below explains the way in which the EMS system levitates the train.



From
http://www.hk-phy.org/articles/maglev/maglev_e.html

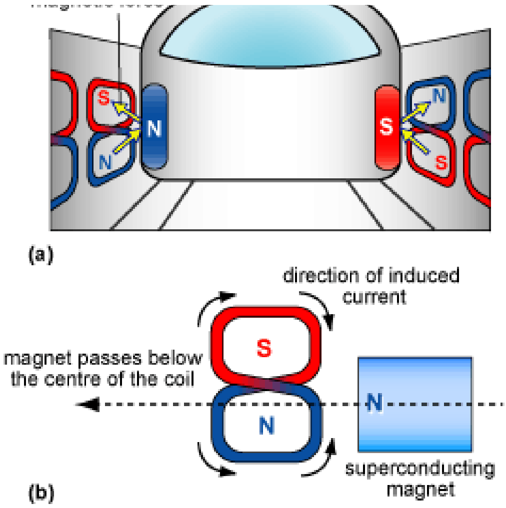
This picture shows the electromagnets of the train being attracted to the electromagnetic rail above and that by finding the right balance between the strength of the magnet and gravity a medium can be reached where the train can then levitate on air. The air gap then has to be maintained by sophisticated electronic control systems. Variations in payload weight, dynamic loads, and guideway irregularities are compensated for by changing the magnetic field in response to vehicle to guideway air gap measurements. Other guidance magnets embedded in the train's body keep it stable during travel. This system is currently being tested in Germany, America and China where the world first revenue producing Maglev system is going to be introduced.

The EDS System

The EDS or Electrodynamics Suspension is the other system in design and acts on the theory of repulsion rather than attraction. It does not require the constant electric control of the gap like the EMS as the system is inherently stable.
In the EDS-repulsive system, the superconducting magnets levitate of the vehicle, are at the bottom of the vehicle, but above the track. A phenomenon know as the Meisner effect is exploited where superconductors are used to levitate magnets above. The

track is either an aluminium guideway or a set of conductive coils. The magnetic field of the superconducting magnets aboard the maglev vehicle induces an eddy current in the guideway. The polarity of the eddy current is same as the polarity of the Superconducting magnets onboard the vehicle. Repulsion results, "pushing" the vehicle away and thus up from the track. The gap between vehicle and guideway in the EDS-system is considerably wider than the EMS at 1 to 7 inches.

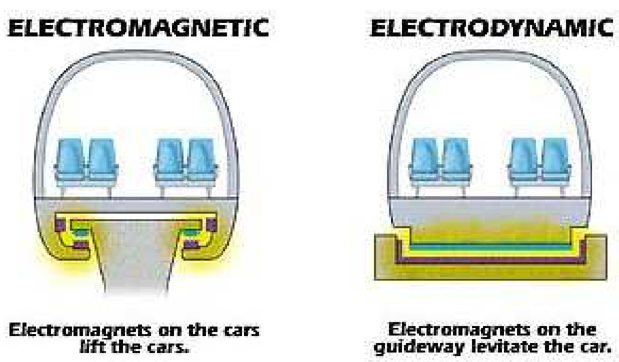
When a magnet moves beside a conductor, the magnetic field inside the conductor will change and a current will be induced. The induced current in turn generates a magnetic field which, according to Lenz's Law that an induced electric current always flows in such a direction that it opposes the change producing it, tends to resist the change that caused the induction. Lenz's law was an advancement from Faraday's law which stated the magnitude of the e.m.f. induced in a conductor equals the rate of change of flux linkages or the rate at which the conductor cuts a magnetic flux. The method of EDS utilizes the principle of electromagnetic induction. The train travels in a guideway which has a series of 8 shaped coils on each side. When the train travels by, the superconducting magnets on each side of the train will induce a current on the coils. The superconducting magnet passes below the centre of the 8 shaped coils, thus the magnetic flux change in the lower half of the 8 shaped coils is greater than that in the upper half, and a current is induced, generating a magnetic force. The magnetic pole in the lower half of the 8 shaped coils is the same as that of the superconducting magnet, while the upper half has the exact opposite of it, so that both halves of the coils generate an upward component of magnetic force on the superconducting magnet and levitates the train. Since the coils can induce a current and generate magnetism only when the superconducting magnets are in motion, the train cannot be levitated when it is at rest. Because of this the train first starts by sliding on wheels. When the magnetic force generated is large enough to overcome the weight of the train, the wheels are hid like those of airplane landing gear



These pictures shows the effects mentioned with the 8 shaped coils providing levitation from electromagnetism

From http://www.hk-phy.org/articles/maglev/maglev_e.html

A more advanced EDS-repulsive system, worked on by the Japanese , utilizes a U-shaped guideway, in which the vehicle nestles in between the U-shaped guideway. Coils are implanted in the walls of the U- shaped guideway, called guidewalls. Thus, the guideway is not below, but out to the sides. Now the repulsion goes perpendicularly outward from the vehicle to the coils in the guidewalls. The perpendicular repulsion still provides lift. The picture below shows the way in which the U shape system operates in comparison to EMS.



From http://www.monorails.org/tMspages/TPMagIntro.html

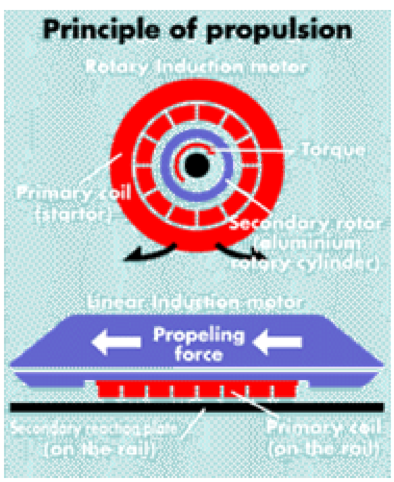
This system uses superconductors which must be kept very cold to maintain there efficiency, this must be done with liquid helium which can keep the temperature as low as 4K. The problem with this is that it is very expensive and very inefficient.

Drifting Correction

How the computer corrects “drifting between the magnets is actually quite simple and relies on basic electromagnet properties. Drift can be caused by wind or going round a corner. The train drifts away from the track and the gap widens more and more as there is a shortage of magnetic force. This is detected by a computer. The electromagnets are then supplied by computers an additional current which increases the magnetic force again. The train is then pulled back to its original position. As computers monitor the system constantly, the effect is kept to a minimum.

Propulsion

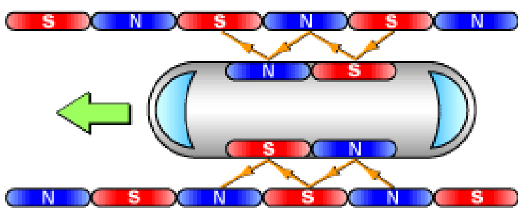
Propulsion for Maglev trains is provided in the shape of an linear motor. Maglev uses a type of motor called a Linear Induction Motor (LIM). They come in two types the Long-stator propulsion using an electrically powered linear motor winding in the guideway appears to be the favoured option for high-speed maglev systems. Short-stator propulsion uses a linear induction motor (LIM) winding onboard and a passive guideway. The picture below shows the way a normal rotary induction motor is laid out flat to give a linear induction motor. The rotary is on top with the linear induction underneath.



From http://www.calpoly.edu/~cm/studpage/clottich/fund.html

Basically these motors generate a force that will directly propel the train car.
The primary coil (stator) of the motor is mounted on the car, and the secondary rotor is in the form of an aluminium reaction plate installed along the rail surface. The combination of these two elements results in a force strong enough to propel the train. The rotating part of the magnetic circuit is called the rotor. It is usually the electromagnet part of the machine. The static part of the machine which carries the coils from which an alternating emf feeds power supplies, this is called the stator.

The train in motion, along with its superconducting magnets, induces a current on the coils on each side of the guideway. Based on these signals, the system will input alternating currents into the propulsion coils on each side of the guideway, producing an alternating series of North and South magnetic poles which pull and push the superconducting magnets and accelerates the train. The basic way in which it moves is explained by the diagram below. The coils in the guideway are excited by an alternating, three-phase current.



From http://www.hk-phy.org/articles/maglev/maglev_e.html

Electromagnets shown in the picture above on the guideway can have their polarity switched as the carriage passes. The acceleration and deceleration come from the attractive and repulsive forces between the permanent magnets and electromagnets. This picture on the page above shows a magnet arrangement where when in these conditions the train would be decelerated as when the poles line up the net force would mean the train could not move forward. To combat this problem the electromagnets are switched from north poles to south poles as the train moves forward, this is done using an ac current. The frequency at which this is done is calculated by computers depending on the speed of the train and the length of the magnets. The difference in drive between the EMS and EDS is slightly different but both run on essentially the same concept. The EMS system surfs with its support magnets on the alternating magnetic field generated in the roadway. The created electromagnetic wave is actually a mobile or travelling electromagnetic wave. The EMS-attractive system is sometimes labelled a pull system: the vehicle is pulled forward. Braking is done by reversing the magnetic field and sometimes by using air flaps.
he EDS-repulsive system can be described as pull- then neutral-then push. In the EDS system, coils or an aluminium sheet in the guideway are used for providing drive, although they also are different than the coils dedicated for the function of levitation.
The coils in the guideway are excited by an alternating, three-phase current. This produces a standing magnetic wave. Sections

of the guideway are excited one after the other, with the excited section being immediately in front of the maglev vehicle. Superconducting magnets onboard the maglev vehicle are attracted to the section of the guideway immediately ahead of it, pulling the vehicle forward. Then, when the vehicle is directly overhead, the direction of the current and the polarity of the particular guideway segment is changed. During the fraction of a section in which the polarity is being changed, there is effectively neither an attractive nor repulsive interaction. But once the change in polarity occurs, and while the front of the vehicle is moving forward to the next excited portion of the guideway, a repulsive force is created, pushing the vehicle from behind. The speed of a linear synchronous motor can be given by the equation V=2fLw where V=velocity, Lw=length of winding turns and f=the frequency of its current. In normal Maglev systems Lw is kept constant while the frequency of the current is changed. A third system of maglev has been thought up where it is the length of the windings that are changed while the frequency is kept constant. This system has been named Amlev. As no inverting would be needed it would use much less power and need no monitoring or control system. This system is still very much in the theory stage.

The Advantages of Maglev

Maglev has many advantages over other forms of travel. One advantage is that unlike conventional trains they are very quiet. The trains produce noise at about 69 decibels from 100m while normal inner city traffic produces 80 decibels from 100m. This is due to the fact that there are rolling wheels or engines with moving parts. This also means they should be easy to maintain and rarely brake down as there is no friction between the rails and train, this would lead to reduced labour costs. Also when you are on board the train the vibrations are just below the human threshold of perception giving exceptional ride quality. As there is no friction the speeds the trains can reach is a lot higher, the fastest current conventional train is the Japanese bullet train which can travel at 300k.p.h, where as the Japanese Maglev train project has managed to make a train reach 550k.p.h although when in normal operation the trains will probably travel slower than this for stability.

They also accelerate much quicker than normal trains. If for instance the track must go uphill the guideway can be made thicker to enable it to accelerate to 300k.p.h in 5 km where it would take a normal train 18km. Maglev also uses much less energy than normal trains which is of a benefit to the environment. The table below shows the extent to which this is true.

Speed	ICE Train	Maglev
200k.p.h	32wh/km	32wh/km
250k.p.h	42wh/km	37wh/km
300k.p.h	71wh/km	47wh/km
400k.p.h	-	71wh/km

From http://www.calpoly.edu/~cm/studpage/clottich/advan.html

It has also been calculated that the system will be 20 times safer than an airplane, 250 times safer than other conventional railways and 700 times safer than travel by road. Collision is impossible because only sections of the track are activated as needed. The vehicles always travel in synchronization and at the same speed. Also if the system has a power failure the onboard battery will take the train to the next station, and as the train has no fuel the prospect of a fire is greatly reduced.

Disadvantages of Maglev

One of the main disadvantages of maglev technology is the cost of implementation. As the technology is so advanced the cost of the trains and guidway are very expensive. The is true for the EMS and very true for the EDS system. The normal EMS system costs normally around $10-30 million per mile. The EDS system costs around $148 million per mile, this is due to the fact as it has sophisticated technology as well as the fact that to provide the 4K needed for superconductivity liquid helium must be used to cool the EDS system. This is extremely expensive and inefficient. Severe difficulties lie in the storage of the helium vapour and the reliquidfication of the vapour once it has absorbed the tremendous heat from the Superconducting magnets. Another problem is that there is no existing infostructure meaning none of the existing train tracks could be used for Maglev, the system would have to be built from scratch. The trains also must be designed so that it is very aerodynamically stable as air resistance can be a big problem in Maglev trains. This problem is easy to fix by just designing the train with aerodynamics in mind.

Current and Future Prospects

Currently the three nations involved with maglev the most are Germany, America and Japan. Germany and America are developing several Maglev projects that will use the EMS system. Japan have been developing the EDS system.
The German organisation is known as Transrapid and began work back in 1934 on developing a Maglev train that could be a legitimate transport system. Since then there has been the Transrapid trains from 01 through to 08. A extensive test rack was built in 1987 and allowed testing of any new train. In 1993 the Transrapid 07 set a new speed record of 450k.p.h. The most development has occurred since the year 2000. Since then planning has occurred on a Berlin to Hamburg route, a line in Washington, a line in Netherlands and a line in China. The Chinese route is the one that has advanced the most, it will be the first ever revenue producing Maglev train. On the 31st of December 2002 is had its maiden trip of the Transrapid Maglev Train on its first commercially operated route worldwide from Shanghais Long Yang Road to the Pudong International Airport. They also have planning for a Maglev system in Pittsburgh.

The first section of the Shanghai Transrapid vehicle is leaving the ThyssenKrupp-plant in Kassel.

http://www.transrapid.de/en/index.html

Work began on the Japanese EDS project in 1990 when basic planning began for Maglev and construction of the Yamanashi Test Line was authorized by the Ministry of Transport. Since then extensive testing of many Maglev vehicles has been carried out in Japan. In 1999 records were broken when a 5 car train reached the speed of 552k.p.h. Since then work began in April 2000 on a project called Research 21. There is still no sign of a Japanese EDS system being put into commercial use. This is probably due to the excessive cost in building the line and keeping the 4K needed for superconducting magnets. The Superconducting magnets cost millions themselves and cooling them cost millions more. Research is currently ongoing in finding a superconductor which can operate a higher temperatures or even room temperature by using for instance liquid Nitrogen to cool the magnets. This has been the slowest front in maglev technology.

Bibliography

http://www.calpoly.edu/~cm/studpage/clottich/fund.html
Used for Advantages, disadvantages, drift correction, basic motor information. Not used for advanced physics

http://members.aol.com/marctt/Research/chapter1.htm
Very small amount of info about different types of Maglev

http://www.alcyone.com/max/physics/laws/index.html
Used for Lenz Law info

http://www.howstuffworks.com/maglev-train.htm
Very basic information

http://www.amlevtrans.com/diagram3.htm
V=2fLw equation

http://ntl.bts.gov/DOCS/TNM.html
Small amounts of advanced information on the working of maglev Trains

http://www.dom.com/about/companies/vapower/maglev/future.jsp
Very little useful information

http://faculty.washington.edu/~jbs/itrans/maglevq.htm
Links to other sites

www.magnemotion.com/technology/Maglev/pdf/M3UrbanSystem.pdf
Extensive 40 page pdf file, used for some useful information but to much about specific project and its testing.

http://www.rtri.or.jp/rtri/rtri_E.html
Info on Japanese Maglev project and its history

http://www.hfml.kun.nl/levitation-possible.html
Earnshaw theorem information

http://www.hk-phy.org/articles/maglev/maglev_e.html
Good site with very good information and pictures

http://www.superconductors.org/
Basic superconductor information

http://inventors.about.com/library/inventors/blrailroad3.htm
Used for very small amount of info

http://members.tripod.com/~american_almanac/maglev.htm
Used for a lot of useful information about the workings of Maglev. Not much physics in it.

http://www.monorails.org/tMspages/TPMagIntro.html
Useful site giving me the clear definitions between EDS and EMS as well as pictures

http://www.transrapid.de/
Used for info and history on German and Chinese projects.

Advancing Physics A2 book.
Used for equations for magnets and information on electromagnets

www.trymegaessays.com
Used for information of superconductor problems detailed magnet theory and maglev information. Not written well too confusing.

Physics World magazine
Used for initial info Maglev

Encyclopaedia Britannica 11
Used for small amount of advanced info on magnets. Repulsion picture

http://math.ucr.edu/home/baez/physics/General/Levitation/levitation.html
Earnshaw theorem info

The Complete A-Z of Physics handbook
Equations and magnet theory