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
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Maglev – an unfulfilled dream?

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ABSTRACT

Although Maglev has been technically developed in a variety of forms, and has had some limited operational success, the dream envisaged in the 1960s and 1970s of wide-scale commercial implementation remains elusive. This paper provides a technical and historical appraisal, starting with the expected features believed in the early days to characterise Maglev, and reviews the actual achievements against these expectations, i.e. to assess the progress towards the original dream and its viability. The conclusion includes a commentary on the present day opportunities and barriers, and offers some suggestions for emphasis into the future. The objective is to stimulate a discussion aimed at helping to understand why the dream remains largely unfulfilled.

1. INTRODUCTION

Maglev, an abbreviation for Magnetic Levitation, is described as “a system of transportation that suspends, guides and propels trains using magnetic suspension by means of a number of magnets for lift and propulsion” [adapted from Anon 2012]. It has the potential to be faster, quieter and smoother than wheeled mass transit systems. The power needed for levitation is usually not a large percentage of the overall consumption, because most of the power used is needed for the propulsion system to accelerate the vehicle and to overcome aerodynamic drag, as with any other high speed train. In some senses it’s a slightly unfortunate title, because “levitation” is defined as “to rise or causing to rise into the air and float in apparent defiance of gravity”, i.e. the word implies something mystical or magical, which is clearly not correct: it is just another engineering system that must be subject to the normal scrutiny regarding cost, reliability, etc. Arguably “Magnetic suspension” is perhaps a more appropriate description but “Maglev” is now well established.

The technical origins of Maglev go back many years, certainly as far as the work of Samuel Earnshaw (1842) who made an important theoretical statement regarding stability, but serious technological development only started in the 1960s. At the time there was a generally held view that Maglev would be an important contributor to transport systems in the future, but 50 years later we can only see five applications that are either operational or planned for operation. In date order these are:

- UK Maglev system at Birmingham Airport (1984)
- German Magnetbahn (M-bahn) in Berlin (1989)
- Chinese Transrapid system in Shanghai based on German Transrapid technology (2004)
- Japanese Linimo system in Nagoya (2005)
- Japanese Superconducting Maglev (2027?)

In each case there is only a single system, i.e. there has not been a second system built using the same approach. Also, the first two no longer operate and the fifth is not yet operational, so given the level of investment this clearly cannot be viewed as a satisfactory achievement in comparison with other technologies that started to be developed around the same time (and later). This paper therefore

looks at the early expectations, overviews the technological options and achievements, analyses them in the context of the expectations and makes suggestions for R&D priorities into the future.

The overall aim is to discuss the reasons why extensive take-up of what was an extremely promising technology has not yet happened. The analysis presented is based upon the author's personal views: as an engineer involved in the early work on EMS Maglev during the 1970s and 1980s [Goodall 1976, Taylor et al 1984], as a researcher over a number of years since [Goodall et al 1995, Goodall 2004, Goodall 2008], and in general as an observer of the way the technology has progressed on a worldwide basis over the last four decades.

2. EXPECTATIONS

The key feature of Maglev is that there is no contact between vehicle and track, which means that it should be mechanically-simple, offering zero wear/maintenance, and operating with no noise or vibration. Additional benefits arising from this were expected, and so in the early days the following were widely stated to be the principal characteristics of a Maglev system:

- » Non-contacting suspension
- » Low noise and vibration
- » Mechanical simplicity
- » Efficient
- » Lightweight
- » Cheap

It was of course recognised that lack of contact required the use of an electromagnetic drive system, but the significance was in general not fully understood. It was also commonly stated that the lack of contact between vehicle and track would inherently give a good ride quality, especially for those concepts offering a relatively large air gap between the magnets and the track, but this is incorrect. There is a fundamental trade-off between ride quality and the size of the airgap, or more specifically the “working space” of the suspension which will always be smaller than the airgap itself. If the magnetic suspension is controlled (which applies for some forms of Maglev), a better ride quality is possible within a given airgap, but the trade-off still exists (Goodall, 1994).

3. TECHNOLOGIES

Although Maglev concepts have been well described before, see for example Rote (2004), an overview of possibilities is included here. It is presented using an intuitive rather than a scientific/mathematical approach in order to reveal the range of options for producing magnetic forces for suspension and guidance (also for propulsion and braking). These forces arise from the interaction between more than one source of magnetic field, or between a source and a sink, where a “sink” here means some form of material that interacts in a useful manner with the magnetic field produced by the source. An important distinction is between the schemes that produce a force of attraction, in which case the magnet must be below the track, and those that generate a force of propulsion in which case the magnets will be above the track.

Table 1 Magnetic elements for Maglev suspension systems

<i>Sources</i>	<i>Sinks</i>
Permanent magnet	Ferro-magnetic material (Iron, steel, ...)
DC electromagnet	Conducting elements, coils or sheets (Cu, Al, ...)
AC electromagnet	
Superconducting magnet (coil or bulk material)	

A rigorous mathematical analysis is of course necessary to quantify both the size of the forces and

the variation as the source-to-source or source-to-sink distance changes so that the suspension characteristics can be determined, but it is clear that many source-to-source and source-to-sink pairings are available, i.e. there are lots of the different manifestations of maglev in particular the curves for each “pair” there is a choice as to which is fitted to the vehicle and which to the track. The following sub-sections briefly describe the most important choices but the reader is referred to a wide variety of publications and internet resources for further detail.

3.1 Permanent magnets

Permanent magnets can create an attraction force with a steel track, or a repulsion force when there are permanent magnets in both the vehicle and track. It’s potentially interesting because it offers the prospect of a zero power consumption, but has the disadvantage that with permanent magnets alone there will always be an unstable mode, and some other form of stabilization is essential. It’s also useful to note that, even if the scheme were stable, it would intrinsically have zero or very low damping which makes it problematic from a suspension design viewpoint – this is explained further in section 3.6.

3.2 DC electromagnets

This is one of the most common solutions, usually known as the “electro-magnetic system” (EMS), and uses controlled D.C. electromagnets to provide an attraction force upwards to a simple steel track. Without control of the magnets the system is unstable, but by using a sensor to measure the airgap and controlling the magnet excitation accordingly, stable suspension is readily achievable. The introduction of damping is included as part of the control design, and essentially damping arises through active electronic control. When stable vertical suspension is achieved shear forces from the magnetic field provide guidance in the lateral direction.

Power is dissipated in the coils but this is typically 1-2 kW/tonne of vehicle weight, relatively modest compared with what is needed for propulsion. There is a trade-off between the power consumption and the lift/weight ratio of the magnet (Goodall, 2008).

A number of people have considered using hybrid magnets that incorporate permanent magnet materials to provide the nominal excitation and levitation force, with controlled coils to give stability around the levitation point. The objective is reduced energy consumption in the suspension (see Hennerberger and Rodder 1995, for example), but there is a variety of reasons why this apparently useful concept is not straightforward in practice.

3.3 AC electromagnets

When AC excitation of the magnets is considered for suspension, this also inherently incorporates the propulsion (not mentioned in the previous subsections). There are basically two options:-

- Magnets interacting with a conductive “reaction rail” or coils to make a Linear Induction Motor (LIM) providing repulsion suspension force as well as propulsion/braking. It should however be noted that any linear motor operating with a large air gap is not an efficient machine, and a linear induction motor operating in repulsion mode implies high electrical slip and a correspondingly larger power loss in the track conductors.
- Magnets interacting with a variety of track arrangements to provide attraction suspension force as well as propulsion/braking. This option is inherently more efficient, although the magnetisation field must be controlled to provide stability, exactly the same as for EMS. The track can be plain steel with an aluminium or copper conducting surface for a linear induction motor, or it could have some form of castellated construction to make a linear reluctance motor, or with permanent magnets in the track it becomes a linear synchronous motor.

For both options the AC electromagnets, i.e. the motor windings, can be either vehicle- or track-mounted, a decision that is generally true with respect to the propulsion system for any form of Maglev.

An early proposal based upon AC magnets was the “magnetic river” concept (Laithwaite, 1987)

which had a wound track and an aluminium reaction plate on the vehicle. This is interesting example because it provides a note of caution for people wishing to promote Maglev: although it generated much interest at that time, as the initial concept was developed it proved to be highly impractical for a variety of reasons.

3.4 Electro-Dynamic System (EDS)

This concept has magnets fitted to the vehicle, with some form of conducting elements fitted to the track. When the vehicle is moving, the travelling magnetic field induces eddy currents in the track elements (hence the term “electro-dynamic”), and with a suitable design a repulsion suspension force is generated. Normally powerful superconducting magnets are necessary, and some form of low speed suspension involving wheels is required because there is no suspension force at standstill, but the advantage is that there is no need for control to provide a stable suspension, and there can be a relatively large air gap of 30-40mm typically. There is however no inherent damping in the magnetic suspension provided by this approach.

3.5 Suspension issues

As remarked earlier, for a number of Maglev schemes the magnetic suspension is undamped. When there is only a single stage of suspension, the lack of damping is a significant problem for achieving a satisfactory ride quality (Goodall 1994). In principle a conducting sheet or coils can be inserted into the air gap, but this is practically difficult and in particular has the effect of reducing the available suspension working space.

For higher speeds, perhaps greater than 160 km/h depending on the track quality, a secondary suspension using springs and dampers becomes essential to ensure a satisfactory ride quality, and this opens the possibility of introducing the damping into the primary suspension by means of dampers in the secondary. However this can only be done by increasing the high frequency transmission across the suspension, thereby worsening the ride quality. The undamped nature of the magnetic suspension, which is applicable to all but EMS, presents a difficult problem for the suspension design that can only be accommodated by requiring a higher track alignment quality. In general these and other suspension design issues are often not well appreciated by Maglev engineers.

4. ACHIEVEMENTS

This section explains how various technologies have been applied for full-scale experimental and operational systems. In each case the propulsion system is briefly explained because the level of integration of the suspension and propulsion is the key Systems Engineering choice. This review is covered in two main sections: what can be considered as the main achievements from an operational viewpoint, and then other examples that either provide important messages or perhaps represent new emerging technological possibilities.

This is not intended to be a comprehensive review: it has been written to identify the principal trends that have been seen over the last 50 years. Again the paper has outline descriptions only: some direct references are given for further detail, in other cases web links are provided in the bibliography.

4.1 Main applications

Birmingham Airport EMS Maglev This was the first operational maglev system: it ran in service from 1984 to 1996 (Nevadovic and Riches 1985), but is now discontinued for reasons that were widely described as unreliability but in fact was principally to do with problems of obsolescence, particularly in the power electronics. It was an 8 tonne low-speed (60 km/h) “people mover” system operating a shuttle service from the train station to the airport terminal building, a distance of 600 m. It used DC electro magnets dissipating around 1.5 kW/tonne, with a LIM drive using an aluminium and steel reaction plate fitted to the centre of the track. It was a single-stage electromagnetic system

with no suspension components such as spring or dampers, i.e. mechanically very simple. It's useful to note that the track did not require re-alignment throughout its operational life, thereby demonstrating the promise of very low track maintenance and renewal cost.

Berlin Magnetbahn This system used permanent magnets on both vehicle and track to give a repulsion force, and was driven by a LSM with motor windings in the track. Stabilisation in the vertical direction used a clever but complex of mechanical system with wheels that provided a dynamic stiffness in parallel with the permanent magnets in order to overcome their inherent instability in repulsion mode. It was built to provide a low-medium speed transport system in West Berlin, but was discontinued when Berlin was unified and the original metro system was re-commissioned.

German/Chinese Transrapid Research in Germany started with a major national programme developing both EMS and EDS technologies, and during the 1970s the decision was made to pursue the EMS concept. The Transrapid system is designed to operate at speeds of 430 km/h, and propulsion is by means of a "long stator" linear synchronous motor, in which track coils are energized to provide a travelling magnetic field that drags the vehicle along via interaction with the suspension magnets – the term "magnetic wheel" is used to describe the approach.

The technology was extensively developed on a test track in Northern Germany, and at one stage there were plans for a Transrapid line from the Berlin to Hamburg. Eventually it was applied for the 30 km link from Pudong Airport into the outskirts of Shanghai, where it connects with the city's metro system. At one stage it was considered for the 1300km Shanghai to Beijing route, and more recently the shorter route from Shanghai to Hangzhou, but the status of the latter is currently uncertain.

Nagoya "Linimo" EMS Maglev This was developed by the HSST company, and a system designed for speeds of up to 100km/h was installed for Expo 2005 on the outskirts of Nagoya, where it remains operational. The basic technology is the same as for the Birmingham Airport System with DC electromagnets and LIMs, except that the linear motor operates with reaction rails either side of the vehicle above the two suspension rails. The other difference is that it incorporates a mechanical secondary suspension, including inter-vehicle torsion bars and dampers to provide the necessary dynamic performance from the suspension.

Japanese EDS Superconducting Maglev System This has been extensively developed since the 1960s, now with a major high speed test track facility at Yamanashi which is soon to be extended. It has been chosen as of the technology for the Chuo (Central) Shinkansen, a new 500 km line from Tokyo to Osaka. It has powerful low temperature superconducting magnets that interact with "null-flux" coils in the side wall of the track to provide both an upwards repulsion force and lateral guidance. Propulsion is by means of a long stator LSM controlled by a separate set of coils, also in the side wall of the track, again interacting with the suspension magnets. It has an undercarriage which is deployed below about 100 km/h, and also has a three-stage suspension to overcome the lack of damping: there is a primary magnetic suspension, a suspension with springs and dampers connecting the magnets to the bogie, and a third soft suspension using air springs to provide the necessary ride quality.

4.2 Other applications

Korean Urban Maglev System There has been a Korean Maglev programme for some years and an EMS vehicle with characteristics quite similar to the Japanese EMS has been extensively tested. There are plans to install a system at the international Airport in Seoul (Shin et al 2011).

US Inductrack EDS Maglev This is a novel form of EDS scheme in which the superconducting coils are not required, these being replaced by arrays of permanent magnets on the vehicle (Post and Dyutov,

2000). The track consists of a series of short circuited coils into which eddy currents are induced when the magnetic fields from the permanent magnets passes by; again there is no suspension force at standstill but “lift-off” occurs at much lower speeds, stated to be a few km/h. A demonstration vehicle for low speed operation (80 km/h) has been built and tested, and a high speed variant has been designed having a more complex magnetic arrangement.

US Stabilised Permanent Magnet (SPM) Maglev This scheme uses permanent magnets in both vehicle and track to provide a vertical repulsion force. Earnshaw’s theorem predicts that it would be unstable in the lateral direction, but lateral stabilisation coils are used to provide active control. A full size single suspension has been built to demonstrate the concept, also a model vehicle and track, but not yet a full size vehicle.

Brazilian High-Temperature Superconducting “Cobra” Maglev This is an innovative concept that exploits the “flux-pinning” phenomenon which arises with bulk high temperature superconducting materials ¹. The magnetic field from track-mounted permanent magnets is “pinned” within the superconducting magnets on the vehicle, and the effect is to provide a stable suspension in both lateral and vertical directions. A scale vehicle/track has been demonstrated and a full-size mock-up produced to show the concept for an operational low-medium speed system.

5. ASSESSMENT

The anticipated characteristics identified in Section 2 are repeated in Table 2, and an assessment is given regarding how well each has been delivered. These obviously represent the author’s opinion, although most of the assessments are directly based upon evidence from the summaries provided in this paper, supported by a variety of other references and information sources.

Table 2 Assessment of anticipated characteristics of Maglev systems

Characteristic	Assessment
Non-contacting suspension	Yes
Low noise and vibration	Yes for low speed, but aerodynamic noise dominates at high speed
Mechanical simplicity	Generally not, except for Birmingham Airport EMS Maglev
Efficient	Mostly not due to the need for linear motor propulsion system
Lightweight	Not really - suspension /propulsion system weights similar to wheeled vehicles
Cheap	Studies suggest Life Cycle Costs should be lower, but this is still to be proved

It is clear therefore that the expectations have in general not been satisfied, and there are a variety of reasons for this, some technical, some organisational and some political.

From a technical viewpoint in general the realisations have been significantly more complicated than had been envisaged, and in particular providing non-contacting propulsion via a linear motor of some kind adds complexity and weight. If only it was just the suspension it would be much easier, and some people would argue that the propulsion system is the “Achilles heel” of Maglev. The other technical issue with Maglev is track switching: this has not been discussed in this paper, but most implementations have big, complex switching solutions that compare particularly unfavourably with what is needed for wheeled systems.

A major contributor to the slow take-up of Maglev is that it is still an immature technology which is in competition with a very mature technology, principally railways and other forms of conventional wheeled transport. This means that there is a very limited base of equipment suppliers which leads to expensive components, and if there is an existing railway it is usually cheaper to upgrade for higher

¹ It is also worth noting that high temperature superconducting coils can be used in the magnets for EMS Maglev, which provides a number of system-level benefits, not least zero power consumption (Goodall et al, 1995).

speed operation rather than build a completely new line based upon a new technology.

An additional consideration is that it is not uncommon for there to be a certain amount of technical and organisational antagonism from engineers and operators of the competing mode. The technical advantages of Maglev are clear, but to overcome all these difficulties there must be unambiguous commercial and/or operational (not technological) advantages.

Major investments in Maglev have had a focus upon high speed leading to big, expensive projects that are usually competing with an existing railway, and the development and planning cycles mean that such projects require sustained political support over a decade or more, something that is not always straightforward particularly in democratic systems of government.

6. CONCLUSIONS

So what are the prospects? Can Maglev achieve a key role in future transportation systems? To do this it is important to identify and focus upon the "Unique Selling Points (USPs)".

For high speed systems the USP is the capability for high speed, so key question is "How fast do we need to go?", which of course is quite different from "How fast can we go?" Back in the 1960s and 1970s it was widely believed that 250 km/h was the limit for wheel/rail technology, but now it is generally accepted that 400km/h is feasible. If higher speeds (> 400km/h) are believed to be needed then Maglev is probably the best solution, partly because the non-contacting suspension is favourable, but also because it offers the best solution for taking the propulsion system off the vehicle, thereby reducing the weight and aerodynamic cross-section and the consequent energy consumption. However few suitable "corridors" exist that link large conurbations (> 15 million people?) to justify the investment and provide the basis for a national or continental Maglev network, and if there is an existing railway the investment case is even more difficult.

For low-medium speed systems, especially for intensive city-centre use, the USPs are low noise and vibration and high reliability, which in principle make Maglev an excellent solution. However it is difficult to compete economically with an "at-grade" system utilising wheels (trams, light rail, etc.) because the track for such systems can readily be installed at ground level, but where there is a reserved guideway system, particularly with an elevated construction, the cost equation becomes more favourable and the low maintenance characteristic of Maglev starts to be important.

For both possibilities the fact that Maglev is not yet mature is still a critical factor, which can only be overcome if a significant number of systems can be introduced so that a supply base becomes established. So what is the best way to establish and mature the technology? The author's view is that the more realistic prospect lies with low-medium speed technology for which there is potentially a large number of applications worldwide, and which provides the opportunity to develop the technology and its supply base.

Looking to the future it is possible to anticipate scientific developments which might help with the applicability of Maglev, such as magnetic materials with significantly higher magnetic saturation and/or room temperature superconducting materials, but these rely upon discovery which cannot be guaranteed.

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