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An operation and maintenance perspective of low speed Maglev applications

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Abstract

The unique feature of the maglev technology is the use of magnetic forces for vehicle levitation and linear motors for propulsion which eliminate the physical steel wheel on rail contact. Two approaches have been developed for vehicle levitation. These are the electromagnetic suspension system (EMS) based on attractive magnetic forces and electrodynamic suspension system (EDS) based on repulsive magnetic forces. Since the practical concept of using maglev for ground transport first proposed by Powell and Danby [1], many innovative ideas and configurations of maglev based on EDS as well as EMS have been proposed [2], and much advances have been made. To date, typical examples of commercially available products are the Transrapid (Germany) and the CHSST (Japan) system. These two systems are based on the electromagnetic suspension principle which is critically dependent on the dynamic closed-loop control of iron-cored electromagnets. Maglev as a technology through years of research and development has faced many technical problems and challenges, and a significant number of them have been resolved. There could be very little doubt that maglev is a mature and sophisticated technology from a technical point of view. This paper attempts to highlight and address the issues with ways and means to implement a low speed urban maglev system from an operation and maintenance perspective. The paper also addresses "what if" questions, which very often would be raised from an end user perspective.

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1 Introduction

1.1 Maglev technology

Maglev uses magnetic thrusts for vehicle levitation which eliminates the physical steel wheel on rail contact and provides better performance in terms of noise and vibration compared to the conventional technology. So far, two approaches have been developed for vehicle levitation namely, electromagnetic suspension (EMS) based on attractive magnetic forces, and electrodynamic suspension (EDS) based on repulsive magnetic forces. Typical examples for EMS are the high speed Transrapid (Germany) system and the low speed CHSST system (Japan), both of which are commercially available in the market today. Typical example for EDS is the Japanese MLU design which employs super-conducting magnets. The latter is still very much under intensive research and development, and speed trial in Yamanashi, Japan.

Electromagnetic suspension is critically dependent on the dynamic control of iron-cored electromagnets and is limited to an air-gap flux density of 1.2 – 1.5 Tesla. In practice, essentially the whole length of the vehicle, on the both sides, is taken up by a multiplicity of suspension and/or guidance magnets which must be independently excited and controlled for dynamic stability, reliability and redundant operation.

Both EMS and EDS employ linear motors for propulsion. This allows contact-less propulsion. The linear induction motor (LIM) is simple in structure, which normally has the stator installed on the vehicle (commonly referred to as the short stator approach) and the passive rotor (reaction plate) installed along the guideway. Linear synchronous motors (LSM) are used for high speed maglev such as Transrapid, in which the stator windings are installed along the guideway (referred to as the long stator approach), and the rotor is installed in the vehicle being excited by the on-board battery or other means.

1.2 Maglev status

Maglev technology has evolved a long way from an innovative concept into a ready for sale product. The original concept of magnetically levitated trains can be traced back to the early 1900's in the USA. In the 1960's, the first practical concept of using maglev as a means for ground transport was introduced by Powell and Danby [1]. Since then many innovative ideas and maglev configurations have been proposed. Over the last few decades, research and development programmes in maglev technology have been conducted by a number of countries including: Great Britain, Canada, Germany, Japan and the USA. Recently, Korea and China have also undertaken research and development into maglev since the 1980's.

In the 1990's, under a cooperative effort of various government bodies in the USA, including FRA, DOT, the USACE and the DOE with support from other agencies. a National Maglev Initiative (NMI) was established to conduct research into maglev technology with an objective to improve intercity

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transportation. The NMI study commenced in 1990 and a final report was published in 1993/94 with a recommendation to provide funding to investigate further into the feasibility and viability of developing the U.S. maglev system (USML).

Below is a brief summary capturing most of the maglev systems proposed and/or under development in the recent years.

System	Country	Speed range	Configuration	Status/Applications
Transrapid TR-08	Germany	High speed (500 km/h)	EMS	Ready for sale, Shanghai Pudong Airport Link by 2004
CHSST 100L	Japan	Low speed (100 km/h)	EMS	Ready for sale, Nagoya Tobu Kyuryo Line by 2005
Yamanashi EDS ULM 02	Japan	High speed (500 km/h)	EDS	Prototype under extensive trials
Birmingham Maglev	UK	Low speed (54 km/h)	EMS	Decommissioned in 1995 after 10 years of commercial service
Bechtel EDS ladder levitation	USA	High speed (480 km/h)	EDS	Conceptual
Foster Miller EDS sidewall null flux	USA	High speed (480 km/h)	EDS	Conceptual
Grumman EMS common lift & guidance	USA	High speed (480 km/h)	EMS	Conceptual
Magne-plane EDS	USA	High speed (480 km/h)	EDS	Conceptual
KOROS UTM 01, 02	Korea	Low speed (100 km/h)	EMS	Prototype under trails
Southwest Jiaotong University, National University of Defence Technology	China	Low speed (100 km/h)	EMS	Prototype under trials

It should be noted that there is at the moment no maglev system providing revenue service to the travelling public in the world, apart from a number of testing facilities, such as the one in Emsland (TVE), Germany for testing the Transrapid TR06, TR07 and TR08 vehicles, the CHSST facility in Nagoya, Japan for testing the CHSST 100S and 100L vehicles, and the RTRI facility in Yamanashi, Japan for the MLU vehicles. In addition, a number of experimental maglev projects using scaled down models have continued in various research venues in the USA. The low speed maglev introduced in 1984 in Birmingham, U.K., linking the airport and nearby railway station was decommissioned after 10 years of service, as the original developer did not support and update the technology.

Albeit there have been substantial amount of effort spent on the research and development of maglev, the real success of maglev is still subject to a series of issues and concerns for both high speed and low speed applications, such as safety of the braking, evacuation, levitating control systems, energy consumption, vehicle weight, environmental impacts, possible health concern due to magnetic fields, visual intrusion of placing guideway in urban or suburban

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areas, capital cost and life cycle cost versus potential revenues, and the potential rate of returns, etc. These issues and concerns are very much application specific, some of them are specific to high speed applications, and some of them apply to both high speed and low speed applications, in particular the cost issue.

Currently, there are two lines being designed and constructed for revenue service namely the Shanghai Pudong Airport Demonstration Line in China based on Transrapid technology, and the Tobu Kyuryo Line in Nagoya, Japan based on the CHSST technology. These two systems are envisaged to be in revenue service in 2004 and 2005 respectively. Intuitively, any success of these systems would perhaps secure a niche for future maglev applications.

In the following sections, the focus of discussion will be placed on the low speed maglev applications (line speed in a range of 100 km/h), with specific reference to the commercial viability of applying maglev to the low to medium capacity market sector from an operation and maintenace perspective. Attention is given to the following topics which would affect the overall performance and cost:

a) Failure mode and incident management, and what if scenarios;
b) Collision and safety;
c) Evacuation and Guideway Interface; and
d) Level of automation.

2 Failure mode/incident management and what if's

2.1 On-board power failure

In a conventional EMU train, an on-board power failure would only affect the module or the power car concerned. Once the faulty part is isolated, the train would be very likely able to complete its journey to the next station stop or nearby refuge. For the low speed short stator maglev, the levitation of the defected vehicle would be impaired, if and when there is a on-board power failure. The train would have to be de-levitated onto its skids. This would inhibit the train to continue its journey.

On-board batteries are normally provided to maintain the levitation for a period of time when there is a power failure. The battery back-up power supply would enable a soft-landing to avoid a sudden drop in the landing process and to ensure passenger comfort. Normally, the battery back-up supply could provide electricity for a very short period which would not have sufficient capacity to maintain the levitation enabling the train to complete the journey. The design of the magnet structural support and the topology of control of each electromagnet will also help to increase the fault tolerance. The use of under-car rollers, as adopted by many maglev designers, is also a good means to enhance the vehicle availability. The material and durability of the roller material would however need to be selected carefully, as it will generate heat and rather excessive noise when it is running on the guideway surface.

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2.2 Rescue mode operation and emergency roller operation

When there is a levitation failure leading to a rescue operation, a healthy train will be used to couple and tow away the broken down train from the scene to the nearby siding or back to the depot. Assuming the train is designed with sufficient installed power for push out or pull a crippled train away, provision of rollers or equivalent means would be necessary for the incident train to be moved, as the defective car would not be able to be levitated. With the use of rollers, the crippled train could be towed away by another maglev train or a self-propelled vehicle. The rollers could be of hydraulic activated (retractable) type or permanent type dependent on the under-car space available and the suspension design. The roller and guideway interface would need to be considered in designing the guideway. It would not be desirable for the rollers to be dropped onto and run on the LIM reaction plate, although the frequency of roller landing may not be very high.

Another aspect that the designer would need to look into carefully is the use of skids as parking brakes used by many maglev systems. When the emergency rollers are activated which is basically equivalent to releasing the parking brake, the train is then free for movement. Some form of interlocking between the emergency brake and roller activation system would be necessary for rescue operations to avoid the break-away or run-away scenario. A mechanical parking system could be considered as an alternative for the skids which could hold the train on rollers and on a gradient. It is envisaged that this could be in a rail clamp form and integrated with the emergency brake system, if there is not enough under-car space.

2.3 Overloading capacity of the levitation magnet

Short stator maglev trains have a nominal levitation capacity of 1.0 tonne/metre plus some design margin on the top of the declared load carrying capacity. Typically, the electromagnet lift/weight ratio is in the range of 8 to 12, and 10 is quite often regarded as a nominal ratio. The Birmingham maglev with a laminated rail achieved a lift/weight ratio of 11.7 at 15mm gap, with a current density at 1 A/mm^2 per magnet [4]. The levitation capacity (tonne/metre) and lift/weight ratio are a very good yardstick in determining the passenger carrying capacity and the weight effectiveness of the levitation system. In order to optimise the weight and the lift capacity, the electromagnets need to be designed to cope with most foreseeable loading scenarios.

Originally, low speed maglev was envisaged to be a potential replacement of people mover, light rail or monorail type systems which are all of relatively low passenger carrying capacity with short train length, narrow car compartment and a high seated versus standee ratio. Changes to the seat arrangement and car body width would be required for this type of maglev to accommodate more passenger, if the low speed maglev is to be targeted into the medium capacity systems for a wider market sector. Some re-design would need to be done to the magnet and guideway iron rail to increase the effective pole area, and perhaps

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with the use of laminated rail but this would be more expensive in terms of capital cost. There is a certain physical limit on the overloading capacity of the levitation magnet. Changing the ampere-turn and improving the magnet duty cycle would also help in optimising the design. The designer would need to consider carefully in their thought process in conjunction with the overall weight of the vehicle, as this would lead to the overall energy consumption performance as well.

From an automation point of view, some indication system could be used on board and at station through audio buzzer and video display to alert passenger and to discourage them getting on board by means of "Stand Back from the Door" type of pre-recorded message, when the loading reaches a preset threshold limit which is close to the overloading margin. This in a way could assure a smooth operation without overloading the magnets which would cause the train to de-levitate, and also avoid over-designing the magnet thereby reducing the overall vehicle weight as well as electricity energy consumption.

2.4 Levitation and guidance control and objects on the guideway

Typically in an EMS system the air gap between the levitation magnet and the guideway surface is about 8 to 10 mm. The control of the primary suspension, i.e. the electromagnets, through a positional type closed loop controller, is critical to the overall reliability and availability of the system. The design of the controller would need to take into account the bandwidth for providing the necessary guidance and tracking, ride comfort, loading variations, external forces such as wind gust forces and the irregularities of guideway such as horizontal guideway gaps and joints etc. A control problem of this kind is of multi-variables and multi objective nature. The smaller the rms air gap would entail a tighter tolerance upon the guideway structure, but potentially with less energy consumption and potentially a higher uplift force, with the same magnet and iron rail pole face design. This in effect represents a "best compromise" between different objectives in terms of performance and costs.

Since the levitation and guidance control is critical to the overall reliability and availability of the system, a highly fault-tolerant design with a distributed magnet module structure should be devised with due attention on the overall primary and secondary suspension configuration, gap sensors arrangement, modular and independent switching elements and control with provision of back-up from the adjacent or nearby magnet modules. Apart from the fault tolerant provisions, fault prediction and monitoring in the form of conditional based maintenance should also be put in place to increase system reliability.

In order to ensure safety and protection of the levitation equipment and guideway, gap sensors are used to provide the physical gap separation feedback to the controller. The gap controller based on the feedback signal and among other variables will regulate the pulse width modulation (PWM) signal to the electromagnet power circuits to maintain the gap at the nominal value. Since this built-in feature already exists, automatic monitoring of the guideway condition could be carried out and recorded by running an empty train round the alignment

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before the first train commences its service in the morning. A guideway data base could be establish for maintaining a record of the irregularities of guideway, based on which preventive and corrective maintenance could be set up cost-effectively. Having these data made available, anomalies and defects could be predicted with the use of some intelligent computer based supporting system. From an automation viewpoint, the "guideway data" could be relaid to the on board Train Management System through which the Operation Control Centre and Maintenance/Fault Reporting Centre would have a complete picture.

Maglev guideway is normally completed with a flat and horizontal surface which is open to foreign objects, e.g. news paper, lighters, drink cans, paper clips, steel nuts and bolts etc. Light objects would be blown away by wind or pushed away by the train front, depending the weight of the object. In order to protect the levitation equipment and guideway, deflector plate with extended heavy duty brush type device could be mounted at the front end under-car to prevent small objects got trapped between the magnets and the guideway. This has been proved to be very effective in a number of low speed maglev prototypes.

2.5 Magnetic field strength and residual flux in the guideway iron rail

There has been much concern regarding passengers exposure to magnetic fields. Having conducted a series of tests and measurements by various maglev suppliers, this is no longer an issue for the EMS system. But the EDS vehicles have yet to resolve this issue in designing the super-conducting magnets and adding ferromagnetic shields to protect the passengers.

Since the electromagnets are constantly energised during normal operating hours, the guideway iron rail would be easily magnetised after some time of continuous operation. Intuitively, this should not cause any serious problem, as the residual field strength in the iron rail would not be high enough to cause any harmful effect. However, this would need to be inspected and/or monitored from an operation point of view, as small iron objects such as iron scrapes, iron nails, book clips etc. would get stuck onto the rail which may need to be cleared from time to time.

3 Collision performance and safety

Historically, maglev vehicles are designed based on standards used in the aircraft industry as well as those in the railway industry. The approach to specify collision performance in conventional rolling stock is to specify minimum buff strength, collision post strength and other design loadings. These requirements are a result of long experience of conventional rolling stock behaviour in collisions. There is however no equivalent experience for maglev vehicles. The conventional collision survivability approach in specifying various structural requirements for a maglev vehicle would not be a viable option, increase in vehicle weight to achieve this would prevent the vehicle from being levitated. A holistic approach should be used to develop collision safety requirements for a

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maglev system, consistent with an overall system safety requirement specified in terms of accident frequency versus severity.

As regards the structural integrity of the maglev vehicle, loads that the vehicle is expected to experience in service should be properly identified such that the vehicle could respond to these loads safely. One unique feature of the maglev vehicle is that the structural design is similar to an aircraft, and would not be able to withstand the compression load, collision post load or other loads related to conventional rolling stock. In general, there is no need for maglev vehicles to sustain such loads due to rather different application. The risk of collision with other type of vehicles does not exist. The probability of "head-on" collision with the same type of vehicle is negligible, if a proper collision avoidance system based on the modern train control and signalling technology is utilised. In addition, as a result of levitation and absence of wheel-rail contact, there is no influence of the dynamic impact loads induced through the primary and secondary suspension system to the carbody.

A maglev vehicle is considered to be between a conventional rolling stock and an aircraft in respect of structural failure risks. The maglev module wraps around the guideway in a manner that the vehicle can only separate from the guideway when there is a structural failure. As long as the structural design is adequate in bearing all the expected loads, the scenario of vehicle separation from the guideway is not possible. Overturning due to strong side wind is not possible either.

4 Evacuation and guideway interface

With the adoption of magnetic levitation there is no longer a physical interface with the support or guideway structure. This provides the benefits of minimum guideway wear and tear, thus reducing maintenance. Traditional problems caused by variations in the wheel rail interface, such as corrugations and gauge corner cracking are no longer applicable. However a new set of problems arise.

With the adoption of a support beam structure to fix the levitation rails an economic structure can be developed. Adopting a mono rail type configuration allows extensive off site casting and simple beam and column head construction. However train evacuation in an emergency is now an issue. On a traditional railway, evacuation is either by side or end doors, down to ground level or some walkway structure. In both cases when on a viaduct the parapet is used to ensure a safe route is maintained. With a maglev system even operating at "ground level", the vehicle floor is likely to be over 2m in the air, making side evacuation a logistical problem. Clearly, to provide a side parapet on a maglev system would diminish the infrastructure cost saved provided by the adoption of a simple beam arrangement. Thus alternative solutions are required.

Evacuation of small numbers of passengers can be achieved with chutes and ladders, providing the alignment does not impose impractical surface or height restrictions. However, this may not possible and alternative solutions will need to be adopted; one solution identified provides for end evacuation into a

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walkway located within the guideway beam. This is achieved by converting the beam from a closed box structure to an open box beam.

With the levitation iron rails attached to the side of the guideway problems of corrosion protection become a major maintenance issue. If the levitation rail is not protected, rust staining on the beam will become a major visual problem. If the rail is provided with a protective system, such as galvanising or paint the material must be compatible with the mechanical braking system and not delaminate or provide a reduced friction surface. Options to change the rail steel to a more weather resistant steel mix may be limited by the cost impact or the environmental conditions anticipated.

The high construction tolerances required for the guideway and levitation iron rails are far higher than the normal civil tolerances, but similar to traditional high speed permanent way installation tolerances. However since the iron rail does not need to be continuous the problems associated with handling long welded rail, rail stress and movement joints is no longer an issue.

5 Level of automation

Since the maglev technology was first introduced, all the maglev systems proposed thus far have been hitherto designed with a very high level of automation. Modern central control facilities coupled with manless trains and stations have been always part of the standard design of a maglev system. The major benefit of having such a highly automated system is two-fold. Firstly, it eliminates the human intervention which in turn eliminates all the human errors thereby achieving a safer system. Secondly, a highly automated system could bring a significant resource saving which is one of the major elements in the operating costs. The latter would play an important role in evaluating an overall viability of a maglev project and the rate of returns on investment.

With the maglev train operating in manless mode, the level of on board system intelligence, system health monitoring and system self healing properties, will be similar to that on a conventional steel wheel on rail manless EMU train set. With maglev though there are some special requirements.

The central controller needs to be provided with the capability to drive the train in restricted mode, in the event of an onboard system failure, that has incapacitated the train. This will necessitate him being provided with controls that allow him to manage the train braking system, the train levitation system and the train emergency rollers system.

As previously discussed maglev trains can only continue to operate providing the levitation force can continue to support the load. If any one car, including just one end or one side becomes overloaded to the point where the gap sensor detects an out of tolerance levitation gap, then unless the levitation magnet strength in the effected area can be increased to rectify the situation, that car will shut down and de-levitate, causing the whole train to shut down. This is obviously a situation to be avoided and therefore, load sensor readouts and magnet strength status readouts need to be displayed to the central controller, providing priority warning and alarm status messages. The warnings will trigger

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DVA messages in the effected train, and on the platform to alert passengers that the train is full, thereby averting the possibility of a car de-levitating. Likewise a partial loss of levitation magnet strength in an individual, or a group of magnets may result in an out of tolerance gap being detected. The on board levitation system will try and compensate for the loss, by increasing the current of the adjacent magnets, to maintain the correct gap. If this cannot be achieved then this needs to be alerted to the central controller to restrict the passenger load in the effected train car. The secondary suspension comprises of air bags, again if an air bag or a group of air bags partially deflated, then if the on board compensation logic cannot maintain the required gap either through increasing air pressure and/or increasing the adjacent magnets strength, this information needs to be alerted to the central controller, so as to restrict the passenger load in the effected train car. A reduction in passenger load will act as a compensating factor against the reduction in levitation ability, caused by magnet or air bag system problems, the reduction in load allowing the train to complete its operating schedule.

6 Concluding remarks

There could be very little doubt that maglev is a mature and sophisticated technology. Notwithstanding the advancements in the Transrapid and CHSST systems, there are an array of factors which need to be contemplated objectively in respect of capital investment, life cycle costs and return on investment before a decision as to the viability of a maglev project could be made. To date, there is no revenue maglev system in the world upon which railway authorities could gain sufficient experience and confidence that a maglev system could be regarded as a proven alternative means of urban transport. Of equal importance, the operation, reliability and availability aspects of the technology need to be ascertained. And these could only be attained by prudent design coupled with experience gained from revenue maglev systems. To this very end, the Shanghai and Tobu Kyuryo projects when they are in operation would provide some "feedback" and insights. This paper reviews a number of areas which are critical to the overall reliability and availability of a maglev system, with a view that maglev would be able to find an appropriate niche for applications, provided that the merits of the technology such as low noise emissions, low wear and tear etc. are best utilised, and the cost of the vehicle itself is competitive.

It is the authors intention to probe further beyond that of the dedicated effort from the maglev researchers and developers in conjunction with the advances of other technologies in power electronics and computer control systems. Some new standards particularly those relating to collision performance, levitation and guidance system would need to be established based on a holistic approach to the technology, such that maglev could perhaps evolve into a stage as another kind of sustainable transport system.

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References

[1] Powell, J.R. and Danby, G.T. "High Speed Transport by Magnetically Suspended Trains." Paper 66-WA/RR-5, 1966 ASME Winter Annual Meeting, N.Y. Nov. 1966.

[2] Eastham, T.R. "A Re-evaluation of maglev for High Speed Ground Transport." 4^{th} International Conference on Unconventional Electromechanical and Electrical Systems. St Petersburg, Russia, 21-24 June 1999.

[3] Eastham, T.R. and Masada, E. "Electric Urban Transit Technologies for the Reduction of Air Pollution in Cities." Proceeding of the 16^{th} International Conference on Magnetically Levitated Systems and Linear Drives. Rio De Janeiro, Brazil, 7-10 June 2000.

[4] Nenadovic, V. and Riches, E.E. "Maglev at Birmingham Airport: From System Concept to Successful Operation." GEC Review. Vol. 1, No. 1 1985.

[5] Siu, L.K., Chan, D., Kato, J., Takahashi, M., Fujino, M., Carden, D. "Failure Mode and Endurance Tests of the CHSST 100L System." The 17^{th} International Conference on Magnetically Levitated Systems and Linear Drives. Lausanne, Switzerland, 3-5 September 2002. [To appear]