MagneMotion
A Force in Electro-Magnetic Systems

The Future of Maglev

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***Abstract*-This paper presents a personal opinion concerning the future potential for maglev and linear motor technology to create improved transportation systems for a wide range of applications.**

I. INTRODUCTION

Any paper that attempts to predict the long term future of an emerging technology is necessarily a personal statement but it sometimes helps to look beyond the short term problems and conjecture on what maglev technology might be able to contribute to improving transportation worldwide. All of the ideas presented here can be supported by analysis, but new ideas and market reactions defy predictions. The objective is to stimulate a discussion not bounded by devilish details.

Maglev ideas go back more than a century but major funding of development did not start until the 1970s. The earliest efforts were hampered by a lack of supporting technology and by preconceived notion that maglev was primarily good for short shuttles or for speeds higher than could be achieved with steel wheels running on steel rails. This thinking led to several operational maglev designs: Birmingham England shuttle, Japanese HSST, German Transrapid, and Japanese Yamanashi Maglev Test Line (YMTL). In spite of outstanding design and fabrication efforts, these systems are all based on designs developed many years ago and do not represent the best that maglev technology can offer with today's know-how and technology.

I would like to answer the "Future of Maglev" question in three speed ranges. In each range the combination of basic physics and people's traveling habits lead to quite different designs. Table 1 gives a summary of what I believe will be the general features of maglev transportation for each of the three speed ranges. This paper describes the history and status of maglev in these speed ranges and suggests directions for new designs. Most of the maglev designs and technologies described here can be explored in more detail on several web sites.

II. PERSONAL RAPID TRANSIT

Personal rapid transit is an old idea: automated point-to-point travel in automobile size vehicles with minimum time spent waiting and stopping. The key ideas were elucidated in the 1960s and in 1975 a quasi-PRT system became operational in Morgantown West Virginia. This system has a 5.8 km long dual guideway and now carries an average of 15,000 people per day with availability over 99%. The vehicles are designed to carry up to 20 people so it is not PRT in modern use of the term but it has demonstrated the potential for reliable, automated and people-friendly transportation.

TABLE 1. PROPOSED MAGLEV DESIGNS FOR THREE SPEED RANGES.

Category	*Personal Rapid Transit*	*High Speed Ground Transportation*	*Super Speed Tube Travel*
Most important features	Easy access, short wait time, reasonable speed	Ability to travel a few hundred km at an average speed significantly faster than a personal automobile	Ability to travel long distances at speeds comparable to commercial jets
Key design ideas	Automobile size vehicles, off-line loading, point to point travel	Bus-size vehicles, short headway, few stops in spite of frequent stations	Very fast with slower speed maglev used to feed stations and avoid station congestion
Max. speed *m/s* *km/h* *mph*	 15-30 54-108 34-67	 40-120 144-432 89-268	 150-? 540-? 336-?
Passengers per vehicle	3-6	20-60	80-160
Station spacing, km	0.5-1	2-20	100-400
Competition	Automobiles Buses Rail transit	Automobiles Trains Commuter jets	Commercial jets Supersonic aircraft
Suspension technology	EMS with permanent magnets	EMS with permanent magnets or high temp. superconductors	EDS with high temperature superconductors
Propulsion technology	LSM	LSM	LSM

Taxi 2000 was a PRT project by Chicago and Raytheon and led to construction of a prototype in Marlborough Massachusetts in the 1990s. The original concept was sound but the implementation was overweight and too expensive for commercialization. A number of other PRT designs have been demonstrated on small test tracks but it was not until 2006 that there was a planned installation, in this case an installation of the ULTra system at the London Heathrow Airport. Other developments in New Zealand and Sweden have promise for future implementation.

The most important requirement for PRT is the ability to provide transportation that rivals the automobile for privacy and point-to-point travel with few if any stops. The station spacing must be short enough to allow access by walking and the wait time should be less than a minute at all times. The top speed is a function of application but I believe the winning design will be one that has the capability to go at least 108 km/h for longer distances, such as city to airport, while a top speed of half of this is adequate for operation within an urban area. None of the existing designs have this capability, and I believe they are too slow with too little capacity to receive wide acceptance.

A key feature of PRT is the use of off-line loading and unloading. It is a formidable challenge to provide offline loading while still maintaining enough capacity for typical applications and at a cost that is competitive with alternatives. The vehicles must be able to switch to a station siding while still allowing the short vehicle headway that is needed for reasonable capacity. This requires that switching be done without any moving parts on the guideway and requires switching to a siding at a reasonable speed so trailing vehicles do not have to slow very much. There is a compromise between high speed switching, with the necessity for long deceleration and acceleration lanes, and low speed switching that reduces the average speed of travel for the entire system. As with all maglev applications, the devil is the details and this includes: safe control with short headway, empty vehicle management, emergency evacuation station design, etc.

The Linear Synchronous Motor (LSM) is an ideal candidate for propelling PRT vehicles because there is no need to transfer power to the vehicle and all of the time-critical control functions are on the guideway; vehicle communication is required, but it is not safety critical. The LSM also provides friction free propulsion so that acceleration and braking rates are not dependent on wheel traction. Most proposed PRT designs use wheel based onboard propulsion but these designs will have a hard time meeting safety requirements while achieving an acceptable capacity. The Vectus PRT uses a long stator Linear Induction Motor (LIM) for propulsion but I believe the LSM can provide higher performance at lower capital and operating cost.

A good PRT system can be built using wheel suspension with LSM propulsion, but it is also possible to use maglev. The best maglev technology for this application is ElectroMagnetic Suspension, or the use of attraction of magnets to ferromagnetic material. The evolution of Neodymium-Iron-Boron (NdFeB) magnets makes the use of permanent magnets the best choice for providing the suspension force and also the field for an LSM propulsion system.

Figure 1 shows the concept of magnetic switching based on an operational material handling system that uses the same principle. At a switch there are electromagnets that can pull the vehicle into a branch but if the magnets are inoperative the vehicle will go straight with no safety problem. The vehicles have wheels that serve as emergency landing when traveling and can be loaded while stationary and resting on the wheels. All propulsion is by an LSM that uses the same permanent magnets that provide the main lift. Vehicle onboard power for HVAC is provided by inductive transfer from the LSM. The vehicles have small batteries to provide power for suspension control but there is no need for an onboard propulsion system so the vehicles are light with cost comparable to a wheel-based PRT vehicle.

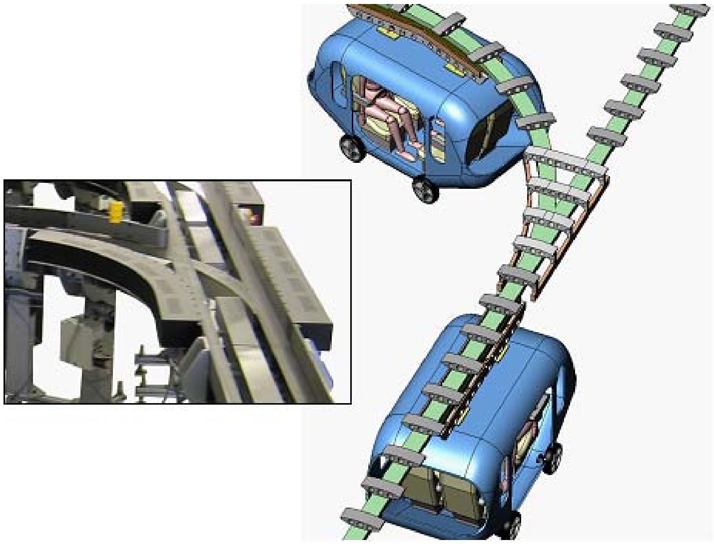

Fig. 1. Overhead suspended maglev PRT, also showing magnetic switching for an existing wheel suspension design.

Fig. 2 shows an alternate design based on tube travel. This design can provide capacity comparable to many rapid transit systems and better than most light rail systems at far lower cost. The vehicles travel in small diameter tubes that can be installed underground at much lower cost than for conventional subway systems. The vehicle size can be increased, if desired, but the key is to keep the size small enough so that point-to-point travel is possible. As an example, a system like this can have the capacity of the system proposed for Dulles Airport in Washington DC where a conventional transit design has a recently been estimated to cost $120 million per km.

Table 2 gives parameters for a proposed maglev PRT. The maximum speed can be lower where travel distances are shorter, but the advantage of LSM propulsion is that there is very little added cost if we design for higher top speed where it is useful, such as airport access from a city or as a replacement for commuter rail. When demand is high and stations closely spaced the average speed will approach the switching speed, but for longer distances the average speed will be much higher. With a minimum headway of 2 seconds and assuming 4 passengers per vehicle the capacity is 7,200 passengers per hour per direction (pphpd).

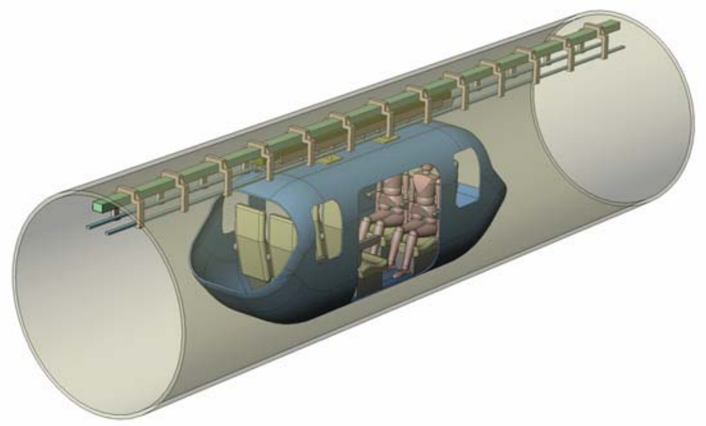

Fig. 2. PRT tube maglev.

Table 2. Design parameters for baseline maglev PRT.

Parameter						
Maximum speed	30	m/s	67	mph	108	km/h
Cruise speed	24	m/s	54	mph	86	km/h
Switching speed	12	m/s	27	mph	43	km/h
Sharp turn speed	6	m/s	13	mph	22	km/h
Maximum acceleration and braking	2	m/s^2	0.2	g		
Maximum emergency braking	3	m/s^2	0.3	g		

III. High Speed Ground Transportation

This is the speed region that motivated early high speed maglev development and led to the German Transrapid and Japanese Yamanashi Maglev Test Line (YMTL). In Europe and Japan the focus was on replacing trains, but the U.S. National Maglev Initiative funded the development of four design concepts and all of them were based on using vehicles the size of commuter jets. The reason is simple: in the U.S. the competition is jet travel and people tend to live in corridors, rather than in cities, so it was essential to have relatively short station spacing. With relatively small vehicles and LSM propulsion it is economically feasible to design a propulsion system that provides high acceleration and with close spaced vehicles regenerative braking can produce significant energy savings. The concept is to use relatively short station spacing but vehicles scheduled to stop at relatively few stations. This can be done without the need for off-line loading if the vehicles travel in clusters with short headway between vehicles in a cluster and brick-wall headway between clusters.

A good example of the advantage of small vehicles is a comparison of the Shanghai maglev trains with an alternate design using bus-size vehicles. The Shanghai maglev uses trains capable of carrying 574 passengers with 10 minute spacing between trains and with an 8 minute travel time for a 30 km trip. The capacity is thus 3,444 passengers per hour per direction (pphpd). The Shanghai vehicles achieve a top speed of 420 km/h, but the average speed is only 225 mph. If you compute trip time as travel time plus the average wait time, the average speed is only 138 km/h. An alternative is to use 40 passenger vehicles with 15 seconds spacing to achieve a capacity of 9,600 pphpd. If we design for a top speed of 216 km/h and 2 m/s^2 acceleration, the average travel speed is 204 km/h and the average trip speed is 201 km/h. With small vehicles accelerating faster but traveling slower the average travel speed is almost as high and the average trip time is substantially less.

With small vehicles traveling slower capital cost is greatly reduced for two reasons: the guideway beams only need to be stiff enough to handle a single, relatively light vehicle and the lower speed means that guideway tolerances are less critical. With a lower top speed operating cost is reduced for two reasons: the propulsion power for cruise is reduced and with short headway it is feasible to reuse energy recovered from regenerative braking to propel nearby vehicles. The short vehicles are practical because the power they require can be provided by inexpensive inverters using mass produced power electronic devices and inexpensive high performance microprocessors, neither of which was available when the Transrapid and YMTL systems were developed. The cost per kVA for an inverter is relatively independent of the kVA rating of the inverters, so using many small inverters does not pose a cost disadvantage to using small vehicles.

If we define HSGT as high speed compared to existing technology, then there are two speed ranges to consider. The U.S. DOT funded the development of Urban Maglev with a top speed on the order of 50 m/s (180 km/h, 112 mph). This speed range has a wide range of applicability including transportation in and around airports, commuter rail, and connectors between intercity maglev and airports. For intercity applications the objective is to be competitive with high speed trains and significantly faster than private automobile. The German and Japanese high speed maglev efforts focused on speeds of 420 km/h or higher, but I believe that operating at a somewhat lower speed has many advantages in capital and operating cost. If the top speed is reduced to 360 km/h the system is still competitive with commercial jets for distances up to 800 km and increasing the speed to 420 km/h adds more cost than it is worth. In this speed range the propulsive power is primarily to overcome aerodynamic drag and varies as the cube of speed and the minimum turn radius varies as the square of speed; a 20% reduction in speed has major implications in propulsion power and guideway cost. Table 3 gives suggested parameters for Urban and Intercity maglev.

Table 3. Parameters for two types of HSGT.

Parameter	*Urban*	*Intercity*	*Units*
Maximum speed	50	100	m/s
	180	360	km/h
	112	224	mph
Minimum headway	8	16	s
Passengers per vehicle	32	64	
Station spacing	2	20	km
Capacity	14400	14400	pphpd

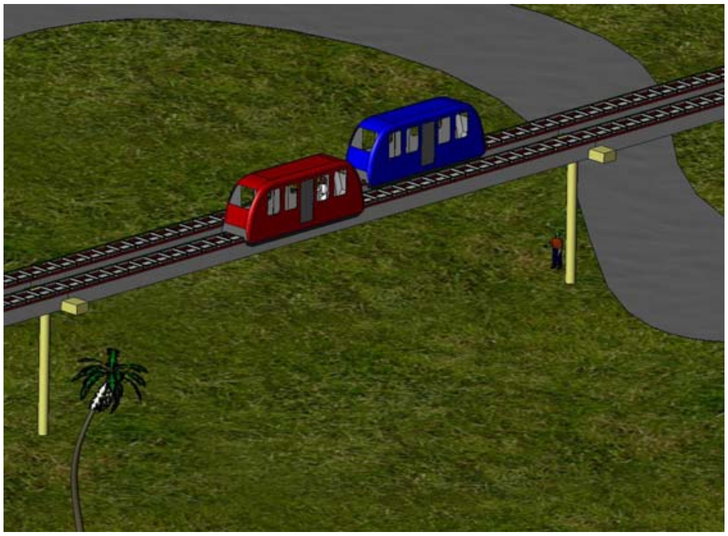

Fig. 3. *M3* Urban Maglev.

Figure 3 shows what the *M3* urban maglev system might look like. For intercity applications the suspension and propulsion are the same but the vehicles would be longer and the beams would be beefier. The MagneMotion *M3* permanent magnet suspension and LSM propulsion have been tested at low speeds and will soon be tested at higher speeds. It features a 20 mm magnetic gap with control in three dimensions done via control coils on the magnets. The guideway mass is much less than if the vehicles were replaced by trains.

IV. SUPER SPEED TUBE TRAVEL

HSGT travel at speeds up to 360 km/h makes maglev competitive will all existing high speed trains but it does not make maglev competitive with air travel for distances over about 800 km. The Japanese Yamanashi Maglev Test Line (YMTL) is designed to operate at 500 km/h and has been tested at 581 km/h. I believe that there is little incentive to pay the high capital and operating cost for this system if it is only marginally more competitive with commercial jet travel. Japan may some day construct a version of the YMTL design but it is unlikely that any other country has a potential application that can justify this level of investment. Probably the only way to be truly competitive with air travel is to use a design that has been proposed by many “visionaries”: operate vehicles in evacuated underground tubes. We need to answer the question: Can maglev SSTT be a practical system for world wide application?

The answer is yes, it is technically possible, and perhaps economically feasible, but will take a major investment to provide quantitative answers this question. This section discusses some of the major issues. I believe there are two possibilities: subsonic speeds in partially evacuated tubes and the equivalent of supersonic speeds in nearly totally evacuated tubes.

There are many technical problems that must be solved to achieve SSTT. A very important requirement is that the right-of-way must be incredibly straight. For example, at 250 m/s (900 km/h) the minimum turn turning radius must be 25 km if radial acceleration is to be held to 2.5 m/s^2. Also, at speeds over about one half of the speed of sound, which is 340 m/s, the tube must be partially evacuated to make the energy consumption reasonable. Clearly there must be a major investment in construction equipment to allow the installation of the tube at an acceptable cost and for maintaining an evacuated atmosphere.

I believe that the proper suspension and propulsion system for subsonic SSTT is an ElectroDynamic Suspension (EDS) with LSM propulsion. YMTL uses this approach, but their suspension design is unlikely to be able to be modified to achieve operational speeds much higher than 600 km/h. All EDS designs create an inherently under-damped suspension and the damping system used by YMTL has serious limitations. By using a partially evacuated tube the propulsion requirements could be dramatically reduced and this creates new opportunities for providing better control of ride quality.

All SSTT ideas are highly speculative, but for subsonic travel I believe the best approach is to evacuate the tubes to about 10% of atmospheric pressure and limit vehicle speed to about 280 m/s. In order to reduce drag the tube diameter should be at least 2.5 times the vehicle diameter, so there are advantages in restricting vehicle size to about the size used by YMTL, or 3 meters in outside diameter with 4 abreast seating. The suspension system would then use high temperature superconducting magnets mounted in wings that protrude from the sides of the vehicle and interact with guideway mounted suspension and propulsion structures. I would look seriously at the use of aerodynamic control surfaces to help damp oscillations produced by the EDS suspension system.

The advantage of using only partially evacuated tubes is that the vehicle technology is very similar to that used by existing commercial jets and aerodynamics can be used for control. The air pressure is high enough to allow conventional cabin atmosphere control systems. The tubes would not need to be evacuated until the speed reached about 140 m/s, so the system could be used without evacuation at speeds comparable to those described under HSGT. The question is: can underground tubes be installed at a cost competitive with elevated guideways. Several years ago a study by a group at Bechtel indicated that underground tubes could, in some cases, be installed at a competitive price with the big advantage that it is possible to achieve a straighter right-of-way than it is possible if it necessary to use an elevated guideway that follows existing transportation corridors.

For some “visionaries” it is not enough to operate at subsonic speeds, they want to reach supersonic speeds. I doubt that this is possible unless the tubes are almost totally evacuated so that the definition of supersonic should be changed to mean greater than 340 m/s. I know of no known reason that SSTT can not exceed 340 m/s, but it will require significant new inventions on how to provide stable suspension and propulsion. Clearly the tubes will have to be incredibly straight and this poses severe construction cost issues. I have heard proposals construct the tubes underwater, but this will not work unless the tubes are buried because even very slight currents or thermal fluctuations would make it impossible to maintain an adequately straight guideway.

The future of supersonic travel in space or tubes is unlikely to happen in a major way in the foreseeable future.

V. SUMMARY

The ideas presented here are personal conjectures based on 40 years of work at MIT and MagneMotion developing linear motors and maglev. The PRT and HSGT ideas are based on existing hardware and there is little doubt that they can be translated into commercially viable designs. Once a few installations have proven their validity I believe that there will be a rapid growth in applications on a world wide basis. The SSTT option is a very real possibility but there is no existing suspension design that will meet the objectives. Before any meaningful prototypes can be built there will need to be a substantial investment in research and development.

My recommendation is to focus on maglev speeds below about 100 m/s (360 km/h) until the technology has been fully tested in commercial applications. I also believe permanent magnet suspension, LSM propulsion, and automobile or bus-size vehicles have major advantages over trains. The development of systems for controlling vehicles operating with short headway will take a major effort, but it will be possible to provide very safe operation at headways comparable to the ones used by human drivers on a highway. I am convinced that we are on the verge of an era where creative new maglev and linear motor ideas will revolutionize transportation technology.

ACKNOWLEDGMENT

The ideas expressed in this paper are personal, but are also the result of 40 years of working with many outstanding engineers on the development of linear motors and maglev. I owe particular debts to many students and faculty at MIT and all of the staff at MagneMotion. I particularly acknowledge the work of Tracy Clark, Brian Perreault and Marc Thompson and the research and development support of NSF and DOT.

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