Future Prospects for Maglev Technology Applications

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Abstract
This paper examines the prospects for the future of maglev technology in general. Future applications will depend on a variety of factors including the extent to which Transrapid or other maglev technologies can be proven superior to its competitors technically, environmentally, and economically. This paper will address the extent to which the potentially beneficial attributes of maglev technology have been realized and what additional developments are required to improve the prospects for future deployment. Past and current proposed maglev projects are reviewed and evaluated from the viewpoint of how they might enhance maglev competitiveness. In view of the recent announcement by the Bush Administration to expand the manned-space flight program, prospects for maglev space applications will also be considered. Proposed concepts for both high-speed and urban transit (low speed) applications, including the use of electromagnetic, permanent and superconducting magnets are reviewed. Recent developments in high temperature superconductivity and their possible advantages for maglev technology will also be considered.

1 Introduction

Now that maglev has become a commercial reality, what are its prospects for the future? It has taken over three decades of dedicated effort and financial support to reach this point. And, it has become increasingly evident that maglev deployment is as much a political as a technical challenge.

Future prospects depend very much on the extent to which the technology can win popular acceptance and political support. This in turn requires that, for each type of application, the technology must be proven superior to its competitors technically, economically, and environmentally.

In the U S, and in many other countries, growth in demand for conventional, mostly-petroleum-fueled modes of transportation has led to traffic congestion, excessive time delays, environmental issues and energy supply problems. Decades ago, visionaries recognized the solution to be a new mode of transportation - one whose attributes would permit convenient, high-speed, high-frequency, reliable service at competitive costs, that is environmentally friendly, and independent of petroleum imports. Early on, maglev technology appeared to possess the necessary attributes. It promised high speed, rapid acceleration, smooth, quiet, non-contact, environmentally friendly operation with competitive costs. To what extent have these promises been met. If they have not been fully met, what technical developments are required in the future? These issues are addressed in the following sections.

2 Prospects for Inter-City and Long-Distance Applications

2.1 Requirements & Existing Modes

Commercial jet aircraft and motor vehicles on interstate highways meet most of the demand for inter-city transportation in the US. Most railroad right-of-ways are owned by freight companies and used primarily for freight. Top speeds are limited to 127 km/h. The fraction of passenger travel by rail is quite small except for the Northeast corridor between Boston and Washington DC, where the top speed of 241 km/h is reached on limited sections of track. Generally, the requirements of speed (i.e., short trip times), and frequent reliable service have not been met by passenger railroads. Incremental improvements have done little to increase rail ridership, and safety at grade crossings remains a serious problem. Amtrak continues to be heavily subsidized by the government.

Jet aircraft provide high speed and, for major city pairs in the US, relatively frequent service. However, the demand for air travel has increased faster than capacity and there is strong opposition to expanding airports or building new ones. The FAA's 2001 "Airport Capacity Enhancement Plan" [1] notes that from 1995 to 2000, operations increased by 11% and delays by 90%. Similarly, in the US, the use of highways has increased faster than highway capacity growth and there is little land left, especially in urban areas, to build additional traffic lanes.

The most serious shortcoming of these efforts to meet travel demand with these conventional modes in the US is that they increase noise, pollution, and the demand for petroleum imports.

Elsewhere in the world, e.g., Japan and Europe, there is a tradition of reliance on passenger train travel, and the demand for fast, reliable, frequent service has been met in part by electrified high-speed rail (HSR) systems including the French TGV, the German ICE, and the Japanese Shinkansen. In fact, these HSR systems have been so successful that they are also becoming saturated, prompting the need for greater capacity and newer technologies. Revenue service speeds are currently on the order of 270 to 322 km/h, and provided certain technical challenges can be met, they are likely to reach 360 km/h. However, accelerations are relatively low, requiring 15 to 20 km or more to reach maximum operating speeds. Fig.1 shows the distances required to reach various speeds from rest for several technologies. While higher speeds for HSR have been demonstrated, the corresponding required distances become quite excessive. Where steeper grades are required, maglev also performs better than conventional advanced trains.

2.2 Present Maglev Technologies and Possible Future Developments

By far the greatest emphasis to date has been focused on the development of high-speed maglev systems for passenger travel. Electromagnetic suspension (EMS) and electrodynamic suspension (EDS) systems have attained speeds in access of 450 and 580 km/h, respectively, and accelerations well in access of HSR as illustrated in Fig. 1. Further increases in speed are technically feasible, but the potential benefits must be weighed against the increased costs in required installed power capacity and the additional energy use. These costs could, in principle, be mitigated with operation in partially evacuated tunnels. Added benefits would include eliminating the need for elevated guideways and reduction of the cost of right-of-way acquisition and protection. In mountainous terrain, as in Switzerland and Japan, where there are limited alternatives, partially evacuated tunnels such as proposed for the Swissmetro system [2] might prove cost effective. However, the technology faces major engineering challenges and will require considerable development and testing before it is ready for commercial application.

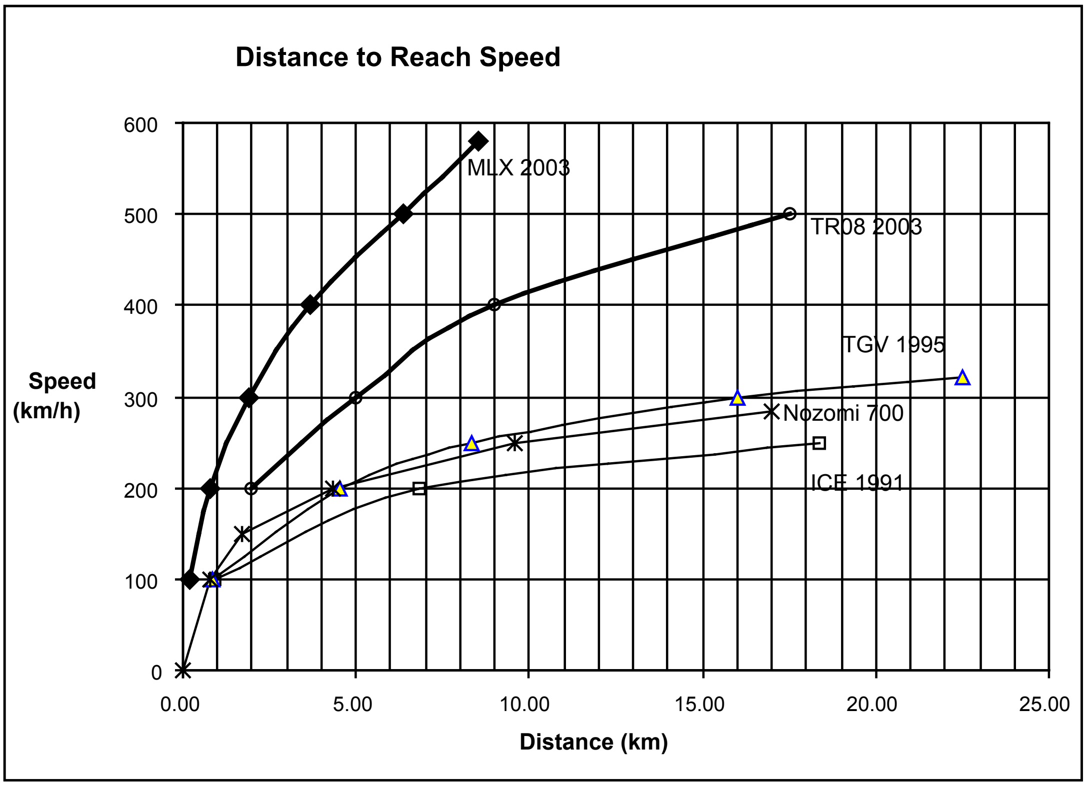

Figure 1:   Distance to Reach Operating Speed for Conventional and Maglev Trains.

To meet the demand for expanded transportation options in the near term, the choices are limited to existing proven technology. The immediate availability of the Transrapid system gives it a considerable commercial advantage for near-term applications in many countries. For the longer-term, EDS and EMS systems will be highly competitive and the choices will depend on how well the attributes of each match the application requirements. The ability of EMS technology to levitate at low speeds and at rest is advantageous for applications combining commuter and inter-city service. In the seismically active mountainous terrain of Central Japan, the Japanese EDS system operating mostly in open tunnels, is a good choice. Elevated guideways and right-of-way problems are eliminated by the use of tunnels. In addition, while maintaining high-speeds in the tunnels has been proven at the Yamanashi Test Track, tradeoffs are required between the costs of large cross-section tunneling (to permit safe, high-speed operation), energy use and power demand.

Applications of EDS and EMS systems in most other parts of the world, including the US, will generally involve considerably less difficult terrain conditions and therefore less cost, power demand and energy use. In the US, where few rail lines are electrified, both EMS and EDS are expected to be highly competitive with new proposed HSR lines. In comparison with new HSR systems, the greater thrust capability of non-contact linear synchronous motors, are advantageous for acceleration, braking, and greater grade climbing, which permits greater flexibility in route selection as well as shorter trip times. Even HSR builders now appreciate the benefits of distributed traction systems such as are an inherent part of EDS and EMS systems. Both the German ICE and the French TGV systems are now replacing power-car-drawn consists with electric multiple-unit (EMU) type traction systems (Shinkansen trains have always used EMU traction). Such traction systems enhance performance and passenger capacity per unit weight. In addition, non-contact operation is expected to reduce maintenance costs. JR Central Railroad [3] has noted that the use of distributed traction systems also reduces construction and track maintenance costs. In the National Maglev Initiative (NMI) study [4] completed in the US a decade ago, it was concluded that elevated civil structures for some maglev conceptual designs would be less costly than that required for HSR. However, that important finding has yet to be demonstrated in practice.

2.3 Cost/Benefit and Deployment Considerations

Total cost/benefit comparisons between maglev and HSR systems are not easy to make. To be fair, one should take into account costs and benefits in the context of deployment strategies that fully capitalize on the potential attributes of each technology. That has generally not been the case in past studies. While such a comparison will not be attempted here, a few points are worth noting.

As is well known, high-speed maglev technology transfers much of the traction equipment from the power cars in conventional trains to the guideway, thus increasing the guideway construction cost/km . Conversely, the vehicles can, in principle, be made simpler and lighter, and the stresses on the guideway are more evenly distributed, reducing the need for heavy civil structures and reducing the propulsion power and energy use (for a given speed and acceleration).

Greater speed and acceleration implies that more round trips can be made with the same number of cars, thus serving more passengers or serving the same number with fewer cars. In addition, maglev permits high frequency service by using small consists (two or three cars), an option that is less practical for locomotive-drawn HSR consists. This is especially important in less densely populated areas characteristic of many locations in the U.S.

The extent to which the differences mentioned above will alter or eliminate cost differences between maglev and HSR deployments has yet to be fully evaluated. With regard to deployment strategies in the US, the immense inter-state highway system affords ample right of way (ROW), in most locations, for elevated guideways.The use of existing railway ROW's would require extensive upgrade, realignment, and electrification. Since the maglev system can be deployed along existing highways, with the development of strategic multi-modal stations along its route, a new generation of ridership that is frustrated with spending hours in their own automobiles going to and from from work will definitely be created. With the advent of such a high speed maglev system, people living in San

Diego, for example, could easily work in downtown Los Angles and vice versa. It is conceivable that one could live as far as 200 km away from a major city and able to get to work in 45 minutes with the installation of such maglev systems.

However, deploying maglev systems in a manner that capitalizes on the attributes of the technology requires considerable planning. In the US, for example, J. Harding [5] has observed that Maglev Deployment Program planners have squandered much of the potential advantages of maglev. "Speed, trip time, energy efficiency, extendibility and cost have all been severely compromised".

2.4 Future Technology Developments

The foregoing argues in favor of careful deployment planning as well as continued maglev technology development. The latter should focus on cost and weight reduction as well as on improved energy efficiency. Fig.2 illustrates changes over time of vehicle mass per passenger seat for both HSR and maglev technologies. Early results indicated a substantial gap between the maglev and HSR masses/seat. However, more recently that gap is being narrowed by the use of lighter materials and EMU traction systems. Fortunately, several efforts are underway that may widen the gap again.

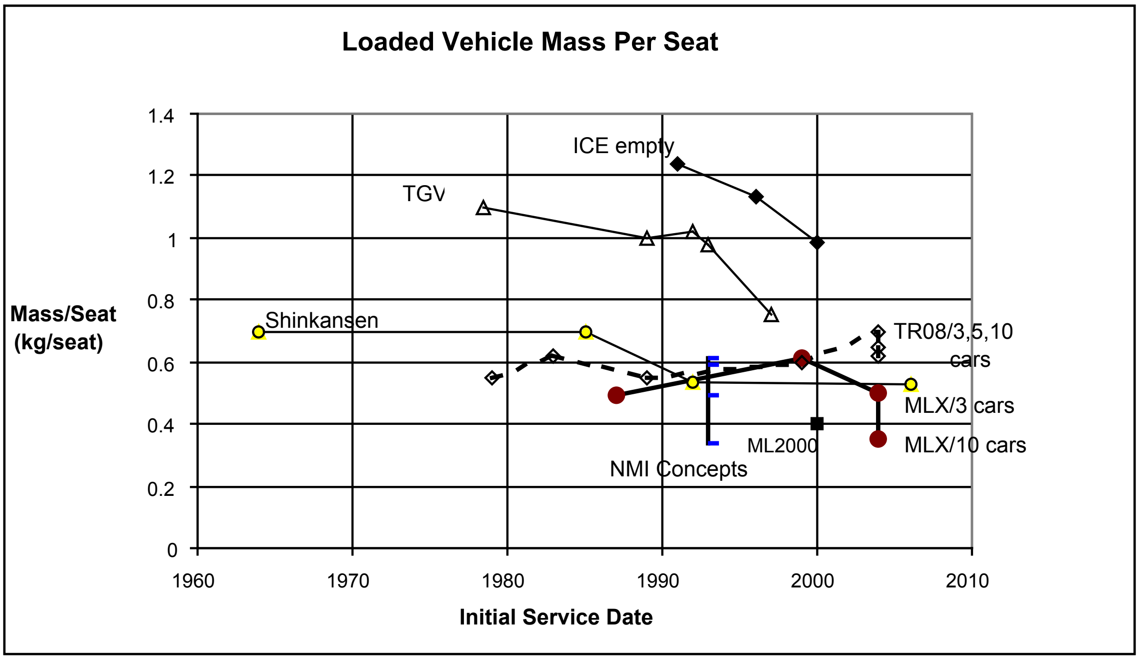

Figure 2. Comparison of the Reduction of HSR Mass/Seat with that for Maglev Systems.

The JR Central has recently reported [6] several approaches to cost and weight reduction. These include the use of high-strength fiber-reinforced cement, which is projected to reduce guideway structural weight by as much as 40% and the application of high-temperature superconductors (HTS), (see section 2.5 below for details) that will reduce the cost and weight of the onboard superconducting magnets. In the U.S., the Maglev 2000 group led by Powell and Danby in Florida [7] is currently developing a light-weight, low-cost EDS system, capable of carrying passengers and freight, that employs low-temperature superconducting magnets and a monorail type guideway. (See the datum marked ML2000 in Fig. 2). In the early 90's the National Maglev Initiative (NMI) sponsored the development of four conceptual maglev designs, including a monorail-based EDS design proposed by the Bechtel consortium, and a hybrid EMS design by Grumman Aerospace Corp. The latter design employed iron-core magnets with low-temperature superconducting windings to supply the main field and normal windings to provide field control. Of these US concepts, only the Maglev 2000 Group continues to develop their design. For a detailed description and evaluation of the four NMI concepts, please refer to reference [4].

Other maglev technological advances that could possibly enhance its advantage over HSR include the use of sequencially commutated propulsion motors [8, 9] instead of the conventional linear induction motor (LIM) and linear syschronous motor (LSM) options and the locally-commutated LSM design by the Foster Miller Corp.[4].

2.5 The Application of Superconductivity to Maglev Design Concepts

Reducing power consumption has been a major objective of designers since the beginning of maglev research. Since superconductors carry current without any losses, it has always been a dream to apply superconductivity to maglev applications. Indeed superconductors, independent of whether they have low or high critical temperatures, are only lossless in the absence of AC currents. AC losses have to be addressed when AC currents are imposed (directly or induced) into the superconductors. In the late 80's and early 90's, special low-loss AC low-temperature superconductors were developed both in France and Japan for the applications in Maglev and magnetic resonance imaging (MRI) commercial units. However, to the authors' knowledge, there have been no innovative applications of AC superconductors to maglev propulsion or levitation systems. The Japanese JR superconducting maglev system employs DC superconducting magnets for levitation and propulsion. These powerful superconducting magnets are primarily responsible for the fact that the JR system has the largest levitation gap, up to 10 cm. in operation. However, extensive R&D was required to minimize AC and eddy current losses induced by exposure to time varying magnetic flux.

The discovery of HTS opened the door to promising new ways to simplify magnet designs and reduce the cost, weight, and power demands of maglev vehicles. However, daunting problems with properties of materials have severely limited practical applications. One early EMS design concept [10] employed the use of iron core magnets wound with HTS wires that provided the main field and auxiliary normal windings that were used to control the air gaps. Subsequently, Goodall, et al, [11] showed that it was possible to eliminate the normal control windings and control the air gaps directly by varying the HTS coil excitation. Comparison of a lift magnet composed of a controlled normal winding on a solid iron core (used by the Birmingham maglev system) with a magnet made of a HTS tape coil over a laminated iron core reduced the magnet weight by 44% while increasing the lift to weight ratio by 78%. They estimated that the overall vehicle weight would be reduced by at least 5%.

More recently, significant progress has been reported by JR Central [6] in the development of wire-wound HTS coils fabricated from BiSrCaCuO (BSCCO). A test coil was reportedly cooled by conduction and operated at 20K, avoiding the need for cryogenic liquids. The coil performed well in

bench tests under high field and current density conditions equivalent to those used in the JR EDS maglev system. Application to JR's maglev system is anticipated to increase reliability and reduce cost, but no estimates of possible vehicle weight reduction have yet been reported.
Work has also continued on the use of bulk HTS materials used either for flux-trapped or flux-exclusion magnet designs. Researchers in several countries have reported studies using such bulk superconducting magnets. For example, a Jiaotong University group [12] built a 5-passenger test vehicle supported by the interaction of permanent magnets (NdFeB) fixed to the guideway with liquid-nitrogen-cooled HTS bulk material (melt-textured YBaCuO) mounted onboard. Lift force was measured with bulk HTS material in the flux exclusion state and the guidance force in the trapped-flux state. The measured forces were found to be relatively stable, decaying by less than 10% over a period of one year.

The silver based Bi-2223 and Bi-2212 (HTS) superconductors, since their availability in quantity starting around 1994, have been applied to many test applications [13] such as the fault current limiters, motors, transformers, power transmission cables, generators, and maglev. Tests of these prototypes were generally successful However, a combination of relatively high cost (100 – 300 $/kAm at present) and unfavorable mechanical properties (silver yields at 2000 psi) makes these 1st generation HTS superconductors unattractive for commercial applications including maglev.

The 2nd generation HTS conductor consisting of the deposition of YBaCuO (coating a substrate) using various techniques [14] on nickel based alloys (e.g. Hastelloy) potentially would lower the cost to less than or equal to $10/kAm and afford a flexible and high strength base material for applications. The authors are most optimistic about applications of this superconductor to high-speed and low-speed maglev.

3 Prospects for Urban/Suburban & People Mover Applications

3.1 Requirements & Existing Modes

In most urban/suburban areas throughout the world, people travel by motor vehicles and low- to moderate-speed transit systems such as light rail, trolleys, buses, passenger carrying vans and the more advanced underground subways. The speeds for all these systems are usually below 100 km/h. In large and modern cities, expensive underground subway systems dominate. In the U.S., single-occupancy autos and light-duty trucks (vans and SUVs) transport the vast majority of commuters. This, of course, is not only wasteful, but leads to heavily congested roadways during the "rush-hours". Both the size of the regions and the time durations affected by this recurring congestion have grown substantially over time. Recently-built transit systems tend to use electric propulsion systems with modern power electronic controllers. However, some still use inefficient rheostat speed controls or diesel electric propulsion systems. To be successful, i.e., to attract ridership away from autos, new transit systems must provide safe, comfortable, economical, fast, frequent, and reliable service. In addition, to be socio-economically acceptable, they should be efficient, quiet, and independent of petroleum imports.

3.2 Application of Low Speed Maglev to the Urban Environment

Although significantly less effort has been devoted to low-speed maglev systems, they have been under development as long as high-speed systems. This may be due in part to the widely-held belief that maglev's main benefit is high speed. However, maglev attributes that pertain to low-speed applications have long been speculated on but have received very little attention in the literature. These include light-weight, low-cost, elevated guideways, low-noise operation, no air pollutant emissions, and low maintenance costs. In the absence of published data, one can only speculate that these attributes of a low speed maglev, when compared with existing advanced underground/above ground state-of-the-art subway systems, could lead to significant construction and operating cost savings.

Generally speaking, proposed transit system installions in a large, modern metropolitan area, must deal with four major factors: system capital and operating costs, demand for right of way (ROW), system reliability, and environmental factors. Construction and ROW acquisition costs represent the largest cost factors. If a maglev system employing a light-weight, unobtrusive elevated guideway could be used in place of a conventional subway system utilizing above and below ground installation, the total cost and the demand for ROW could potentially be significantly reduced. As an example, the BART system in San Francisco requires between $30M and $130M/mile for construction cost, depending on the nature of the ROW. In contrast, a low speed maglev system, if designed correctly, could use a light guideway which requires support column footprints of 5 ft by 5 ft every 100 ft or so along the ROW. Capital costs for such a system would range from $20M to $60M/mile depending on the terrain and the type of vehicle as well as the system design. Operating cost for the non-contact maglev system is generally estimated to be a factor of 3 lower than that of a subway system. System reliability, however, remains a major obstacle for introducing a low speed maglev system – most city planners demand a proven system design for any transit system. Urban maglev technology is not considered proven at this time, and therefore more creative financing and extraordinary support from the people and politicians are required. Presumably, successful operation of the HSST system in Nagoya will help to prove the technology's reliability.

3.3 Present Maglev Technologies and Possible Future Developments

One of the first full-scale low-speed maglev systems was an overhead suspension system demonstrated by Rohr Industries in the U.S. in 1972. Since then, myriad system designs have been proposed and demonstrated. The German M-Bahn system began operation on a test track in Braunsweig in 1976 and was later demonstrated in Berlin, but was never put in commercial service. The first commercial system was the Birmingham system in the UK. It transported passengers between the airport and a convention center for 13 years. The HSST system , which was exhibited in Canada, and in several venues in Japan , is currently being deployed on a commercial route in Nagoya, Japan, and HSST–type systems are being developed in several other countries including Korea and the US.

Most of the low-speed systems listed above utilized EMS-type technology with short-stator linear induction motors (LIM's), resulting in a simpler, inexpensive guideway. While quite suitable for low-speed applications, such systems are generally not readily extendable to higher speeds. There are several reasons for this, including the need to transfer the propulsion and levitation system power from the guideway to the moving vehicle via sliding contacts. In addition, the performance of LIM's tends to degrade with increasing speed. Also, vehicle weight increases with the increased propulsion motor thrust requirements, leading to diminishing returns.

In contrast to the HSST-type systems, the MagneMotion Maglev System under development by Thornton et al [15], utilizes an LSM in lieu of an LIM for propulsion and utilizes the same vehicle-borne magnets for lift, guidance, and the propulsion motor field. The system incorporates controlled-dc windings supplemented with permanent magnets (PM's) to produce an EMS system that draws less energy than the unbiased field suspension system designs. (Transrapid and HSST employ unbiased field suspension system designs). Although this design will increase the guideway cost, it has the potential to double the air gap, substantially reduce vehicle weight and on-board power demand, and may be applicable to higher operating speed applications. It will be interesting to see how well this design compares with the more conventional EMS system designs.

It should be noted that the use of biased field systems is not new. Such designs were proposed by Wey et al [16] at Braunsweig University. The M-Bahn used PM's to provide attractive force lift and the field for LSM propulsion. In the 80's, Wey's group also proposed using PM's embedded in iron cores with controlled wire-wound DC magnets for levitation and guidance in the Transrapid system. In the US, as mentioned earlier, the Grumman Aerospace Corp. [4,10] proposed a suspension system utilizing superconducting coils wound around iron cores to produce the bias field.

An important challenge to the application of EDS systems to urban and commuter applications is the need for relatively low lift-off speed. (The JR maglev system has a lift-off speed in access of 100 km/h). A number of EDS design concepts have been tried in the U.S. to address this problem. These include early continuous-sheet guideway designs [17,4], and, more recently, a design concept [18] using on-board PM's and guideway-mounted null-flux lift coils. Among other innovative ideas, this design incorporated a propulsion motor that used the vehicle as a moving switch to sequentially transfer power to guideway windings adjacent to the passing vehicle borne PM's. Although the concept worked at low speed and demonstrated a lift-off speed less than 48 km/h, funding problems forced the project to be terminated. An innovative EDS design employing Halbach arrays of PM's (developed at Lawrence Livermore National Laboratory) is currently being tested by a consortium lead by General Atomics Corporation [19]. This design, has a very low lift-off speed of about 9 km/h, and, if successful, has the potential to operate at top speeds exceeding other low-speed systems. In another approach to permit urban applications, the Maglev 2000 group [7] is retrofitting their high-speed EDS system design with auxiliary coils to accommodate hovering/lift-off from rest.

4 Prospects for Space Applications

Linear motors and even magnetic levitation systems could find important applications in space transport. NASA has recently funded several studies of maglev design concepts that could augment spacecraft launches [20,21] from Earth's surface. In addition, now that manned-travel to the Moon and beyond is being contemplated again, other applications are possible in the more distant future. For example, electromagnetic launch of a spacecraft could be made from an orbiting satellite. Although the satellite would have to counteract the reaction to the launch with its own propulsion system, the amount of propellant carried on the spacecraft would be reduced. In the absence of any atmosphere, electromagnetic launches could be made from the Moon's surface directly to escape velocity without the need to carry the normally required rocket propellant. Similarly, launches could also be made from the Martian surface, although its thin atmosphere might restrict the maximum launch velocity somewhat. These latter applications would, of course, require the establishment of bases on the Moon and perhaps on Mars, as well, to fabricate the necessary launch facilities from materials mined from the Moon and Martian surfaces.

5 Conclusions

From the perspective of economic, environmental, and societal benefits, maglev technology has promised the technical attributes necessary to become the next generation of ground transportation. Many of those promised attributes have been partially met, but there remains more work to be done. Obviously, maglev exists here and now. But could it be better and more economical? Does the present state of the technology warrant further development? There is a tendency to look at the present implementation, as good as it is, and say we are finished. But we would like to suggest that greater improvements are not only possible, but highly desirable if maglev is to be perceived as significantly superior to its competitors. Cost and weight reduction should continue to be the focus of development efforts for the foreseeable future. Applied superconductivity is envisioned to play a significant part in this continual effort now that the coated HTS technology is maturing. In the US, funding for maglev R&D continues to be a serious problem. Hopefully, the deployment of an EMS system in China, the HSST in Japan, and the expected deployment of an EDS system in Japan will provide the impetus needed to accelerate efforts in the US and elsewhere. However, careful planning is essential if deployments are to fully capitalize on all of maglev's technical attributes.

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