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**Urban Maglev Technology Development Program
Colorado Maglev Project**

***Comparison of Linear Synchronous
and Induction Motors***

June 2004

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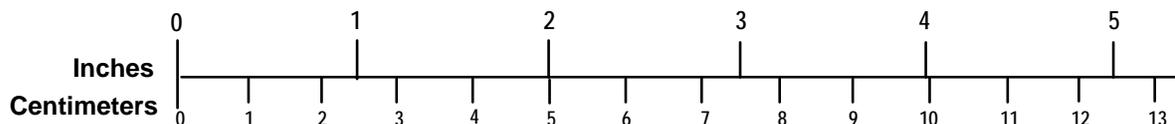
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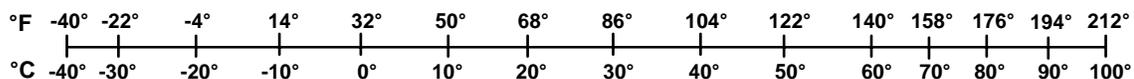
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Colorado Maglev Project

Comparison of Linear Synchronous and Induction Motors

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Abstract

A Propulsion Trade Study was conducted as part of the Colorado Maglev Project of FTA's Urban Maglev Technology Development Program to identify and evaluate prospective linear motor designs that could potentially meet the system performance requirements of the Colorado Dept. of Transportation (CDOT) Project, and be applicable to other urban maglev transit corridors. The study focused primarily on the performance of the linear induction motor (LIM) propulsion system of the Chubu HSST (CHSST) that had been selected as the baseline technology for that project. Potential near-term improvements and modifications to that propulsion system have been considered and appear feasible. This report compares the relative advantages and disadvantages of that linear induction motor and mature linear synchronous motor options for urban and suburban maglev transit systems.

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1 INTRODUCTION

A Propulsion Trade Study was conducted as part of the Colorado Maglev Project of FTA's Urban Maglev Technology Development Program to identify and evaluate prospective linear motor designs that could potentially meet the system performance requirements of the Colorado Dept. of Transportation (CDOT) Project, and be applicable to other urban maglev transit corridors.[1] The study focused primarily on the performance of the linear induction motor (LIM) propulsion system of the Chubu HSST (CHSST) that had been selected as the project baseline technology. Potential near-term improvements to that propulsion system have been considered and reported.[2] These modifications have been reviewed by CHSST and Toyo Denki Inc., and their implementation appears feasible. This report compares the relative advantages and disadvantages of the linear induction and linear synchronous motor options for urban and suburban maglev transit systems.

For maglev applications, two specific configurations of these linear motors are considered that have been practically tested and applied: the short-stator linear induction motor and the long-stator linear synchronous motor. Conversely, the long-stator linear induction motor utilizes an armature winding in the guideway creating the traveling wave, and a short, reaction rail on the vehicle. This technique has been utilized for drives in factory transportation systems, however its performance as a public transportation system is inferior to the linear synchronous motor with similar structure. Likewise, the short-stator linear synchronous drive with an armature winding on the vehicle creating the traveling wave, and discrete field windings distributed along the guideway has a complicated guideway structure that is too difficult to negotiate with the route profile of a transportation system, and is economically impractical. The inductor-type linear synchronous motor has also been considered by many researchers, but the increase of vehicle weight and complexity of the rail structure makes this system impractical for commercial systems. The following discussion focuses on the comparison between the short-stator, linear induction motor drive and the long-stator linear synchronous motor drive, in particular, the most mature drives presently being installed and implemented for transportation, which are the LIM-driven, Chubu HSST and LSM-driven Transrapid maglev systems. Both of these systems use iron-core propulsion motors with relatively small (10-15 mm) propulsion air gaps, and electromagnetic-type (EMS) levitation.

2 SHORT-STATOR LINEAR INDUCTION MOTOR DRIVE

2.1 Basic configuration

The LIM was developed and is utilized for the Chubu HSST (Maglev) and Linear Metro (Subway supported by the conventional wheels-rail system) for urban transport in Japan. [3,4,5,6] It is also used by Bombardier Transportation in the driverless Advanced Rapid Transit (ART) system to access New York's JFK International Airport. Similar systems are operating in Kuala Lumpur, Malaysia, and on the SkyTrain Millennium Line, in Vancouver, Canada. There also is, or has been, limited scale applications with the Birmingham Maglev (United Kingdom), Otis People Mover, H-Bahn Dortmund (Germany), and the Mitsubishi Heavy Industries People Mover (Hiroshima, Japan).

The basic system construction of the short-stator linear induction motor (LIM) drive is shown in Figures 1-4. Figure 1 shows the Chubu HSST maglev vehicles that are being installed on the Tobu Kyuryo Line in Nagoya, Japan as part of a 9 km urban transit line. Four propulsion-

levitation modules are located on each side of each vehicle that wrap around the guideway levitation-reaction rail. Each vehicle module contains a LIM motor above the aluminum reaction rail and four levitation magnets that pull the vehicle up to the steel section of the guideway rail. Figure 3 shows a side-view cross-section of the LIM with the 3-phase primary winding embedded in the LIM core on the vehicle and the guideway's aluminum sheet and steel that form the secondary circuit of the motor.



Figure 1: HSST Linimo maglev vehicles for the Tobu Kyuryo Line in Nagoya, Japan

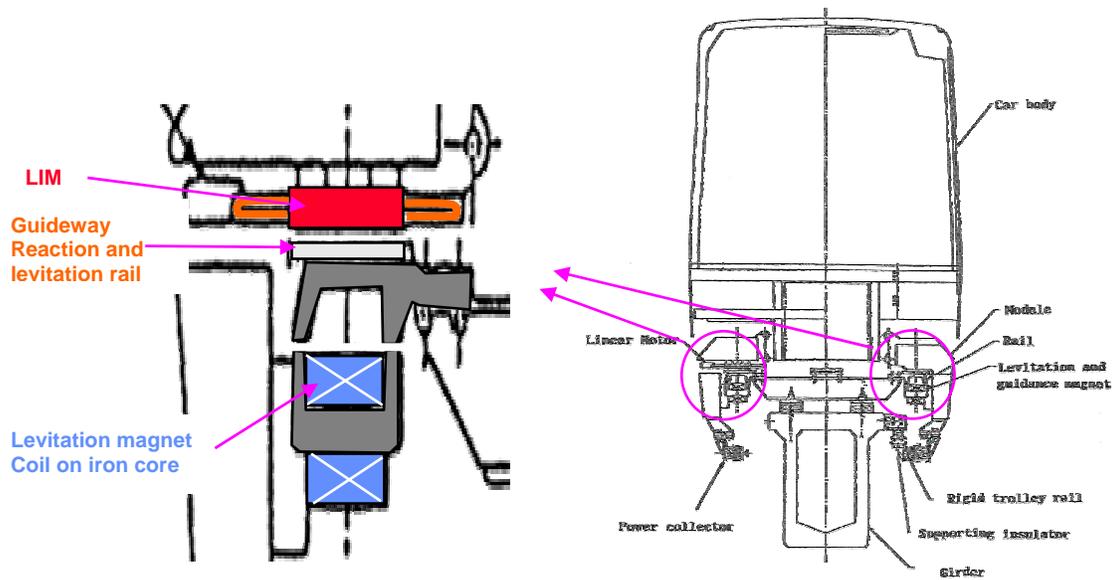


Figure 2: Close-up of propulsion/levitation module for LIM.

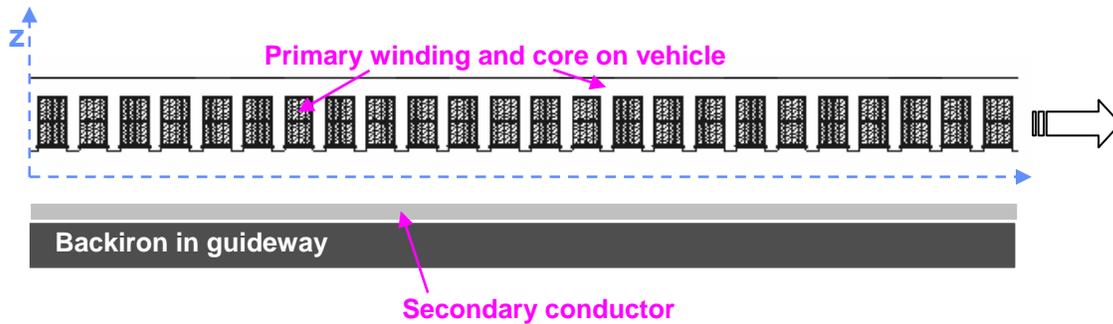


Figure 3: Side-view, cross-section of single-sided LIM components.

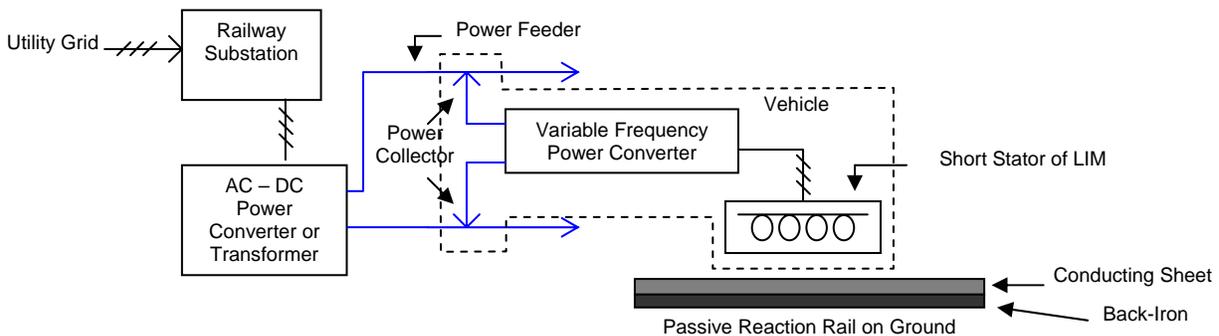


Figure 4: Block diagram of the power circuit for the LIM.

The power feeder shown in Figure 4 is a solid rail carrying DC power (or AC single-phase) such as is currently used in conventional railways. The power collectors are the vehicle's sliding or wheel contacts to the power feeder. Sliding collectors have been operated up to 130 kph at the CHSST Nagoya test track, though testing facilities for higher speed operation exists at the Railway Technical Research Institute (RTRI) Test Track in Kokubunji, Tokyo. Wheeled collectors have been tested up to 200 kph at the RTRI for the DC linear motor car project.

The on-board power converter conditions the input DC or AC power from the power feeder to the appropriate variable-voltage, variable-frequency, multi-phase power needed for LIM operation. The converter also contains input and output filters. This equipment is widely used in conventional high-speed urban railways. The linear induction motor as shown is a single-sided structure that generates a non-uniform normal force, side force, and rotational moments on the LIM. Its operation is less efficient compared to conventional rotary induction motors because of the large air gap between the on-board stator and guideway rail resulting in a high leakage flux. This motor has been used in public transportation by the HSST and Linear Metro Subway in Japan. A double-sided LIM with stator windings and cores on both sides of the guideway reaction rail was developed and tested, but the geometry is very difficult to implement with a small clearance gap.

Finally, the passive reaction rail in the guideway consists of an aluminum or copper plate backed by iron. It is structurally very simple, and can be integrated with the levitation rail as is the case with the HSST. The rail's performance and durability has been tested thoroughly for the development of the HSST maglev system and the steel-wheel Linear Metro subway in cooperation with the Japanese Ministry of Transportation.

2.2 Advantages

A significant advantage of the LIM drive is that the on-board power conditioning system and construction is very similar to that used in conventional urban and high speed electric railway vehicles. This is important from several perspectives. Many of the power conditioning equipment system sections and components are common, and there exists a significant database of practical experience and design with manufacturers and line operators. The basic technology has been well established, and the technical step to move from rotary induction motor drives for steel-wheel vehicles to LIM propulsion is not large. The incentive for this transition to LIM propulsion is the all-weather capability to negotiate tight curves and steep grades, and meet precise stopping requirements with high deceleration that is not possible with power-driven steel-wheels. From the perspective of the public consumer, the transition provides improvement in service and ride quality, and meets their expectations of safety and reliability for transit systems.

The LIM utilizes a very simple reaction rail track, hot-rail power pickup on the vehicle, and passive guideway rails which simplifies the track switches. The reaction rail can be installed discretely along the track, if needed. Vehicles with different design and performance parameters are easily adaptable without changes to the guideway within the guideway load (electrical and mechanical) limits. The guideway can provide small radius horizontal and vertical curves, and a bending switch similar to monorail is applicable. The simple, passive guideway system has been shown to be as safe and reliable as a conventional rail track.

A LIM-driven transit system has a great degree of flexibility to respond to variable or uncertain demand. This includes adjusting the number and size of vehicles on a short-term or long-term basis. In the short term, the ability to add and move vehicles provides rapid response capability for the operator to volatile demand and the recovery from any off-normal shutdown or schedule deviation. In the long-term, if additional power is needed to accommodate an upgrade in the system capacity, the impact to the guideway is almost negligible with the addition of way-side power electrification and conditioning equipment. To meet operational requirements, the block control can be easily adjusted with little, if any, modification to the civil structures.

2.3 Disadvantages

In general, the energy efficiency of the LIM is lower than the rotary induction motor and the LSM. With the rotary induction motor the air gap between the stator winding and the rotor is much smaller (few millimeters) since the gap does not vary which resulting in greater efficiency. Air gaps of 10-15 mm are used for LIM drives due to clearance requirements with a varying gap from the vehicle suspension. The on-board LIM primary winding provides all the power that generates the gap field and the induced currents in the reaction rail. As such, with the larger air gap, the efficiency is lower than the LSM which uses electro or permanent magnets for the field winding. The weight and size of the on-board power conditioning equipment must also be larger as must the size of the wayside power systems. This increase in weight is what limits the operational speed capability of the LIM-driven system to 200 – 250 kph since the weight penalty makes higher speed operation impractical. However, this is not to say that the efficiency of the LIM is impractical. For the Colorado I-70 route the anticipated average and maximum speeds are 144 and 160 kph, respectively. For this route, higher speed did not provide significant advantages, but the maximum speed of ~225 kph could be obtained with the COL-200 LIM-driven vehicle. The electrical-to-mechanical efficiency of the LIM at the power pickup hot-rail is 70% at the average speed and 77% at maximum speed.

With the LIM there are also 3-dimensional forces that may influence ride quality. This is due to the coupling between the thrust and the attraction/repulsion force between the primary stator and the reaction rail (commonly referred to as the normal force), and the coupling between these forces and the guiding/de-centering lateral force which is transverse to both these forces. Because of eddy currents in the secondary, these forces are not uniform along LIM in the direction of vehicle motion. These forces do not preclude the utilization of the LIM for propulsion, however, they must be accounted in the design of the guidance and levitation systems. Issues such as harmonics in the normal force and the magnitude of normal and lateral forces at high thrust must be considered as well as the changes in these forces with primary-secondary clearance gap. If the air gap length between the primary and the reaction rail is reduced, the normal force between them becomes larger which can disturb the performance of the levitation system. This being said, it must be noted that LIM-driven systems have been successfully operated at 100 kph and designed for operation at 200 kph mitigating these issues. This coupling of forces also exists for the linear synchronous motor, but forces are uniform along the track due to the laminated structure of active rail. In designs such as the Transrapid Maglev system, the levitation and thrust forces are applied within the same physical structure and air gap which reduces the mechanical moments applied to the propulsion-levitation bogie module on the vehicle, lessening the requirements of the levitation control system to accommodate the force perturbations.

3 LONG-STATOR LINEAR SYNCHRONOUS MOTOR DRIVE

3.1 Basic configuration

LSM drives with electromagnets were developed and are utilized for the German Transrapid maglev system for high-speed transportation.[7] This system has been tested in Emsland, Germany since 1984, and is now applied to the 30 km Shanghai Pudong Airport connection to city-center. A very low-speed system for urban applications, the German M-Bahn, was utilized in Berlin for a few years beginning in 1988 as a demonstration track.[8]

The basic system construction of the long-stator linear synchronous motor (LSM) drive is shown in Figure 5 through Figure 7. Figure 5 shows the Transrapid TR08 maglev vehicle that is the type of vehicle being installed in the Shanghai airport-city connector line. As with the LIM-driven system, propulsion-levitation modules that wrap around the guideway are located on each side of each vehicle. Each module contains the exciting field magnets of the LSM that also serve as the levitation magnets that pull the vehicle up to the LSM stator magnets packs attached to the guideway. Figure 6 shows a side-view cross-section of the LSM with the 3-phase primary winding embedded in the stator core on the guideway and the vehicle's levitation magnets.

The long stators of the LSM located on the guideway form the active track. The reactive forces of propulsion and vehicle levitation act on the stator cores. Its supporting structure is required to have enough strength to handle repeated loading of this force, and the stator coils need to be isolated from ground. Dimensions of the stators are determined by the highest performance requirement of the systems.

In order to reduce operational losses and for stability of the power supply system, the long stator of the LSM is separated into a number of sections controlled by the section switches. The minimum length between two section switches depends on the required acceleration and length of a train. The operating frequency of the section switches becomes high if a large number of

trains are operated on the track each day. [7, Figure 4, page 52]

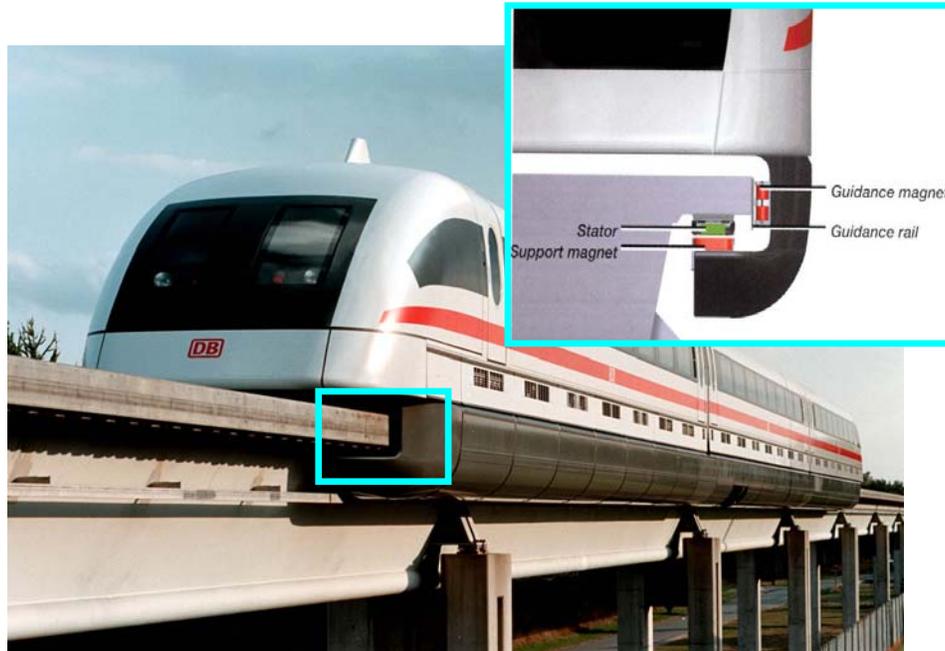


Figure 5: Transrapid TR08 vehicle and close-up of propulsion/levitation module containing on-board exciting magnets for LSM

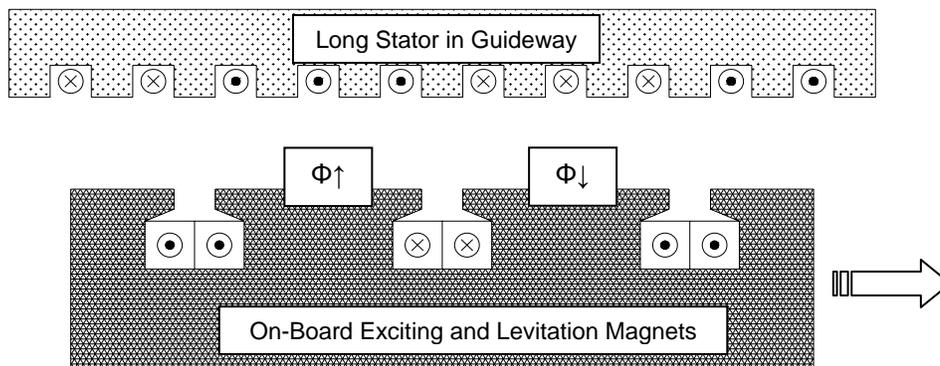


Figure 6: Cross-section of segment of LSM. Flux, Φ , from the exciting magnet interacts with the traveling magnetic wave from the stator to generate vehicle thrust.

The currents in the stator coils must be synchronized with the train's position and velocity. Proper control of the train can only be accomplished by sending information to the converter stations through the use of sensing equipment and signal transmission systems. Because synchronization is essential to the LSM, the sensing and signal transmission system must have high precision and reliability.

The railway substation shown in Figure 7 is connected to the power grid, so its location may be constrained. In some cases it is advantageous for the system operator to own the transmission line from the grid. The power converter station feeds variable-voltage power to the long stator sections through the transmission lines, and controls both the power's frequency and phase as required by the train's position and velocity. This means that the number of converter stations

must equal the maximum number of trains possible on the whole track. An increased number of converter stations will be required near train terminals and intermediate stations. Operational voltage of the converter is limited by the maximum voltage level capability of transmission cables, section switches, and stator windings to prevent arcing and electrical breakdown.

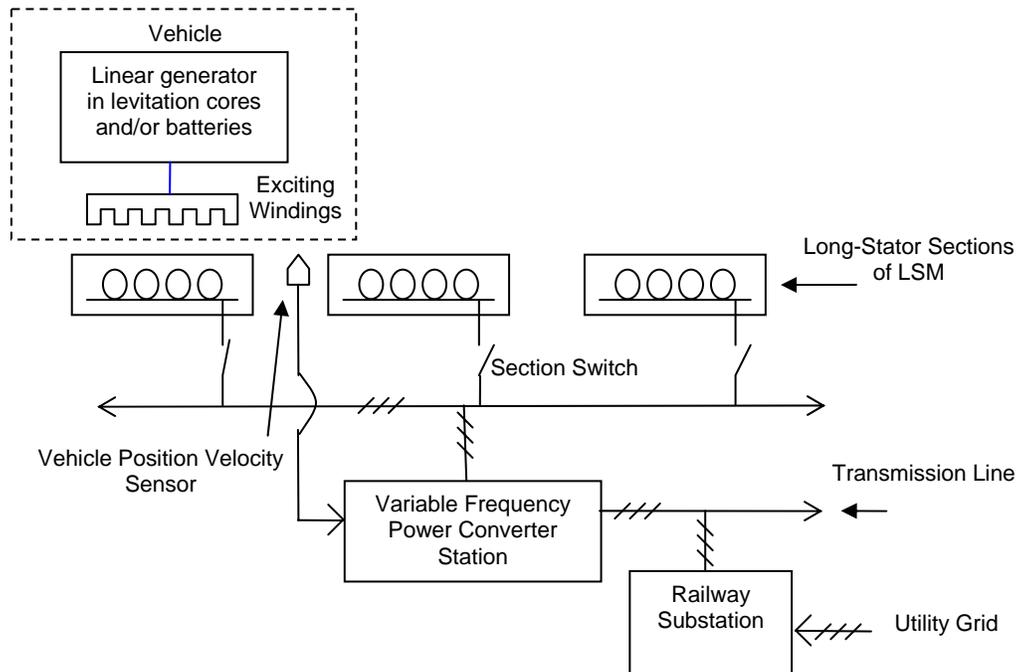


Figure 7: Block diagram of the power circuit for the LSM

3.2 Advantages

Vehicle drive power is supplied by the long-stator, winding attached to the guideway. Because the stator winding and power conditioning equipment is located wayside, the vehicle should be generally lighter. This permits the operation at high-speed (up to 500 kph has been demonstrated) because the vehicle does not bear the weight of the high-power primary propulsion components needed to obtain these speeds, nor does the electric power need to be transferred to the vehicle. The power-rating capability of the motor can be tailored to the requirements of the specific section of route such as regions of high grade or at the station for high acceleration.

The Transrapid and other proposed LSM systems also use the on-board levitation electromagnets (or permanent magnets) as part of the field source for the LSM propulsion. This results in a highly integrated bogie design that reduces vehicle weight, and helps reduce the requirements of the levitation control system to mitigate the effects of transverse forces on ride quality. Other systems such as power generation and operation control can be integrated with drive system.

The placement of main power components on the wayside and reduction in vehicle weight results in high acceleration and deceleration capability. However, the utility of the high acceleration is limited by ride comfort, seat-belt operating conditions, and safety requirements.

Within these limits for the FTA urban maglev program, both LIM and LSM have the capability to meet the high-acceleration requirements, and neither has a particular advantage in terms of the superiority of these three factors.

The electrical-to-mechanical conversion efficiency of LSM is high at the terminals of the guideway motor, but the impedance of the active block length of the motor reduces that value. A detailed analysis conducted for the U.S. Dept. of Transportation National Maglev Initiative modeled the Transrapid TR07 LSM with a lumped-parameter synchronous motor circuit model.[9] This model was benchmarked with data from the Transrapid TR06-II motor, and the author of that study indicates that the agreement with data was excellent. For the TR07 with an on-board active length of 45 meter with a relatively-short LSM block section length of 300 meters, the efficiency at the terminals of the LSM immediately below the vehicle is 98% at a vehicle speed of 200 kph in maximum-thrust operating mode. The efficiency at the terminals of the LSM block section is 85%, and at the output of the variable-voltage, variable-frequency converter, the efficiency drops to 62% at the same speed and operating condition. The maximum efficiency at the converter output for this LSM, which was designed for higher speed, is 87% at a speed of 480 kph. However, it should be noted that if the block section length of the active LSM is longer, the efficiency is reduced.

3.3 Disadvantages

One disadvantage of the LSM drive is that it requires data for the exact position of the on-board magnets to ensure that the vehicle is synchronous with the traveling wave generated by the stator winding in the guideway. A very reliable and precise vehicle position and velocity sensing system is essential. This information must be transmitted to the converter station to generate the traveling magnetic field at the appropriate magnitude and frequency.

Compared to the simple reaction rail of the LIM, the active track structure of the LSM is very complicated. It requires continuous installation of stator coils in the guideway and wayside converters to energize each block section of track. This results in many components that must be maintained to assure the safety of the system. The maintenance of proper position of the guideway stator coils is particularly critical so that the proper clearance gap is maintained to the on-board levitation/excitation magnets. Reduction of the normal 1 cm gap can result in significant increase in the vehicle lift force causing the vehicle to “lock-on” to the guideway or impact between the vehicle magnets and the guideway stator. Frequent inspection and maintenance of the guideway coils and stator core is necessary to ensure proper alignment.

There are several operational requirements for the vehicles relative to the guideway. Each block section of the guideway can drive only one vehicle at a time, and that section requires its own converter. The operational density of trains on the route determines the number of converter stations, which implies many converters are necessary for short headway systems. This has particular impact near terminals where the power feeding system becomes complicated and many converters are needed since vehicles are moving slowly, more closely spaced, and switching direction or routes. The vehicle has an LSM motor on both the port and starboard sides, and each of these is powered by independent power supplies at the transitions between stator sections. These supplies must have high reliability for balanced thrust from both sides of the vehicle. The field magnet of LSM is also commonly used for vertical suspension, which means it is operated continuously. This requires a very reliable on-board power supply including batteries. In the event of a malfunction of trackside stators, the riding comfort is significantly deteriorated.

The performance of the transportation system is determined by the configuration of the active guideway, and the system is not adaptable to the change of passenger demand. Vehicles cannot be added easily to accommodate changes outside the original design (although they are easily removed). The LSM must be configured, and the initial investment made to accommodate the highest demand anticipated over the life of the design. For efficient use of capital investment, a very accurate estimate of demand is necessary.

3.4 Alternative LSM design

To permit more flexibility of operation and allow short headways for high-capacity operation, a design has been proposed with very short stator sections. With appropriate design, the operation control system (signaling system) can be integrated with the power feeding system. The stator sections of the Locally Commutated Linear Synchronous Motor (LCLSM) are essentially individual coils, each energized by its own wayside inverter.[10] While this reduction in stator length improves the electrical efficiency at the converter to 95% and increases the power factor, it requires an inverter for each coil (or pair) in the guideway. In a previous proposal of this technology in the U.S. National Maglev Initiative, this required 2400 inverters per kilometer of double guideway. The technical assessment of that proposal by the U.S. Government Maglev Assessment Team (USGMAT) concluded that while the LCLSM offered high efficiency and possibility for very short vehicle headways and operational flexibility, the guideway stator investment cost was “critically dependent upon the high-volume cost reduction (factor of 10)” for the IGBT switch based inverters.

Another important issue with the concept is the potential reliability of the system with such a large number of inverters. The USGMAT report makes reference to the fact that with individually-controlled coils, the system could operate in a degraded mode even if a few coils or inverters fail. However, this capability will be highly dependent upon the nature of the failure. The resulting ride quality and operational safety may be significantly affected, and the ability to operate in degraded mode is not at all obvious, particularly in light of the team’s assessment that the synthesis of the stator’s traveling wave from individually-energized coils was a demanding technical requirement and unproven at that time. Sub-scale testing of this concept has been done that shows thrust can be delivered even with some faulted coils, but it is not clear that a full-scale system with such faults would be necessarily operational, or that any level of operation other than vehicle recovery is desirable.

A concept of this type of linear motor for the maglev railway was proposed by Dr. Matsui of RTRI Japan in late 1960’s.[11] It was named as “Linear DC Motor”, because its principle of operation was quite similar with the brushless DC motor. The idea and its characteristics have been reported by Dr. Matsui and his colleague, Mr. Umemori. [12] The primary coils and the H-bridge switches are located along the track. The on-board electromagnet acts as the field magnet of the motor. The on-board magnets also give the lift force to the vehicle, though high current must be fed to the vehicle to have enough levitation performance.

A feasibility study of this type of maglev system was also carried out by a technical committee of the Railway Electrification Association of Japan with the support of former Japan National Railways, and the author (Masada) was a member of that committee. The committee’s assessment of the system identified two problems: 1) large and heavy on-board magnets are needed for levitation, and 2) H-bridges with power electronic devices for commutation between ground windings are too expensive and complicated for reliable operation. RTRI has changed the concept of system to solve the first problem with rubber-tire wheels and studied its feasibility for suburban transport in Yokohama as Automated Linear-motor Pneumatic-tire System (ALPS).

[13] A report written by Mr. Miki of RTRI shows that the construction costs for the system are about 20% less than a conventional system because of smaller curvature and higher gradient track allowed to the linear motor drive. However, uncertainty of the reliable operation of rubber tires in high speed and of the basis of investment costs, the project was dropped, and RTRI has stopped further study.

Dr. Matsui has shifted his interests from the original concept to the Belt type Transit System by Magnet (BTM) people mover to solve the second problem. A rotating magnetic belt equipped along the track adheres on board magnets and propels the vehicle in the original system, analogous to an LSM. It was utilized as a transport system of an International fair 1990 in Osaka. Because it was noisy and expensive, the design was modified to equip the moving belt with permanent magnets arrays on board. The belt adheres to the ferromagnetic rail of the track and propels the vehicle. A small scale practical application has been installed and operated since 2003 as a incline-type people mover, which has a mean gradient of 30° at Katsura-dai near Otsuki about 90 km west of the city center of Tokyo, Japan. [14]. While this example is neither a conventional LSM nor LIM, the simplicity and low-cost of the on-board driven propulsion for this low speed system is evident.

Based on the design reviews and experience with this type of system, it is concluded that the locally commutated linear synchronous motor has theoretically interesting characteristics for a maglev or a railway transport, but its realization as a practical system is difficult due to costs and reliability of a large number of switches.

3.5 Permanent magnet linear synchronous motor

Permanent magnets have been successfully applied to linear synchronous drives for automated transfer machines and transportation systems in factories. Their application to the propulsion system of maglev transport has been done for studies and test operations, both as the linear synchronous motor (long stator type) and as the linear inductor type (short stator type). In the followings, the permanent magnets application to the linear synchronous motor is only discussed. The rotational type of sealed, synchronous motor with permanent magnets is being tested as a direct-drive motor for the next-generation advanced commuter train (ac@train) of Japanese Railway-East Group.[15] This motor will be installed into a new series of commuter trains which will be put into service in about one year.

Development of rare earth permanent magnets has enlarged the applications of permanent magnets. They are used widely in devices for home appliances, audio and video equipment, computer peripheral equipment, office automation, factory automation, medical equipment, and automobiles. Rare earth permanent magnets have demonstrated the following properties:

Material	Nd-Fe-B	Sm-Co
BH max	~ 400 kJ/m ³	~ 200 kJ/m ³
Remnant magnetization	~ 1.1-1.4 T	~ 1.1 T
Coercive force	~ 900-1100 kA/m	~ 800 kA/m
Curie temperature	310°C	840°C

The lower Curie temperature of Nd-Fe-B compared with Sm-Co causes its magnetic properties to deteriorate roughly three times more rapidly with elevated temperatures. Nd-Fe-B is lower cost, but also significantly more susceptible to corrosion and steps must be taken for environmental conditions. Rare earth magnets are usually manufactured with sintering. They

are brittle materials and must be protected against fracture which would change their magnetic properties.

The permanent magnet linear synchronous motor (PM-LSM) has been used mainly in factory automation and robotic equipment because of the high energy efficiency and high thrust force, which make high-speed operation possible. The same servo control components and configuration applicable for rotational motors can be used. However, the span of movement and weight of loads of the PM-LSM are not large. The moving part is rather limited in size, and may be a significant part of the equipment mass. The typical application environment is indoor in mostly conditioned, clean atmosphere. In general, PM-LSMs are unique designs produced for a specific machine or function.

The PM-LSM system is similar to the linear pulse motor system in its structure, drive mechanism and control scheme. The linear pulse motor is utilized widely in factory automation and automated machines. The PM-LSM is considered a special type of linear pulse motor in these application fields.

The only practical example of PM-LSM applied to the public transportation system is the M-Bahn. The system was used for demonstration in part of the subway network of Berlin for a few years from 1989. Its maximum speed in service was 50 kph, but it could operate up to 90 kph. The rated frequency was 95 Hz and the pole pitch was 0.12 m with 80 poles of magnets per side of a car. Samarium-cobalt permanent magnets were used for propulsion and attractive levitation, but mechanical rollers were used for levitation-gap control and guidance.

Assuming the application for a system up to 200 kph, the product of pole pitch with supply frequency of inverter should be increased. If the highest operational frequency of the inverter is presumed 300 Hz based on today's technology, the pole pitch is 0.15 m. If some margin is taken for its operational capability, pole pitch increases further. This requires large pieces of permanent magnets. The large size makes uniform magnetization of the permanent magnet difficult, as well as complicates the fixture and support structures due to large magnet forces.

In the case where Nd-Fe-B magnets are used, measures must be taken for thermal cycling and corrosion from moisture. Covering and supporting structure of magnet pieces are required, which inevitably increases the length of air gap reducing the gap field strength. No practical data on the characteristics of weather proofing of rare earth magnets utilized under outdoor conditions for extensive periods is published. Even in conventional railways, sealed, PM-motors have not been utilized heretofore because of practical considerations, and long-term testing data will only now be generated by the advanced commuter train in Japan. Likewise, such data must be generated for PM-LSM motors as there is insufficient practical experience to quickly introduce it for passenger service at this time.

The long stator of PM-LSM is similar to that of Transrapid (cable winding) or M-Bahn (molded winding). However, the limited size of permanent magnet pole pieces makes application of cable winding difficult. The design of molded long stator is considered a key issue of PM-LSM system for the construction cost and the operational reliability. The former had been evaluated in various applications of M-Bahn, but the system had a rather simple configuration. If more sophisticated construction and new materials are introduced, considerable efforts should be put into their evaluation. Rigorous inspection and maintenance procedures of the fixing and supporting structure of permanent magnets must be established for the safety of operation. The latter problem should be solved with optimization of system design. However, because the characteristics of PM-LSM depend on distribution of electromagnetic field, especially in the case

of Halbach array configuration, the parameter studies related to long stators and inverters become rather difficult. From a practical point of view, large-size rare-earth magnets and the molded, active rail are specialized products distinct from other industrial applications. The initial cost of the application of PM-LSM system will be high due to the limited scale of production of these components.

Although the PM-LSM has been fielded for low speed, extensive test and demonstrations of a new PM-LSM design (such as at LSM test tracks in Emsland (Germany), Yamanashi (Japan) and in Shanghai) are needed under practical use conditions to evaluate the long-term reliability and service requirements of the electrical and mechanical components.

4 COMPARISON BETWEEN MOTOR DRIVES

4.1 Flexibility to variable and uncertain demand

As discussed above, a LIM-driven transit system has a great degree of flexibility to respond to variable or uncertain demand by adjusting the number and size of vehicles on a short-term or long-term basis. The ability to add and move vehicles provides the operator rapid response capability to volatile demand and the recovery from any off-normal shutdown or schedule deviation. If additional power is needed to accommodate an upgrade in the system capacity, the impact to the guideway is almost negligible requiring only the addition of way-side power electrification and conditioning equipment. To meet operational requirements, the train control can also be easily adjusted with little, if any, modification to the civil structures.

The LSM lacks flexibility to change system performance. Replacement of ground facilities is necessary to change system capacity or its operational mode, which is quite similar to building a new system. Its active track and power supply installation must be designed and installed for the highest demand and capacity of the system contemplated during the design phase. This may significantly shorten the useful life of the system or greatly increase the life-cycle costs if actual demand does not follow planned usage.

Line operators may experience off-normal schedule delays, interruptions, or shutdowns due to causes beyond their control or equipment failure. Rapid recovery of scheduled operation is critical to maintaining ridership. The ability of the LIM drive to move and stage vehicles on the guideway with moving block control provides a great amount of flexibility to rapidly restore service. This includes tailoring vehicle configurations for short-term, high-capacity operation to immediately accommodate the high-demand resulting from any unscheduled stoppage or deviation from normal scheduled service. The LSM requires a single vehicle per section of track, and cannot accommodate a surge in service throughput, unless the system was highly underutilized previously. The required movement of a single vehicle on a fixed guideway section greatly limits the flexibility to stage vehicles to respond to off-normal demand profiles or incidents.

In the event of a malfunction of the propulsion motor, the speed of recovery of service is very important. In the case of LIM propulsion, the vehicle is simply moved and replaced. This can be done with the aid of another transit vehicle or special service vehicle. If the vehicle is LSM powered, it is much more likely that the track may need time-intensive repair or replacement of stator winding sections. During that repair and re-qualification testing, the entire track is out of service. Service vehicles for such incidents may need to be independently powered, and may

be unable to utilize the guideway structure effectively.

4.2 Reliability of operation

Operational reliability of the LSM strongly depends on the detection and signal transmission system for vehicle position and velocity to ensure that the magnetic wave generated in the stator winding is synchronous with the movement of the excitation magnets on the vehicle. Doubly-redundant systems are required. Reliability of the LIM in a high-vehicle-density operation of a transportation system is based on existing conventional-rail technologies, and has been well established, for example, in the Linear Metro system in Tokyo, Japan.

Although many future transit systems are contemplating driverless operation, for systems where drivers are determined to be necessary, the human factors have been well established for the LIM drives. The operators of conventional railways can easily adapt to the new LIM system using much of their previous experience.

The reliability of the electrical and mechanical components of the linear drive must be evaluated, and it is very important to obtain duration-test data from the designed track to fully qualify the reliability of the drive. This information is compared to corresponding data from previous installations or test tracks to determine the effects of design, fabrication, or installation process modifications. The larger the database of previous applications and lifetime testing of a technology, the higher the confidence will be in a planned system's reliability. The application of LIM drives in steel-wheel transit systems and the historic usage of similar power conditioning equipment in conventional, rotary drive rails systems provides a significant experience base for confident projection of LIM designs to future maglev applications. Although LSM has been significantly evaluated at test tracks, the reliability of active tracks and section switches must be established with duration tests under revenue service conditions. Collection of this data is still in progress, and will not be completed for a few years.

4.3 Capital cost

The capital cost for a maglev system is dominated by the cost of the civil structures including the guideway, and the size of that structure depends on the loadings, including the weight of the vehicles. To obtain an accurate cost comparison between the LIM and LSM propulsion methods, a detailed analysis must be done for a given route and ridership requirements. However, there are features of each drive system than can be identified which have significantly different cost elements.

The weight of the vehicle using the LSM drive is expected to be lighter than one using the LIM since there is little on-board power conditioning equipment. This would, in principle, reduce the cost of the guideway. However, from the design experience for the Colorado Urban Maglev Project, the live load is a small part compared to the dead load weight of the structure itself, and the weight of the car does not strongly influence the cost of the guideway. It is also interesting to note that the 24.3 meter long, LIM-driven COL-200 vehicle that carries 103 passengers weighs 44 tonne fully loaded, while the 24.8 meter long, LSM-driven Transrapid vehicle that carries 126 passengers weighs approximately 60 tonnes fully loaded.[16] While the Transrapid vehicle can achieve higher speed, its weight would not decrease if the vehicle were limited to the 200 kph design speed of the COL-200.

The reaction rail structure in the guideway of a LIM-driven vehicle is very simple with a conducting sheet anchored to steel that serves as backiron for the motor. The active guideway

of the LSM drive includes laminated stator cores, stator coils, section switches, feeder cables, and signaling system for synchronization of operation that is much more expensive. The stator coils and core components must be very rugged to withstand the repeated cycling of mechanical forces without degradation of insulation, operate for years in all-weather conditions, and be low cost.

As the complexity of the reaction rail and power distribution of a LIM-driven system is significantly less than that for an LSM system, the time required for construction and operational testing is also considerably shorter. This results in lower overall capital investments costs.

The number of power converters per unit length of track may be similar assuming the same number and type of vehicles on that given length of track. The LIM drive requires only a wayside rectification system to supply the constant DC voltage to the vehicle on a single or double hot rail from the wayside distributed utility electric power. However, each vehicle has a variable-voltage, variable frequency inverter on board to drive the LIM. The power to each of the LSM guideway stators is also conditioned through rectification to DC and then reformed to 3-phase AC at variable voltage and frequency, and one inverter is needed per stator section assuming each section powers a separate vehicle. However, even if the LSM track is not utilized at full capacity, all the inverters and distribution network are required in the initial capital investment and all are operated as vehicles use each stator section.

While the LIM drive may have lower energy efficiency, power factor, and feeder voltage, this does not significantly increase the investment cost compared to the LSM. This is because the LSM has a more complicated converter station, lower voltage coils, and 3-phase feeder to stators.

Because of the complexity of the LSM active guideway structure and the synchronous operation of a LSM train, the system structure near end terminals requires more physical space than LIM-driven systems which further increases investment cost. The mechanical switch from track to track is larger, and it takes more physical space to transfer LSM vehicles from one track to another. As every LSM track section requires a converter, transfers of many vehicles with short headways at slow speed requires more power converters in these areas, all installed at the time of initial operation.

In the comparison of capital cost between maglev systems based on LIM and LSM, it is very clear that the capital cost of the guideway for the system with LSM is very substantially higher than that for the LIM. Conversely, the capital cost of vehicles for the LIM-driven system is higher than for one driven with an LSM. While the total capital costs of either the LIM or LSM may be greater than that for a conventional railway system, the increase of the LIM-driven system cost above the conventional system cost is certainly less than the cost increase for an LSM-driven system.

Projected capital costs for single and double-track applications of the Transrapid LSM system can be found in the literature and are shown in Table 1. [17, 18, 19, 20] Perhaps the most important entry is the 30 km Shanghai airport to city center connection that has been recently constructed and is in commercial service, compared to the estimated costs from the other projects' plans. Although the cost data has not been corrected for inflation, the values originate mostly from two reports that are quite recent and use similar methodology. Most cost data from the references are given in German Marks (DM) or Euros (€), and the conversion to U.S. dollars is cited in the table footnote. Variation in the cost per unit track length is expected due to the different operational, geographic, environmental, and ridership requirements of the individual

routes. However, the table shows the cost per unit track length decreases with distance as expected.

Urban and suburban type maglev costs may be closest to the estimates for the Metrorapid system that has 6 stations total and 16 km average distance between stations. This affects the cost of the system and reduces the average speed significantly. A plot of the data as a function of average speed is shown in Figure 8 where a trendline has been added for the LSM data (excluding the value for the Berlin Airport Connection that is much greater than the other data due to tunneling and number of stops). While there is scatter in the data, there is a definite trend for decreasing cost per unit track length as average speed increases. A data point for the FTA Urban Maglev CDOT Project (256 km, 114 kph average speed, double track, 36.7 M\$/mile including contingency) has been added for comparison that shows the significantly lower cost for this LIM-driven technology.[21]

Table 1. Comparison of Investment Costs Between Various Transrapid Applications

System	Distance km	Avg Velocity kph	Track Type	Investment Costs per Unit Guideway Length			Reference		
				MDM/km	M €/km	M\$/km*	Number	Date	
Berlin Airport Connection	25	94	double	189		121	194	17	2000
Shanghai Airport Connection	30	222	single			43	69	15	2003
Munich Airport Connection	37	220	double	78.3		50	81	17	2000
Metrorapid Dusseldorf	78	120	double	93		53	85	18	2002
					42.2	59	96	17	2000
					39.7	50	80	18	2002
Frankfurt-Hahn Airport	116	166	single/double	54		35	56	17	2000
Berlin-Hamburg	284	233	double	31.4		20	32	16	1994
Gronigen-Hamburg	293	245	double	35.9		23	37	17	2000

* Cost Conversion of DM to Euro using 31December 1998 irrevocably fixed conversion rate of 1.95583 DM/Euro adopted by European Monetary Union Member States.
Conversion of Euro to US Dollar at current rate of 0.8 €/USD

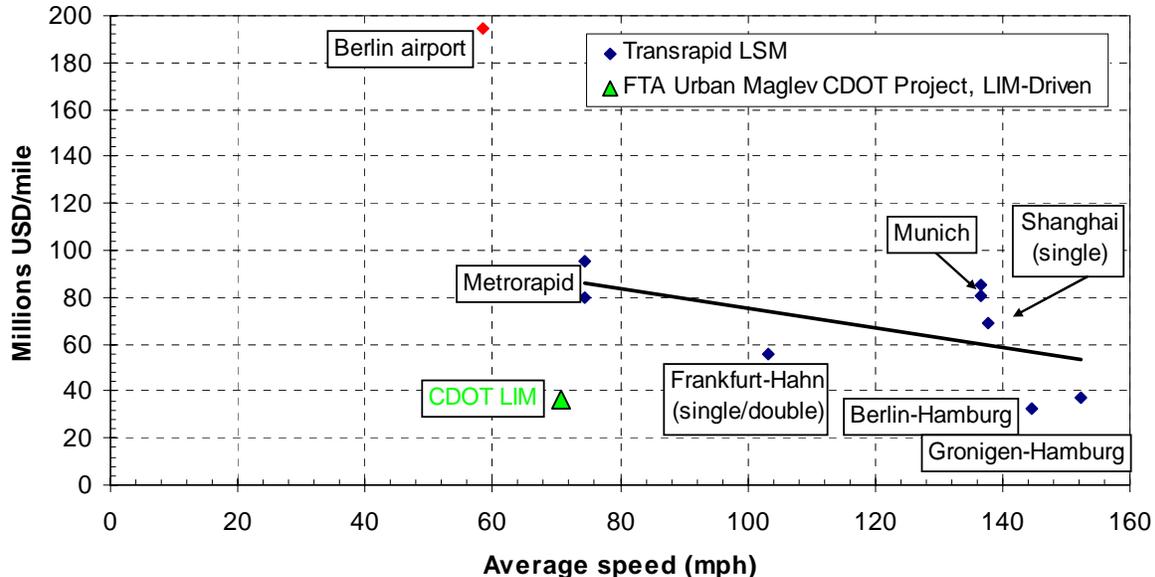


Figure 8. Comparison of investment costs between LSM-driven Transrapid applications. Guideways are double tracks unless noted. Linear fit is to Transrapid data only excluding the Berlin Airport Connection. Cost estimate for the LIM-driven CDOT system was performed in the FTA Urban Maglev Program.

4.4 Operational cost

The operational cost for a maglev system has major contributions including energy and manpower. Again, an accurate cost comparison between the LIM and LSM propulsion methods requires a detailed analysis for a given route and ridership requirements. However, there are features of each drive system than can be identified which can significantly affect these cost elements.

In general, the higher energy efficiency of LSM drives will reduce the energy cost compared to LIM systems. However, this very much depends on the design of motor and power supply system. If the section length of the LSM stator becomes long, the efficiency is reduced. For comparison of the two drive types, the efficiency and power factor of the TR07 LSM discussed above and the LIM motor that has been proposed for the COL-200 vehicle are shown in Figure 9. The values for the LIM are taken at the input terminals, and the values for the LSM at the input to the block section. [2, 9(pg.67)]. The figure shows that the efficiency (ratio of mechanical power to input real power) of the two drives is very similar, but the power factor (ratio of real power to apparent power) is larger for the LSM. The load seen by the utility is the real power, and hence, for this case, the energy usage is the same assuming the same thrust vs. speed profiles along the route. The consequence of the lower power factor for the LIM is the penalty of increased weight of the on-board power conditioning equipment to deliver the higher apparent power.

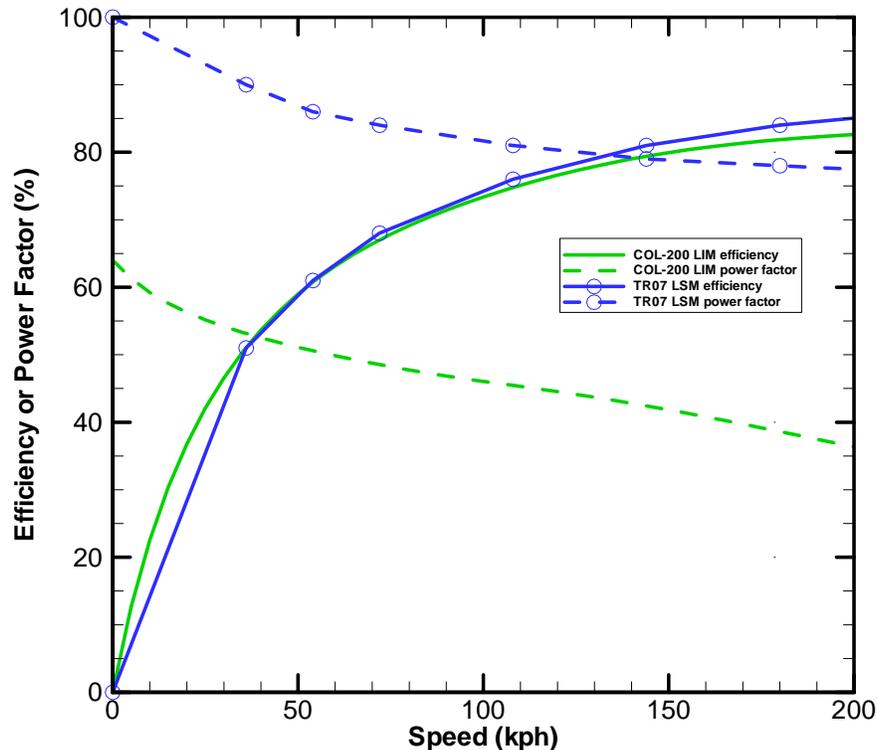


Figure 9. Efficiency and power factor at the terminals of the LIM for the COL-200 vehicle [1], and the input to a 300 meter block section of the TR07 LSM. [8].

Since most future maglev systems are expected to utilize driverless operation, manpower for drivers is not considered here. A more significant manpower staff, however, is associated with the maintenance of the vehicle and guideway system. Vehicle maintenance between the two technologies is expected to be similar with the exception of the periodic maintenance of the on-

board LIM stator and power conditioning equipment. The incremental effort for that inspection of a few parts is further minimized by the incorporation of a few sensors that provide state-of-health indications to monitor systems. To ensure the safety of operation, the guideway must also be inspected, and the manpower required for that effort is directly related to the complexity of the guideway system. The inspection and maintenance costs of LIM systems are estimated to be significantly lower than for LSM-driven systems due to the lower complexity and the significant degree of experience with LIM reaction structures in revenue service. It is highly probable that the LIM reaction structure inspection can be conducted with automated equipment. Development of the experience with the LSM is especially required in the early stage of operation. Because the LSM is a new type of system scheduled for revenue service, its operational cost estimate will have a greater uncertainty. It is not presently clear that inspection of the LSM stators in the guideway can be fully automated due to the complexity of the LSM stator winding and laminated core. If such automation is possible, the inspection equipment would necessarily be much more complicated than that needed for a LIM reaction rail.

5 CONCLUSION

Each of the LIM and LSM type drives has their advantages and disadvantages for maglev propulsion. Although the guideway is more costly for the LSM, it is the only appropriate choice for high-speed operation ($>>200$ kph) as the weight penalty of the on-board power conditioning equipment for the LIM alternative becomes prohibitive at high speed, and the ability to transfer the high electrical power to the vehicle for LIM propulsion becomes impractical in this speed regime. At low speeds (≤ 100 kph) the LIM drive has already demonstrated the capability to provide economical, all-weather propulsion in maglev and steel-wheel transit systems. For speeds on the order of 200 kph, with high passenger demand and short headways, the issue is which technology is most cost effective considering the life-cycle of the installed design.

Calculations and designs for the Colorado Project of the Urban Maglev Program have shown that the modified design of the tested and proven Chubu HSST LIMs can achieve speeds approaching 200 kph and operate on high grades. Speeds of 230 kph can be reached on level grade (with 90 kph headwind) with this design, and with additional, minor improvements, 250 kph is feasible. The LIM technology is very similar to, and directly benefits from, the experience in the rotary-motor powered, steel-wheel, conventional rail industry. The simple structure of the LIM's reaction rail in the guideway and adaptive moving-block control provides a high degree of flexibility for the line operator to adjust the performance of the transit system in response to short-term ridership fluctuations, rapid recovery to scheduled service from off-normal events, and long-term growth in passenger demand with minimal modifications to civil structures. The simple construction of the propulsion track will result in a less costly guideway investment, lower cost maintenance, and higher reliability. While the electrical efficiency and power factor are, in general, lower for the LIM compared to the LSM, the efficiency of the COL-200 LIM design is comparable to the LSM-driven Transrapid TR07.

From the various aspects of the technologies discussed above, the LIM-drive is preferable for Colorado Project route. The base technologies for the propulsion and levitation have been well established and proven in testing as a transportation system. This LIM-drive is a lower cost alternative with flexibility to changes in demand to maximize the utility of the capital investment.

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