Urban Maglev in the United States — A Vision of the Future

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ABSTRACT: Maglev is viewed by most people as an expensive way to go fast with few advantages in comparison with other transit technology. This view is reinforced by the installed Linear Induction Motor (LIM) powered urban maglev systems that replicate light rail performance. Urban transit powered with Linear Synchronous Motor (LSM) technology, including both maglev and rail, allows system designers to take advantage of maglev technology offering lower cost, lower energy intensity, and higher capacity systems. LSM combined with inductive power and data transfer allow wireless electric transit.

1 INTRODUCTION

At present the most important urban transit market in the U.S. is for growing metropolitan areas that have extreme highway congestion, but not enough demand to justify rapid transit systems of the type used in the largest cities. At present this need is being met by light rail— 20 light rail systems have been installed in the last 12 years— but there is not convincing evidence that these installations have achieved their objectives. In the U.S. in 2009 National Transit Database (2009) the average operating cost of light rail was $0.52 per passenger km, only 25% of which was recovered in fares, average speed was rarely over 20 mph, vehicle headways was usually more than 10 minutes so wait times are large, and at times of peak load more than 70% of the passengers must stand so users are reluctant to travel large distances. And there is the question of safety: light rail passengers are very safe, but there have been a number of serious accidents when light rail vehicles operate on a non-exclusive right-of-way.

This paper shows that an optimized urban maglev system has many advantages. From studies of performance data of existing transit systems and newspaper accounts of transit controversies, we know what is needed: a service that is as convenient and as easy to use as an elevator with short wait times, high average speeds, and operating costs lower than present rail transit. To meet these needs we start by using automated vehicle operation so it is practical to use smaller vehicles operating with short headway, which then allow less expensive elevated guideways with exclusive rights-of-way and shorter wait time. Then add an optimized control so as to provide cost effective service under widely varying demands— no more long trains carrying few people and no need for all vehicles to stop at all stations. When these features are combined with the proven advantages of maglev— higher top speeds, higher acceleration, reduced noise, better ride quality— we can create a public demand for maglev that will overcome the entrenched status quo.

This paper provides more details on how this future can be achieved, including cost estimates for the *M3* urban maglev system and simulated comparisons with existing rail transit. It also discusses the use of LSM propulsion for rail vehicles in cases where there is an existing rail corridor, such as used by diesel power commuter rail. It is cost effective to convert to LSM powered commuter rail and use many of the control ideas that are possible with urban maglev.

This paper also describes an efficient and cost effective Inductive Power Transfer (IPT) system that provides onboard power and communication so there is no need for overhead or third rail power collection.

2 THE M3 URBAN MAGLEV SYSTEM

Figure 1 shows an example of an *M3* urban maglev vehicle, based on a design developed by MagneMotion with support from the Federal Transit Administration. The FTA requirements were for a maximum speed of 161 km/s (100 mph), maximum acceleration and braking rates of 1.6 m/s^2, and minimum horizontal turn radius of 18.2 m (60’). This system is described in more detail in Thornton (2009), and Wieler (2011).

The *M3* suspension and propulsion have been tested on a full size guideway at low speeds, and simulations have shown that the design can provide good ride quality at much higher speeds. The vehicle body is supported by pods of permanent magnets that provide the forces for levitation, guidance, and the field for a linear synchronous motor (LSM). The vehicle length can be varied by adding or subtracting mid-sections, with each mid-section having a length of 4 meters and capable of carrying 20 to 22 passengers. The short module length allows the vehicle to negotiate turns with a radius of 18.3 m (60').

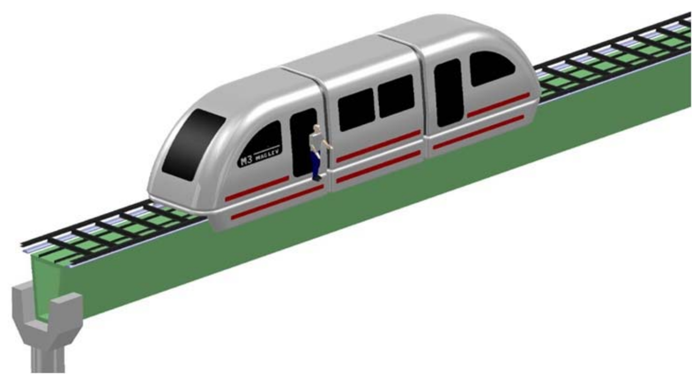

Fig. 1. *M3* urban maglev vehicle capable of carrying 60 passengers, 60% seated.

2.1 Linear Synchronous Motor Propulsion

We believe that LSM propulsion offers the greatest potential for many types of urban transit, including maglev. Although the Linear Induction Motor (LIM) has proved viable for low speed rail and maglev, it requires transferring large amounts of propulsive power to the vehicle and the onboard propulsive components lead to heavier vehicles than is possible with LSM propulsion. Also, with LIM propulsion any automated control system must involve safety-critical communication with the vehicles. In contrast, when LSM is used vehicle weight and cost are substantially reduced, and safety-critical communication is confined to the wayside. There is some added cost due to windings on the stator and the wayside power converters, but for a system with relatively low capacity the total cost of LSM propulsion is comparable to the cost of LIM propulsion. For moderate to high capacity LSM propulsion is less expensive than LIM propulsion, and at the higher speeds required for intercity travel the LSM is the only viable alternative.

Although maglev will often be less expensive than alternatives for new installations, in cases where there is an existing rail corridor it may be less expensive to use wheel suspended vehicles, but the LSM is still an excellent alternative for propulsion. Most of the discussion in this section is applicable to LSM propulsion of both maglev and rail vehicles.

2.2 Clusters of smaller vehicles

With LSM propulsion there is no safety critical communication with the vehicles and propulsion and braking do not depend on friction, so it is feasible to operate with short headway between vehicles, headways comparable to the ones used between cars and buses on a highway. This fact makes it possible to replace long trains with clusters of smaller vehicles and still achieve high capacity.

Figure 2 shows the distance vs. time plot for an example of three clusters of four vehicles, each making successive stops every 1 km. Operational parameters are: top speed of 120 km/h (75 mph);, maximum acceleration and braking rates of 1.6 m/s^2, headway of 7 seconds, which allows a vehicle to stop in the clear distance ahead with an emergency rate of 2.5 m/s^2, and 20 second dwell time. The vehicles are 14.5 meters long and carry 60 passengers each, so with one cluster every 62 seconds the capacity is 14,000 passengers per hour per direction (pphpd). The vehicle size and number of vehicles in a cluster can both be increased— capacities of over 40,000 pphpd are feasible.

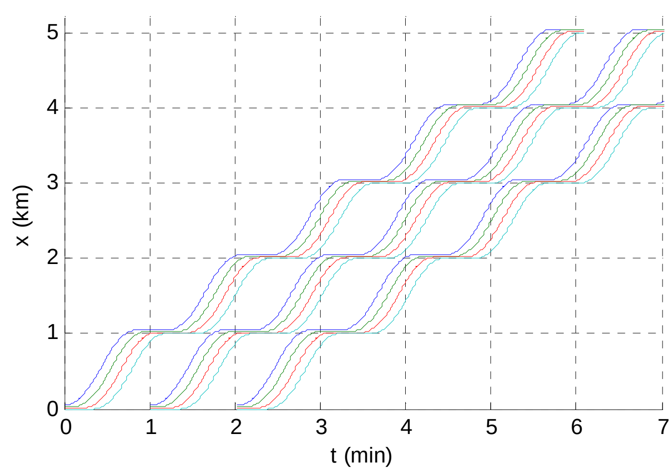

Fig. 2. Distance vs. time plots for clusters of four vehicles making a stop every 1 km.

For the example in Figure 2 the average speed is 52 km/h (32 mph). No U.S. rail-based transit system achieves this high an average speed with such short station spacing—but we can do even better.

2.3 Groups of clusters and station skipping

A principle advantage of clusters is the ability to match capacity to demand by using station skipping control, a well known scheme, but one that is not used in most transit systems. The key idea of Personal Rapid Transit is to allow a person to go to a desired destination with a minimum number of stops, and this idea has been implemented in the

Morgantown WV Group Rapid Transit system. Neither PRT nor GRT can deliver the high capacity required in a large city, but with LSM propulsion we can achieve many of the advantages by using groups of clusters and scheduling each vehicle to stop at only a fraction of the stations.

As an example, consider the use of station skipping on the New York City Broadway Line from Canal Street to Times Square with six intermediate stations. We assume operational parameters as in the last example, but in order to meet demand the vehicles size is increased so it can carry up to 132 passengers. At peak load we need to service all station pairs with every cluster group, but want extra service between the major stations, Union Square and Herald Square. If we use a group of three clusters, six vehicles to a cluster, and each vehicle makes two intermediate stops, we can service 18 intermediate station pairs, so we use the extra 3 pairs for the major stations. Figure 3 is a plot of distance vs. time for two groups of clusters and parts of additional groups.

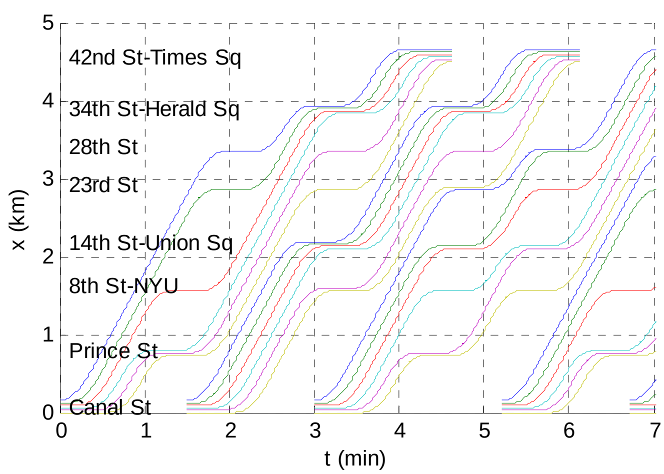

Figure 3. Distance vs. time for one group of clusters and part of an additional group.

The average speed from Canal Street to Times Square is 67 km/h (41 mph) and the capacity is 28,000 people per hour per direction. This speed is three times the speed of the existing local line and almost twice the speed of the express line, which only stops at the major stations. Notice that the minor stations only need space for two or three vehicles so stations can be shorter..

At off-peak we can adopt a strategy that does not service all stations pairs, but does allow any trip with at most one change, a change that requires negligible wait time. This scheme is shown in Figure 4 where each group consists of two clusters of two vehicles, and each vehicle makes three intermediate stops between Canal Street and Times Square. There is service between all minor stations and a major station, and between major stations, but in some cases in order to go from one minor station to another minor station it is necessary to change. For example, to go from Prince Street to 28th Street take a vehicle to Union Square and immediately after arriving at Union Square get on the vehicle that, in only a few seconds, will arrive behind the vehicle you are in. The minor inconvenience of a change for a few passengers allows faster overall travel and reduces cost for the transit agency.

This more sophisticated scheduling will require signs to help riders find the right vehicle, but this is not much more complex than what is done now in places like Washington DC where multiple lines use the same station platform and color coding and electronic signs are used to help riders find the right train.

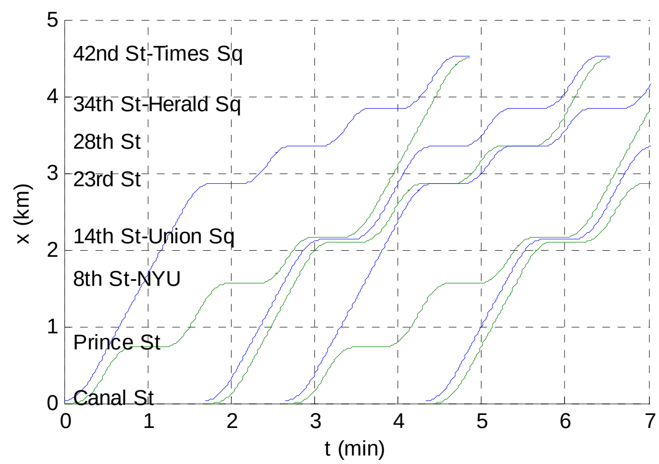

Figure 4. Distance vs. time for two groups of clusters.

For late night travel with very little demand the best strategy is to use small vehicles that circulate every few minutes and stop on demand. Instead of using 132 passenger vehicles, use 40 passenger vehicles that are less expensive to own and operate. Meanwhile the larger vehicles can be serviced for use the next day.

In short, groups of clusters of smaller vehicles can provide much better and less expensive service than long trains. With automation the cost of operation is no more than for long trains, and the versatility allows a much higher average load factor—the key to reducing energy intensity.

3 ENERGY INTENSITY AND BLOCK LENGTH

The LSM has been proved successful in a wide range of applications, but the only operational installations for passenger transport are for high speed maglev. At high speeds the efficiency of the LSM can be relatively high, even when the stators are excited in blocks longer than 1 km, but for urban transit with higher acceleration and braking rates it is imperative to excite the stator in relatively short blocks, sometimes blocks that are shorter than the vehicle. Fortunately it is cost effective to use short blocks and the energy savings more than pay for the added cost. The solution is to use sub-block switching that allows a fraction of one block to be excited, a scheme depicted in Figure 5 where several sub-blocks are excited by two inverters— one excites the even numbered sub-blocks and the other excites the odd numbered sub-blocks.

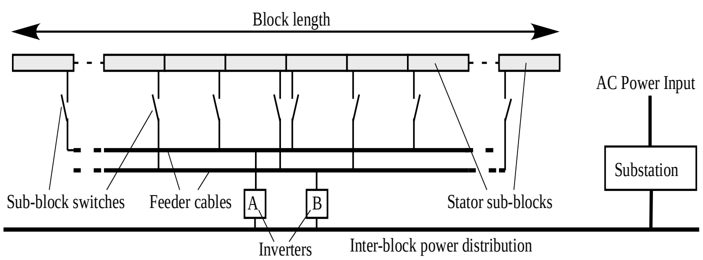

Figure 5. Leap-frog sub-block switching scheme.

For this paper a block is defined as a length of stator that is excited by a group of inverters, and only one vehicle in a block can be propelled. The block length is determined by vehicle spacing, so, for example, with a 14.5 meter long vehicle, headway of 7 seconds, and a speed of over 20 m/s we can use blocks that are 90 meters long, and the control system can require that vehicles are never closer than 120 meters. Shorter blocks are used near stations where speed is reduced. The sub-block length can be shorter than the vehicle, but for a 14.5 meter long vehicle a good choice for sub-block length is 15 meters so there can be 6 sub-blocks per block and two sub-blocks will always be excited. For longer vehicles we can increase sub-block length or use three inverters with up to three sub-blocks excited.

A sub-block switch uses thyristors and costs significantly less than an inverter, so this is a cost effective scheme. This “leap frog” switching has been proven in U.S. Navy aircraft carrier munitions elevators, and allows the use of short sub-blocks without excessive inverter cost.

Energy intensity (EI) is the energy required to move one passenger a given distance— for this paper EI is expressed in units of Wh/pas-km, with 1 Wh/km equal to 3.6 J/m. The energy is almost independent of the number of passengers on the vehicle, so achieving a high load factor is key to achieving low energy intensity.

As an example of achievable EI with LSM propulsion, consider a 60 passenger *M3* vehicle making a 1 km trip with a maximum speed of 120 km/h (75 mph) and maximum acceleration of 1.6 m/s^2. The propulsion is capable of 162 km/h, but in order to reduce energy consumption and allow shorter headway, for a trip of 1 km we assume a reduced speed, but ability to maintain maximum acceleration up to maximum speed. With a 60% load the mass is 12 Mg. The aerodynamic drag is estimated to be 2.4 N at 1 m/s and is assumed to be proportional to the speed squared. Figure 6 shows the velocity and force vs. time for a 1 km trip. Note particularly that the force for cruising at 120 km/h (33.3 m/s) is much less than the force for acceleration and braking.

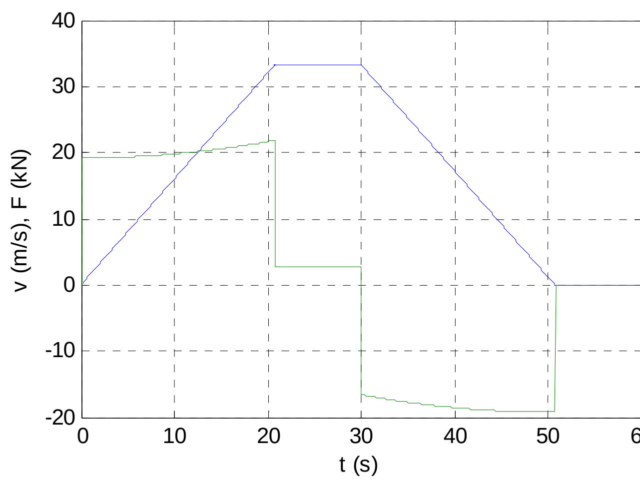

Figure 6. Speed (m/s) and LSM force (kN) vs. t (s) for 1 km trip.

When regenerative braking is used the term efficiency is not well defined, so we choose to calculate inefficiency, the total motor loss divided by the total mechanical energy transferred to and from the vehicle. The LSM loss is due to winding resistance, a loss proportional to the square of the force, and hysteresis and eddy currents in the steel laminations, a loss dependent on speed and speed squared. When accelerating and braking the resistance loss dominates, but when cruising the magnetic loss can be comparable to the winding loss, depending on the speed and properties of the laminations.

Table 1 summarizes the energy usage for a 1 km trip. The trip is analyzed in four segments: acceleration, cruise, braking, and for the total trip. The onboard power is assumed to be 30 kW, primarily for HVAC with less than 1 kW for suspension, and the electronic power conversion efficiency is assumed to be 96%. The LSM has an inefficiency of 28% for the 1 km trip, but is only 8% for the cruise phase.

EI is 56 Wh/pas-km for a 1 km trip, but this approaches 29 Wh/pas-km for a long trip for which the cruise phase dominates. This analysis shows that for low EI it is important to reduce aerodynamic drag, reduce the number of stops, reduce HVAC needs, and increase the load factor. The LSM efficiency is very good in cruise mode, but for acceptable inefficiency when accelerating or braking short sub-blocks are essential.

Table 1. Energy requirements and EI for a 1 km trip.

Parameter	*Accel.*	*Cruise*	*Brake*	*Trip*
Elapsed time, s	20.8	9.2	20.8	50.8
Distance traveled, m	347	306	347	1000
Kinetic energy, Wh	1852	0	-1852	0
Aerodynamic drag loss, Wh	129	226	129	484
Onboard energy, Wh	174	76	174	424
Mechanical energy, Wh	1980	226	1723	3930
Force, kN rms	20.10	2.67	18.33	17.45
LSM I^2R loss, Wh	481	3.7	400	885
LSM Fe loss, Wh	4.8	4.2	4.8	13.9
Electronic loss, Wh	98.7	9.4	85.1	193.2
LSM Inefficiency, %	29.5	7.7	28.4	27.8
Total energy input, Wh	2739	320	-1060	1999
EI, Wh/pas-km	219	29	-85	56

For comparison with other transit technology, in the U.S. the median EI for urban transit modes are, in units of Wh/pas-km: commuter rail, 157; heavy rail, 220; light rail, 224; city bus, 317. Urban maglev has much lower EI than existing urban transit technology, but, most important, it is as good or better than the best technology: a plug-in Prius with 2 passengers has EI = 74 Wh/pas-km, and a Boeing 787 Dreamliner with 90% load on a long trip has EI = 97 Wh/pas-km. Even lower EI is possible for urban maglev if we can decrease losses and increase the load factor— we should try to emulate U.S. airlines which now average over 85% load factor thanks to smart scheduling and the use of vehicles with size matched to demand.

4 INDUCTIVE POWER TRANSFER

The LSM eliminates the need to transfer large amounts of propulsion power to the vehicle, but there is need for some power for heating, air conditioning, lighting, communication, etc. For a vehicle designed with attention to insulation and not an excessive number of windows, onboard power requirement is on the order of 2 kW per meter of vehicle length, possibly a little more or less depending on anticipated weather conditions. Thus a 60 passenger vehicle that is 14.5 meters long might require about 30 kW.

This section describes a simple and robust Inductive Power Transfer (IPT) system that can provide this amount of power across a gap of at least 20 mm, the same gap used for the *M3* urban maglev system and proposed for LSM propulsion of rail vehicles. Note that with LIM or rotary motor propulsion the propulsive power must be transferred and it is more than an order of magnitude larger, so a much more expensive IPT system would be required.

Figure 7 shows the key idea: a secondary loop moving over a transmission line carrying alternating currents. The mutual inductance between the coils creates a transformer capable of transferring substantial power to the load. In this Figure there are two turns in the secondary and one in the primary, but there can be any number of turns in each.

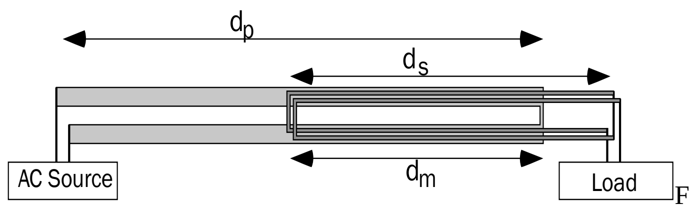

Figure 7. Inductive power transfer module.

Figure 8 shows the field plot for the conductor arrangement, which is two parallel transmission lines, each with elongated cross-section conductors with the closest possible spacing between the conductors of the two lines. The primary current i_p flows in the lower, thinner conductors and the secondary current i_s (the sum of the currents in each turn in Figure 7) flows in the upper, thicker conductors, with thicker conductors used because in an optimized design the secondary current is higher than the primary current. The conductors are constructed from 1 mm diameter Aluminum wire formed into a Litz-wire braid so as to insure constant current over the conductor cross section and minimize eddy currents due to induced current from changing current in neighboring conductors.

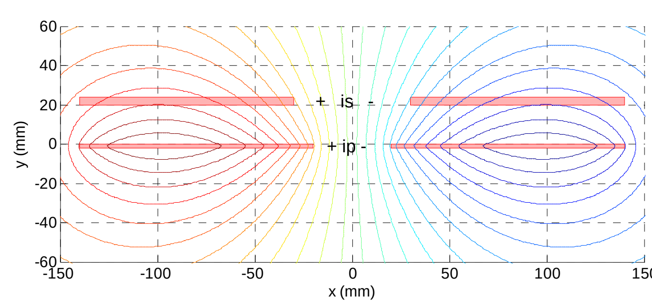

Figure 8. Magnetic field in vicinity of IPT conductors with current only in primary.

Figure 9 shows a complete IPT power transfer module. The IPT transformer primary is supplied by DC input voltage V_i and an H-bridge, which creates a rectangular waveform approximating a sine wave. The frequency choice is dependent on semiconductor device technology, with higher frequencies allowing the use of smaller conductors, but with higher losses in the semiconductor switches. For Silicon IGBT switches, 20 kHz is a good choice, while for MOSFET or Silicon Carbide devices, 50 kHz may be better. The IPT transformer secondary is tuned to the fundamental frequency with parallel capacitor C_s and drives a bridge rectifier to deliver current I_o to an onboard battery with voltage V_o.

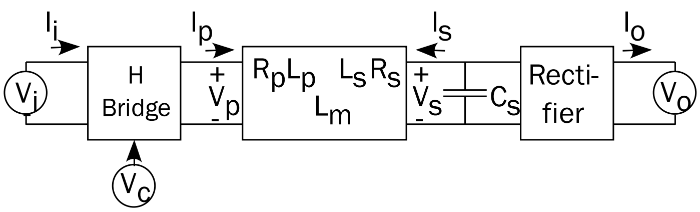

Figure 9. Model of IPT module.

The power transferred is proportional to the square of the input and output voltages with transformer efficiency independent of the amount of power. With optimum design the transformer efficiency is 98%, and the overall efficiency of DC to DC transfer is over 94%. The number of turns in the primary is typically on the order of two so that the same DC bus voltage used for the propulsion can be used to power the IPT primaries, and power regenerated by a braking vehicle can be used to provide onboard power. The secondary is typically constructed as several sections, each with several turns and a rectifier, and connected to a common onboard battery. The transmission line used for IPT may also be used for a communication link between vehicle and guideway via modulated high frequency carriers coupled to the transmission lines.

For a complete IPT system, a sequence of IPT modules is arranged as shown in Figure 10. This Figure shows four modules and two vehicles, one of which spans two modules. A synchronizing signal is used to insure that all modules are in phase so a vehicle moving from one module to another will receive nearly constant power.

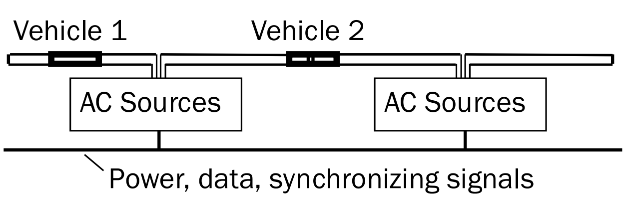

Figure 10. Inductive power transfer system.

5 LSM PROPULSION OF RAIL VEHICLES

Although urban maglev has many advantages over rail transit, the existence of extensive rail networks suggests we take a serious look at using the LSM to propel rail vehicles. For example, many U.S. cities have commuter rail systems that provide cost effective transportation to and from suburbs that are 10 to 100 km from the city center. Most of these lines are not electrified and use diesel locomotives hauling passenger cars. If we can use LSM propulsion of individual cars, we can achieve higher acceleration, reduced emissions, and reduced energy intensity. By using station skipping we can increase the average speed so as to be more competitive with automobiles. With smaller vehicles, or short trains, we can afford to offer better transportation at off-peak times, thereby improving the cost effectiveness of the system.

There are many examples of LIM powered rail vehicles, most notably the Bombardier ART system used in Vancouver BC, Kennedy Airport, and other places. The use of LIM propulsion has enabled Bombardier to reduce the vehicle weight by more than 10% and thereby decrease the energy intensity of these vehicles. The LIM is not more efficient, but the system is because it is possible to reduce the weight of the vehicles, and maintenance is reduced because the wheels are not used for propulsion. The automated Vancouver Sky Train has one of the lowest operating costs of any transit systems in North America, on the order of $0.35 per passenger km in 2009.

For LSM propulsion we replace the LIM primary with a magnet array and install stators on the guideway. The vehicle weight is reduced, and there is no need for transferring propulsive power or safety-critical control signals to the vehicle. This is particularly important in many areas where it is not feasible to install third rails or overhead catenaries.

As an example, assume we wish to convert a modern light rail vehicle to LSM propulsion. Each vehicle is assumed to have three bogeys, and we can install a 3 meter long Halbach Magnet Array under each bogey. The LSM stators would be similar to the *M3* maglev stators, but with a width of 120 mm instead of 80 mm. The magnetic gap is 20 mm, the same as used for maglev suspension and twice the gap used for LIM propulsion. The combination of LSM and IPT makes it possible to achieve the advantages of electric propulsion without the need for third rail or catenaries for power transfer, and offers the potential for secure communication between vehicle and guideway.

6 COST

The *M3* urban maglev design is described in a companion paper Wieler 2011 and the cost estimate given there is summarized in Table 2— an estimate based on the actual cost of installing a test system. For the case of a rail-based but LSM propelled system, there is no guideway cost and, because the single LSM primary has less than the total mass of the two maglev LSM primaries, the LSM stator and inverter costs will be somewhat less. Thus, for LSM powered rail the cost is about $18 million per km ($29 million per mile), including vehicle cost. This cost includes the cost of automatic control, and is competitive with any guided transit system with the same capacity. Considering the higher speed, lower energy consumption, and lower maintenance cost, LSM powered transit should be the first choice for new installations.

Table 2. Cost estimate for *M3* dual guideway urban maglev.

Parameter	$M/km	%
Guideway, installed	8.8	29
LSM stators, installed	7.8	26
DC power, inverters, IPT, software	3.5	12
Vehicles	6.0	20
Maintenance facility	1.3	4
Contingency	2.6	9
Total	30.0	100

7 SUMMARY

The use of urban maglev and linear synchronous motor propulsion makes it feasible to construct urban transit systems with greatly increased speed, lower energy intensity, and lower overall cost than is possible with alternative technology. A key feature of LSM propulsion is the ability to use groups of clusters of small vehicles and station skipping to achieve the capacity of long trains, but with higher average speed and lower operating cost. With larger vehicles the capacity can be greater than 40,000 people per hour per direction, but by using smaller vehicles urban maglev is economically viable for capacities below 5,000 pphpd.

In cases where there is an existing rail system, the use of LSM propelled rail vehicles allows electric propulsion where it is not feasible to install catenaries or third rails. This paper also described an efficient and cost effective inductive transfer system for providing power and communication for a vehicle.

Inexpensive and efficient inductive power and data transfer compliments LSM propulsion and allows wire-less, all-electric transit.

8 ACKNOWLEDGEMENTS

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