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LINEAR SYNCHRONOUS MOTOR PROPULSION OF SMALL TRANSIT VEHICLES

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ABSTRACT

The Linear Synchronous Motor (LSM) has been used for several high speed maglev applications but only recently have developers applied it to urban transit. MagneMotion has worked with the Federal Transit Administration (FTA), as part of their Urban Maglev Project, to develop an LSM propelled maglev transit system called M^3. The top speed is only half that of the Transrapid maglev trains now operational in China but by using small vehicles with short headway and rapid acceleration it is possible to achieve outstanding performance at much lower cost. The combination of LSM technology and small vehicles is a cost effective replacement for rotary motor and Linear Induction Motor (LIM) powered trains for all transit applications, including conventional rail and monorail.

LSM is the enabling technology that makes it economically and technically feasible to achieve high capacity with short vehicles and, conversely, the use of small vehicles makes LSM propulsion economically attractive. Small vehicles operating with short headway and organized in clusters can achieve high capacity without offline loading. Very precise position sensing and guideway based propulsion and control make short headways safe and affordable.

This paper describes the objectives of the MagneMotion LSM development, discusses some of the design features, and presents 3 examples. The examples are based on operational speeds up to 60 m/s (134 mph), accelerations up to 0.16 g, vehicle headways down to 4 seconds, and capacities up to 12,000 passengers per hour per direction (pphpd). Examples include a 1 mile high capacity shuttle, a 4 km unidirectional loop with several stations, and a 30 km high-speed airport connector. Calculations show that an LSM propelled transit system has lower capital cost than conventional transit systems using vehicle-based electric propulsion with either rotary motors or LIMs. Vehicles are simplified, the cost of energy and maintenance is reduced and, most important, users of the transit system experience major reductions in trip times.

INTRODUCTION

The availability of an LSM propulsion system allows the fulfillment of a transit designers dream: A propulsion system that costs less to build and operate and provides faster and safer travel. Other authors have pointed out the advantages of linear motor propulsion [1] but most have focused on the importance of environment-independent traction. There are even more compelling reasons to use an LSM.

The LSM described in this paper provides non-contacting propulsion and precise position sensing with much lower vehicle weight and cost. The propulsion and control is entirely on the guideway and does not depend upon communication with a moving vehicle. Energy consumption and maintenance costs are less than for trains with either rotary motors or Linear Induction Motor (LIM) propulsion. But to achieve the full advantage of an LSM one must adopt a new approach to system design: Use small vehicles operating with short headway and automatic control.

The advantages of a linear motor are well known but there is a wide spread perception that they have significantly higher cost and that the LIM is inherently less expensive than the LSM. This paper is an effort to dispel these myths and promote a system approach to propulsion design.

DESIGN OBJECTIVES

We set five objectives with strategies for achieving them. Some of the objectives are conflicting but there are reasonable compromises. If a majority of these objectives are achieved the result will be a dramatically improved transport system.

1. Minimize cost:

Cost means total lifecycle cost including initial, operating and maintenance cost.

- Reduce vehicle weight and complexity;
- Match the guideway to the vehicle and environment;
- Eliminate power transfer via sliding contacts;
- Reduce energy consumption;
- Reduce the number of vehicles required.

2. Minimize trip time

Trip time means total travel time from source to destination including access time, wait time and travel time.

- Increase average speed;
- Increase acceleration rate;
- Decrease vehicle headway;
- Reduce station spacing;
- Use station skipping control.

3. Minimize environmental impact

Environmental impact means visual obtrusiveness, audible noise, and usage of natural resources. It also means impact on the passengers in the form of ride quality and comfort.

- Use a guideway with reduced visual impact;
- Reduce audible noise;
- Eliminate catenary or third-rail power transfer;
- Minimize energy consumption;
- Improve ride quality by careful guideway design.

4. Minimize risk

Risk means risk of injury to passengers *and* non-passengers and ability to withstand expected types of component failure and environmental extremes.

- Use a dedicated guideway with minimum possibility of unwanted incursion;
- Use automatic control to minimize human-based accidents;
- Use a suspension system that can not derail;
- Use a control system that is not dependent on communication with a moving vehicle;
- Use LSM braking that does not depend on wheel traction and provide backup mechanical braking for emergencies.

5. Use state-of-art but proven technology

The previous objectives can be met using only well established and proven technology.

- Use state-of-art microprocessors and power electronics with emphasis on reliability;
- Use modern control algorithms with emphasis on safety and throughput;
- Use high energy Neodymium-Iron-Boron magnets;
- Use available computer aided design tools to model all critical aspects of the design;
- Use detailed simulation to predict effects of normal and abnormal behavior.

LSM DESIGN

This paper is primarily concerned with the use of LSM technology to power small vehicles operating with short headway and station skipping control. A main feature of the paper is a discussion of a number of examples including estimates of average speed, energy usage, etc. This section is not a treatise on LSM design but presents the key issues that underlie the design examples.

The MagneMotion Maglev M^3

The LSM is particularly attractive when used as part of a maglev suspension. The same magnets that produce the field for the motor can provide the force for the suspension and guidance. This is the basis of the MagneMotion Maglev (M^3) design. More details on the M^3 and its propulsion system can be found at the MagneMotion web site.

MagneMotion has worked on an Urban Maglev project for more than two years and during this time has designed and constructed an LSM for powering a magnetically supported vehicle. This work has included a detailed analysis of the motor and the cost of various parts of the system, including quotes from potential vendors. It also included constructing a demonstration prototype to verify the design.

Figure 1 shows a shortened magnet pod for an M^3 vehicle. The alternating-polarity magnets are 80 mm wide and produce a magnetic field with a wavelength of 500 mm in the longitudinal direction. Some magnets are offset laterally in order to allow lateral damping. Each full-size pod is 3.2 meters long and 4 pods can support up to 9 tonnes (9.9 tons). Control coils wound around the magnets are used to stabilize the suspension at the equilibrium gap where the permanent magnets provide all of the lift. The weight of the magnet structure is less than 15% of the vehicle weight. The suspension power is only a few watts when stationary and about 100 W/tonne when moving.

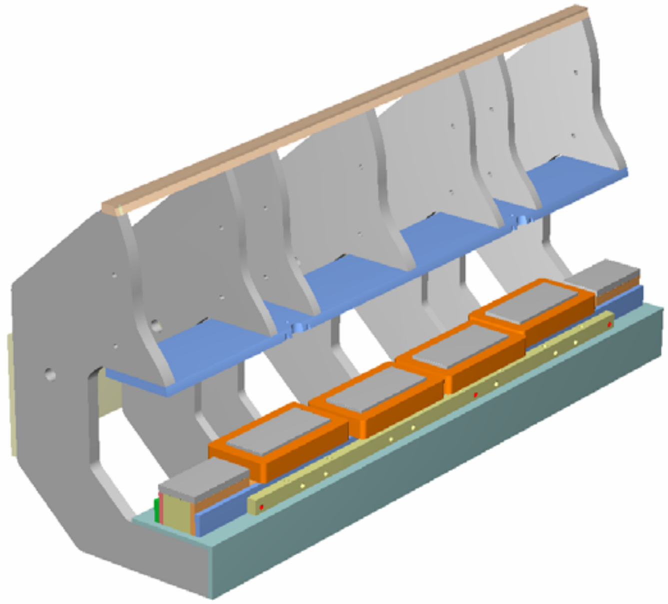

Fig. 1. Magnet pod for M^3 propulsion

Normally the maglev solution will be less expensive than a wheel solution but in some cases, such as where there is existing infrastructure for a wheel suspended system, the LSM can be retrofitted with the magnet arrays mounted under the vehicle. Figure 2 shows the M^3 beam and vehicle. The beam has a weight of 2,000 kg/m plus 150 kg/m for the suspension and propulsion rails and 100 kg/m for attachment components.

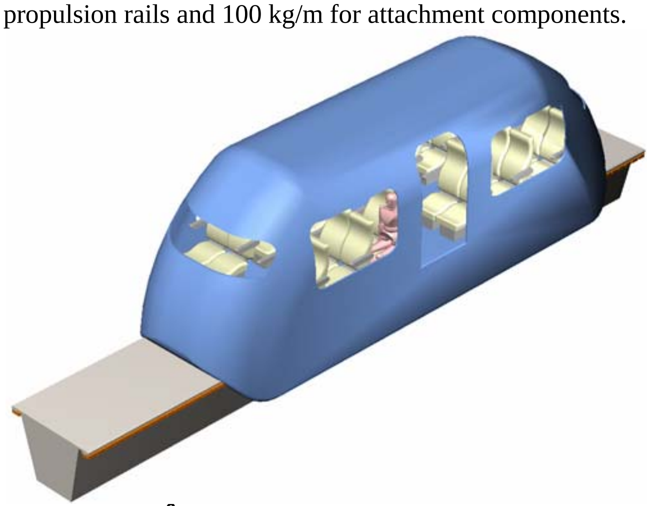

Fig. 2. M^3 vehicle and guideway beam.

Comparison of the LSM and LIM

For transportation applications the term LSM has come to mean a long stator linear synchronous motor. Long stator means the motor primary runs the full length of the guideway with inverter stations located along the guideway. Synchronous means the speed is precisely related to the frequency of the motor excitation. The inverter stations convert available utility voltage and frequency to a variable voltage, variable frequency for exciting a winding on the primary or stator. Precise position sensing and microprocessor-based control ensure that the vehicle stays in synchronism with the traveling magnetic field. The guideway is divided into LSM blocks, each with its own set of inverters, and only one vehicle can be in one LSM block at one time. Wayside switches can be used to connect an inverter to a smaller sub-block in order to improve efficiency and reduce cost. The primary winding creates a moving magnetic field in the vicinity of the vehicle. The vehicle uses onboard electro-magnets or permanent magnets to produce a field for the motor. The propulsion components on the vehicle are lighter, less expensive and consume very little power. The guideway is more complex but not necessarily more expensive. The LSM-produced magnetic field in the vehicle is less than the Earth's magnetic field.

For transportation applications the term LIM has come to mean a short stator linear induction motor. Short stator means the motor primary is on the vehicle. Power is transferred to the vehicle, using either AC or DC, and onboard power electronics convert the input power to variable voltage, variable frequency AC for exciting the primary windings. A conducting reaction plate runs the full length of the guideway and the primary produces a magnetic field that induces current in the reaction plate and thereby creates a propulsive force. The vehicle speed is not precisely related to the excitation frequency so this is sometimes called an asynchronous motor. The LIM has a less complex guideway structure but requires large amounts of power to be transferred to the vehicle and the LIM is less efficient and requires onboard control.

Intuitively it would seem that the LIM is less expensive because the guideway is much longer than the total length of vehicles operating on the guideway. However, the comparison is not that simple. Much lighter vehicles reduce the peak power requirements and save capital cost and energy. The system that transfers power to the vehicle must run the full length of the guideway and it has significant cost. The LSM inverters mounted on the guideway can be less expensive because they do not need to be small or light. Although there are typically three times as many inverters for an LSM design as for an LIM design, the total cost is not three times as great and inverter cost is not dominant. Control is another key issue: with wayside mounted propulsion electronics the control does not require communication to a moving vehicle so it is more reliable and there is less risk from faulty control. Still another advantage is the ability to tailor the propulsive system to the terrain so that high acceleration can be produced near stations or on hills but lower power inverters can be used elsewhere

It is surprising how much heavier the vehicle becomes with either a LIM or rotary induction motor. It would take two 230 kW motors and their controllers to provide the same force and power as the M^3 LSM, but then the power must be increased further because of the onboard motor weight. The 5.5 tonne M^3 vehicle would become at least an 8 tonne vehicle with 35% greater power required for acceleration.

Comparison of LSM propulsion schemes

A long stator LSM powers two operational high speed maglev designs: the Transrapid maglev installations in Emsland, Germany and Shanghai, China and the Japanese superconducting maglev test track in Yamanashi. These LSM designs are very different from the one discussed in this report: they use long trains operating at speeds up to 430 km/h for Transrapid and up to 581 km/h for Yamanashi (267 and 361 mph). The size of the trains and the speed necessitate that the power stations deliver tens of megawatts of propulsive power and even then the acceleration rate is less than 1 m/s^2. This leads to very expensive inverter stations that power long sections of guideway with no possibility for short headway vehicle operation. They require many kilometers of distance to reach maximum speed so there is little advantage to the higher speeds for trips of less than about 40 km (25 miles).

The design discussed here uses much smaller inverter stations located at relatively frequent intervals so as to allow short headway. An interesting feature of power electronic systems is that system cost depends primarily on the total installed power rating, not on how many inverter stations there are. With smaller inverter stations located more frequently the power system cost is actually reduced. A major additional advantage is the potential for using regenerated braking energy. With short headway there is almost always a nearby vehicle accelerating when another is braking so most of the kinetic energy can be recovered. In a typical urban transit application the ability to regenerate energy can reduce energy consumption by up to 50%.

Assumed vehicle attributes

In all of the examples discussed in the next section it is assumed that the baseline vehicle is 9 meters long and capable of carrying 24 people seated with 8 standees *or* 20 people seated with 20 standees. The empty vehicle weight is 5.5 tonnes (5.5 tons) and the maximum loaded vehicle weight is 8.5 tonnes (9.4 tons). The simulations assume a nominal weight of 7 tonnes with 50% of the rated passenger load. The vehicles can be bidirectional or can have a preferred direction with resultant decrease in aerodynamic drag. For the examples the vehicles are assumed to have an aerodynamic drag based on a modestly streamlined vehicle shown in Fig. 2. For high speed operation it is preferable to operate the vehicles in only one direction so that better streamlining and improved suspension dynamics are possible.

The vehicles are powered by two LSMs, one on each side. The two motors have separate power systems so as to provide redundancy in case of failure of one motor. The motors can be accurately modeled by a force limit, due to the current constraints on the inverter and heating of the motor winding, and a power limit, due to the available DC bus voltage and winding inductance. The winding resistance and inductance can be reduced by decreasing the block length, but this increases cost. For the examples it is assumed that excited sections of guideway are 36 m (118') long and that the control ensures that only one 36 meter section is excited, except during brief transitions when two are excited. It is also assumed that the inverters are each rated 500 kVA and operate off of an 850 VDC bus. The result is a propulsion system capable of providing 14 kN of thrust up to 33 m/s and a power limit of 460 kW (617 HP) for speeds from 33 to 60 m/s (74 to 134 mph).

It is possible to vary the baseline design to achieve a different trade-off of cost vs. performance, but the examples based on a one-size-fits-all philosophy will give a good idea of the capabilities of an LSM powering small vehicles.

Performance

In order to understand the capabilities of the M^3 it is instructive to simulate the distance traveled, speed and force required for a given mission. Figure 3 shows these parameters vs. time for a 3.24 km (2 mile) trip. The maximum speed is 60 m/s (134 mph) and the trip takes 93 seconds for an average speed of 80 mph. Up to 13 kN force is required for acceleration but only 4.5 kN is required for cruise at maximum speed. It takes 50 seconds to reach top speed and 36 seconds to brake. The acceleration and braking are limited by the design limit of 1.6 m/s^2 (a limit that can be increased if there are no standing passengers) at low speed and the maximum power capability of the motor at high speeds. The power limit does not affect braking time because aerodynamic drag augments the linear motor. With an efficient motor it is possible to use regenerative braking to recover a substantial fraction of the kinetic energy.

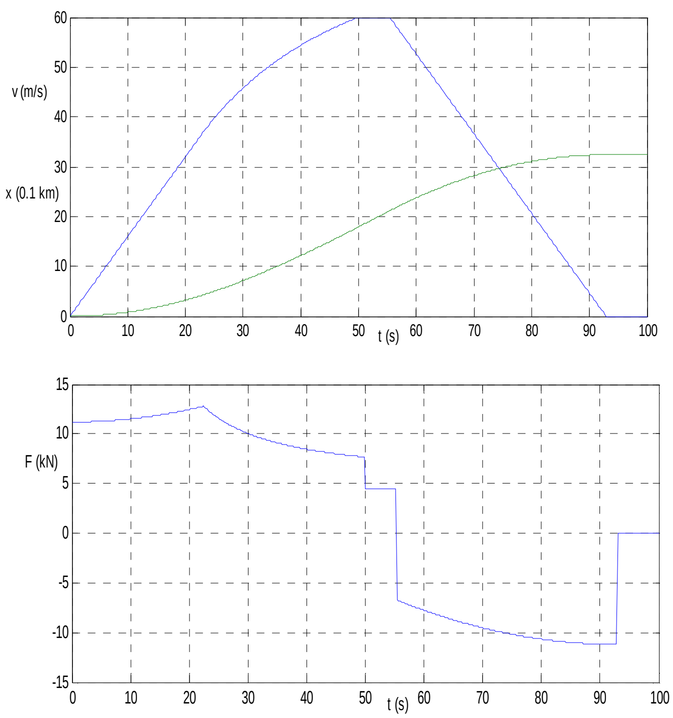

Fig. 3. Distance, velocity and force vs. time.

In many cases it is desirable to limit top speed to less than 60 m/s but with LSM propulsion there are significant advantages of using much higher top speeds than are used with other propulsion means. The higher speed means it takes fewer vehicles to provide a given capacity. The cost disadvantage of higher speeds is surprisingly small and reduced travel time is a very important factor in increasing user acceptance of urban transit. For most urban transit we believe a top speed of 45 m/s (101 mph) is a good objective with still higher speeds used when travel distances are large and lower speeds used for shorter trips. This approach to speed choice is illustrated in the examples.

Control

When short headway is required it is important to pay careful attention to the control system. The LSM system is well suited to safe operation because there is precise position sensing integrated with the motor and there are communication cables interconnecting the wayside inverters. If an unexpected incident occurs to one vehicle it is possible to take immediate action in controlling all other vehicles so as to deal with the problem in an optimum manner. The control system will always ensure that there is no more than one vehicle in an LSM block and that no normal action could cause a problem. Infrequent but expected abnormal events, such as a power failure, should never cause an accident and less frequent but possible events, such as an earthquake, should cause the minimum possible damage.

There are two distinct control algorithms, one for controlling vehicles within a cluster and one for controlling the clusters. The cluster controller is based on a brick-wall criterion: The first vehicle in each cluster must always be able to stop in the clear distance ahead. The clusters are treated as virtual trains and this strategy prevents a trailing cluster from colliding with a leading cluster even if the leading cluster stops instantaneously.

In order to achieve high throughput in the higher speed examples, “safe-approach” headways [3] are used for vehicles within a cluster. While shorter than “brick-wall”, the “safe-approach” headway ensures that if a vehicle instantaneously starts decelerating at maximum deceleration then the following vehicle can stop without colliding and without using a higher deceleration. In the “safe-approach” methodology, regions are considered safe for travel when a preceding vehicle can no longer stop in the region at maximum deceleration. This strategy is similar to one used (ideally!) by drivers on a highway. Even shorter headway has been demonstrated for a platoon of automatically controlled automobiles operating on a specially equipped Interstate Highway.

An argument can be made that a catastrophic event, such as a severed guideway, may affect more than one vehicle using a “safe-approach” headway. However, a single train carries several times more passengers than a cluster so it is even more susceptible to serious damage. A system with small vehicles and short headways may be considered as safe as long trains operating at longer headways. Also, LSM propelled vehicles have a higher deceleration capability, thus requiring less distance to stop and increasing the chance of stopping before the affected location. Simulations of M^3 propulsion show that safe control is possible with 4 second headway if the LSM block lengths are appropriately sized.

The control system is based on the concept of granting permission for vehicles to enter a region where it is safe for them to travel. The system is fail-safe in the sense that if the communication link is severed or a failure occurs, no more movement permissions are granted and vehicles come to a stop in the last LSM block they were granted permission to enter. Fault tolerance through the use of multiple motors and inverters and backup emergency brakes help to ensure a safe system.

In case of power grid failure the control system continues to operate using battery-backup and the DC power bus maintains it's voltage by virtue of the regenerative braking, at least until the vehicles reach a low speed at which time mechanical brakes can be used. Braking resistors are used to limit the bus voltage when all vehicles are braking. Once the vehicles have stopped safely a relatively low power emergency generator can be used to move the vehicles to stations, one by one. Alternatively, a battery backup system can be used to supply reduced power long enough to move vehicles to stations.

Cost

Costs will vary depending on the location, guideway length, maximum speed and who builds and manages the transit system. MagneMotion has done a careful estimate of the cost of building the M^3 maglev system and it is believed that the cost would be similar for a design using wheel suspension. Table 2 gives the estimated cost and weight for an elevated dual guideway transit system with a top speed of 101 mph and the use of 8 vehicles per guideway-mile.

Table 1. Cost estimate for dual guideway M^3

	Cost, M$/mile
Guideway structure	8.4
LSM stator	3.8
Power system	3.2
8 Vehicles	2.4
Total	17.8

The data in Table 1 is based on our latest analysis and, as compared with earlier estimates, shows an increase in the cost of the guideway and a reduction in the cost of the power system. Station and land costs are not included but with short headway there is no need for large stations and with an elevated guideway it is often possible to use an existing right-of-way. The low guideway cost is a direct result of using small vehicles with never more than one vehicle on a guideway beam. For emergency rescue purposes the guideway beams can support much more weight because the design is based on stiffness, not strength.

The LSM can also be used with at-grade systems, such as commuter rail. In this case individual rail cars would be fitted with magnet arrays and the LSM stator mounted between the rails. At road crossings and switches there can be breaks in the stator provided the vehicle is long enough to insure that some magnets are over stators.

For replacement of underground rapid transit the beam height can be reduced with more frequent piers.

For speeds over 60 m/s (134 mph) the guideway cost would be somewhat greater because of the need for stiffer beams and better alignment. For a single-lane guideway all costs would be reduced by almost a factor of two. Many other parameters can be changed but by using a common design for many applications the cost can be reduced substantially.

3 EXAMPLES

One of the best ways to understand the advantages of an LSM is to work through a few examples. These examples are intentionally simplified, but the calculations are based on careful analysis and simulation. Three examples will be described: a short shuttle, a one-way loop, and a high speed airport connector. The examples are discussed and then a comparison of various performance parameters is given.

Shuttle

There are many examples of Automated People Movers (APM) used for shuttling passengers a short distance, such as within an airport or from a parking lot to an arena. This example assumes a much higher speed than would normally be used for such an application, but the speed has very little impact on cost and may even lower it.

Design problem

Design a 1-mile long shuttle for moving 12,000 people per hour per direction (pphpd) at speeds up to 45 m/s (101 mph). Assume a maximum capacity of 40 passengers per vehicle and stopping time of 20 seconds. The design should minimize life-cycle-cost of the vehicles and propulsion system.

Conventional solution

Use light-rail with a top speed of 45 mph and acceleration limit of 0.8 m/s^2. The propulsion is by vehicle based motors, either rotary or LIM, with power transferred to the vehicle via an overhead catenary. A typical design uses a train of 2 vehicles, each of which is articulated for sharper turns. The empty weight of each of the vehicles is 40 tons. For this heavy train it is economically prohibitive to use higher acceleration or speeds. The result is the need to use a larger number of expensive trains and to increase passenger trip time. The use of smaller vehicles would require headways that are too short for conventional control systems. LIM propulsion has more reliable traction than rotary motors but it would increase cost and not allow as short a headway as is possible with an LSM.

LSM solution

The baseline vehicle carries no propulsion or control equipment so it can be light and relatively inexpensive. The light weight makes higher acceleration feasible and this makes higher top speeds useful. LSM propulsion can allow short headway between adjacent vehicles without risk of accident because the propulsion does not depend upon adhesion and the control has precise position information at all times and does not depend upon communication with a moving vehicle. In order to allow stopping without offline loading the vehicles are operated in clusters with sufficient headway between clusters to allow unloading and loading one cluster before the next cluster arrives. Each vehicle in a cluster has its own stopping place so the cluster acts as a virtual train, but without the guideway and propulsion requirements to support and power a physical train.

Because the trip is short the vehicles are configured with fewer seats so as to allow 40 passengers without exceeding the weight limit. Five vehicles are organized as a cluster with one cluster departing from each end every 60 seconds so as to achieve the desired capacity. The individual vehicles operate with headways as short as 4 seconds. At each end of the trip the vehicles negotiate an 18.3 m (60') radius turn. In order to maximize capacity it is important to minimize dwell time. The best way to do this is to use 2 doors on one side and to unload and load at different locations. A total of 24 seconds is available for unloading and also for loading. The vehicle negotiates the turn between the unloading and loading stations. Each vehicle takes 240 seconds for a complete round trip so 4 clusters, or 20 vehicles, are required to provide the desired capacity. The travel time is 65 seconds and with a cluster leaving from each end every 60 seconds the average wait time is 30 seconds. The average trip time is thus 90 seconds giving an average trip speed is 40 mph. There are almost always some vehicles accelerating or cruising while others are decelerating so it is possible to use virtually all of the regenerated energy.

Variations

The length could be changed and intermediate stops could be added. If capacity requirements are reduced there do not need to be loops at each end and single clusters of vehicles could shuttle back and forth on each side, similar to conventional shuttle designs but with faster travel time and increased capacity.

There is presently a plan to install a 3-mile shuttle from Oakland Airport to the BART Coliseum Station with up to 2 intermediate stops. An LSM powered system could provide the required throughput with almost a factor of 2 reduction in travel time and vehicle seats and with a saving in guideway and energy cost. With conventional technology the projected cost of the shuttle is on the order of $300 million; an M^3 system would be dramatically less expensive.

One-way loop

With a high top speed it is feasible to use a 1-way loop for loop distances up to several miles. This reduces cost and minimizes the visual impact of the guideway.

Design problem

Design a 4 km long 1-way loop that can carry at least 3,600 pph at speeds up to 30 m/s (67 mph). There should be 4 stops, a main stop and 3 satellite stops. Most people will be traveling between the main stop and a satellite but a significant number will be traveling between 2 satellite stations.

Conventional solution

A monorail propelled by rotary motors is a common solution. An alternative is a cable propelled system such as the Doppelmayr Cable Liner. These systems can be less expensive than light rail but average speeds are typically only 20 to 25 mph and capacity is usually less than 3,00 pphpd.

LSM solution

The short distance and necessity of turning in a moderately short radius makes a top speed of 30 m/s (67 mph) about all that can be useful. This reduces cost of the propulsion system at the expense of using more vehicles, but for the required capacity the number of vehicles is fairly modest. Cost and travel time are both reduced by using a station skipping strategy. Vehicles are operated in clusters of 3 but each vehicle skips one satellite station on each passage around the loop.

The time allowance for traveling 1 km is 55 seconds and for a 2 km trip it is 90 seconds. Dwell time allowance is 50 seconds at the main station and 40 seconds at the satellite stations. By using 3 clusters of 3 vehicles each there are 120 vehicle round-trips per hour. With 36 passengers per vehicle this provides a system transport capacity of 3,888 pph. The average time between clusters is 100 seconds and the minimum vehicle headway is 4 seconds. There are always some vehicles accelerating while others are decelerating or cruising so it will be possible to use virtually all regenerated energy.

Variations

If required at a later time, the capacity can be increased by adding an additional vehicle to each cluster without any other change except to increase the capacity of the rectifier station. By giving up the station skipping strategy it is possible to add an additional cluster for still higher capacity.

It is instructive to compare an M^3 system with the new $650 million Las Vegas Monorail. This state-of-art monorail has a dual guideway 4 miles long with 6 intermediate stops. Nine 4-car trains, each with a capacity of 72 seated and 152 standing and operating with 2-minute headway provide a capacity of 6,720 pphpd. The maximum speed is 45 mph but travel time from one end to the other is 14 minutes so average travel speed is only 17 mph. An M^3 system with greater capacity would cost on the order of $100 million and reduce travel time to 6.5 minutes. There would be 42 40-passenger vehicles operating in 3-vehicle clusters with 60 second headway between clusters and a capacity of 7,200 pphpd. With the monorail $3 one-way fare and anticipated 19 million riders per year the system could actually operate with a profit.

Airport connector

Design problem

Design a high speed transit system to carry people between an airport and city center. The travel distance is 30 km and the objective is to minimize travel time without exorbitant cost.

Transrapid maglev solution

This example is based on the Transrapid installation in China that is now carrying passengers from Pudong Airport to Shanghai, a distance of 30 km. The top speed is 119 m/s (267 mph), the travel time is 7.5 minutes, train headway is 10 minutes and average trip time is 12.5 minutes. There are three 5-car trains capable of carrying 574 passengers each for a capacity of 3,444 pphpd. The reported cost of the Shanghai installation is $1.2 billion or about $60 million per dual guideway mile. The high cost is due to the heavy trains (260 tonnes each), very heavy guideway (4+ tonnes/m), the high power inverters (7.2 MVA per inverter), and the mass of the suspension rails (160 mm width). The suspension uses electromagnets which require more than 1 kW per tonne and there are separate guideway-mounted guidance rails and onboard magnet structures on each side of the trains. It is necessary to use sliding contact power transfer near stations for powering the suspension system.

M^3 solution

The M^3design delivers comparable performance at much lower cost. The maximum speed is assumed to be 60 m/s (134 mph). Although higher speeds are possible, this example shows that the lower top speed but higher acceleration and shorter vehicle headway gives comparable performance to Transrapid for trips of this length. Since the top speed is only one half that of Transrapid, the guideway layout can tolerate a factor of 4 reduction in turn radii and the guideway beams need not be as stiff or precisely aligned, so guideway cost can be reduced. The cost of the power system and energy consumption are both reduced by a large factor.

The proposed design uses a 3-vehicle cluster with minimum headway of 4 seconds near the stations and 10 seconds in the high speed regions. There are 3 stopping places at each end so each vehicle in the cluster has a unique stopping place. Since the trip is long it is preferable to not have standees so the capacity of a vehicle is assumed to be 24 passengers. A cluster leaves every minute for a capacity of 4,320 pphpd with an average travel time of 9 minutes and an average trip time of 9.5 minutes. At a later time a 4^{th} vehicle could be added to each cluster to increase the capacity to 5,760 pphpd with no change in minimum headway. Each vehicle makes a round trip in 20 minutes, so there are 20 clusters for a total of 60 vehicles. The vehicles seat a total of 1,440 passengers, 16% less than for the lower capacity Transrapid installation, and the vehicles are much less expensive on a per-seat basis.

The guideway has a loop at each end. This allows the vehicles to be designed for unidirectional operation with reduced aerodynamic drag. The option of using a switch and bidirectional vehicles is possible, but this would entail the use of more vehicles for the same capacity and does not allow some of the advantages of unidirectional vehicles. For Transrapid the minimum turn radius is so large that they need to use a switch and bidirectional vehicles.

There are always enough vehicles accelerating or cruising to absorb all regenerated braking energy, but the energy savings are a much smaller percentage of energy usage because the trips are long and fast

Performance comparison

The three examples represent very different types of applications, all served by a common LSM design. Table 2 gives a comparison of some of the performance predictions. The average power is for the time the vehicle is moving and the energy usage assumes full use of regenerated energy and a 50% passenger load factor.

Table 2. Comparison of 3 examples.

	Shuttle	*Loop*	*Airport*
Capacity, pphpd	12,000	3,600	4,300
Maximum speed, m/s	45	30	60
mph	101	67	134
Distance, km	1.6	4	30
Stations	2	4	2
Average speed, mph	55	47	125
Average power , kW/vehicle	60	80	230
Energy, J/pas-meter	524	400	814
BTU/pas-mi	843	644	1,310
Regeneration energy savings, %	50	45	6

For comparison, the Transportation Energy Data Book [2] gives the energy intensities in BTU/pas-mile for conventional transit: commuter rail 2,717; rail transit 3,114; transit bus and trolley bus 4,125 and Amtrak 4,127. This reference assumed an electricity generation and distribution efficiency of 29% so 1 kJ is equivalent to 3.268 BTU and this factor was used in computing the BTU/pas-mi in Table 2. Even allowing for substantial energy increases due to loads such as HVAC, the LSM approach uses much less energy. This is due to kinetic energy recovery, lighter vehicles and more efficient propulsion. Another major source of energy conservation is the ability to fine tune vehicle capacity to need and avoid using long and nearly empty trains for off-peak travel.

SUMMARY

The combination of LSM propulsion and small vehicles operating with short headway allows major improvements in transit performance. High capacity can be achieved by operating vehicles in clusters but the guideway beams need only support a single vehicle so they can be lighter and less expensive.

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