MagneMotion Maglev *M3*

The M^3 Urban Transportation System

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Preface

In the last 35 years maglev has changed from an engineering curiosity to the basis for commercial systems now being built in the U.S., China and Japan. German and Japanese efforts over many years have demonstrated maglev's potential for safe, fast and economically viable transportation but potential users have not been impressed enough to install a major commercial system until very recently. The lack of commercial support has been partly due to emphatic statements by critics from academia, industry and the government that maglev is too expensive in comparison with other types of guided transportation. These criticisms are not based on valid technical arguments but are akin to the criticisms of railroads that were made in the early 1800s when the "smart money" was being invested in canals. Unfortunately, maglev enthusiasts have not helped the cause by often focusing more on the technology than on what it can deliver to the user.

A principal problem with past maglev efforts has been an excessive emphasis on speed and technology without taking a system approach to solving a transportation problem. With this in mind, MagneMotion has stressed the system approach and examined all aspects of the problem of providing high quality and cost effective transportation with maglev by taking advantage of recent advancements in enabling technologies. For U.S. applications MagneMotion believes a key market for maglev today is in the low and middle speed region now dominated by light rail, rapid transit, commuter rail and all versions of Automated People Movers (APM). The MagneMotion Maglev system, called M^3, is currently focused on speeds up to 45 m/s (101 mph) but with minor modifications the system could compete with any guided system including ones with both lower and higher speed capability.

A fundamental property of magnetic structures, called *Earnshaw's Theorem*, is that no static configuration of magnets can be levitated so as to be stable in all degrees of freedom. It is possible to be stable in all but one dimension, so it is possible to have a magnetic suspension stable in the vertical direction but then it must be unstable in a lateral direction. Such structures have been proposed but they tend to be heavier and more complex than if electronic control is used to stabilize the suspension in the vertical direction. The vertical stabilization approach to ElectroMagnetic Suspension (EMS) design has now been proven to be suitable for operation over a wide range of speeds. For example, the new Shanghai Transrapid maglev installation uses this approach and will soon be carrying passengers at speeds up to 430 km/h (267 mph), 43% faster than the fastest high-speed trains in operation today.

Historically, the major disadvantage of EMS is the need to use magnetic gaps no larger than about 10 mm. MagneMotion has overcome this disadvantage by using permanent magnets in conjunction with control coils to allow a magnetic gap of 20 mm. Although some ElectroDynamic Suspension (EDS) designs feature larger gaps, it is not clear there is a need for gaps greater than about 20 mm at speeds that are of interest for urban transportation. The Transrapid suspension has a gap of 10 mm and has been extensively tested at speeds up to 125 m/s (275 mph). If there is a cost advantage for using a larger gap, this has not been proven by any maglev system built to date.

This report gives a description of M^3 as it exists at this time. Although the design is expected to evolve over the next few years it is unlikely to change in any major way. This report can be used to assess the potential merits of M^3 for specific applications.

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Abstract

The MagneMotion Urban Maglev System, called M^3, is designed as an alternative to all conventional guided transportation systems. Advantages include major reductions in travel time, operating cost, capital cost, noise, and energy consumption. Van or small-bus size vehicles operating automatically with headways of only a few seconds can be operated in platoons to achieve capacities of more than 12,000 passengers per hour per direction. Small vehicles lead to lighter guideways, shorter wait time for passengers, lower power requirements for wayside inverters, more effective regenerative braking and reduced station size. The result of the design is a system that can be built for about $20M per mile, including vehicles but excluding land acquisition.

The design objectives were achieved by taking advantage of existing technology including improved microprocessor-based power electronics, high-energy permanent magnets, precise position sensing, lightweight vehicles, a guideway matched to the vehicles and the ability to use sophisticated computer-aided design tools for analysis, simulation and optimization. The vehicles have arrays of permanent magnets to provide suspension and guidance forces as well as provide the field for the Linear Synchronous Motor (LSM) propulsion system. Feedback-controlled currents in control coils wound around the magnets stabilize the suspension. The LSM windings are integrated with the suspension rails and excited by inverters located along the guideway

This report focuses on urban applications with baseline vehicles designed to carry 24 passengers seated with room for 12 standees at times of peak load. The LSM is designed to provide speeds up to 45 m/s (101 mph) and acceleration and braking up to 2 m/s^2 (4.5 mph/s) without onboard propulsion equipment. Installation and operating cost are predicted to be lower than for any competing system and average travel times are reduced by more than a factor of 2. Environmental advantages include a factor of 2 reduction in energy consumption, smaller guideway cross-section with reduced visual impact, and greatly reduced noise.

For some applications it is desirable to use smaller vehicles with lower top speeds or larger vehicles with higher top speeds. Both of these options are possible with the same guideway and suspension system. The only changes necessary are in the size of the power system used for propulsion. A 12 passenger vehicle with a top speed of 30 m/s (67 mph) is discussed in this report as an option when the application requires shorter trips with lower capacity and the reduced cost is an important advantage. An articulated vehicle with 36 seats is a possible option for speeds up to at least 60 m/s (134 mph). The important fact is that, with proper attention to design, it will be possible to upgrade M^3 systems to larger vehicles and higher speeds and capacities if such demands are important in the future. The evolution of railroads has shown the desirability of the ability to change with time.

1 Overview

This report summarizes the key features of the *M*^{3} design. Other reports provide more detailed analysis, simulation and design. This first section gives a broad overview and is followed by sections describing the key subsystems in more detail.

M^3 was designed with the following objectives for improving on conventional transit systems and strategies for realizing the objectives.

?? Decrease travel time by at least a factor of 2:
- o Allow speeds up to 45 m/s (101 mph), acceleration and braking up to 2 m/s^2, short average waiting time and reduced dwell time.

?? Decrease operating cost by at least a factor of 2:
- o Use less energy and reduce labor and life cycle costs.

?? Reduce guideway cost by at least a factor of 2:
- o Reduce guideway weight by reducing vehicle weight and matching the guideway to the vehicle.

?? Reduce environmental impact:
- o Reduce noise, guideway size and energy consumption.

?? Create an improved ElectroMagnetic Suspension (EMS):
- o Use permanent magnets with a 20 mm magnetic gap (15 mm physical gap) and make each magnet contribute to lift, guidance and Linear Synchronous Motor (LSM) propulsion.

?? Provide excellent ride quality:
- o Pay careful attention to guideway design and take advantage of the distributed and non-contacting nature of maglev forces.

?? Create a very safe transportation system:
- o Use a dedicated guideway, vehicles that cannot derail, linear motor propulsion that does not depend on friction and totally automated operation.

A key feature that drives the *M*^{3} System Concept is the use of small and light vehicles operating with short headway. The light weight contributes to reduced guideway cost and the small size, in conjunction with short headway, reduces wait time and allows station-skipping operation. Figure 1.1 shows a 3D view of the baseline vehicle and some of its features.

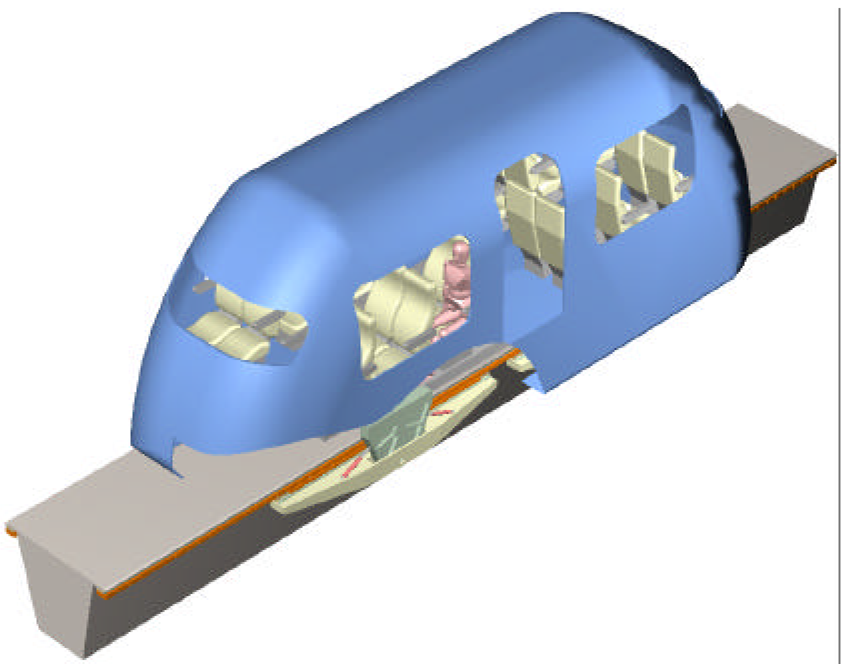


Fig. 1.1. Preliminary vehicle and guideway design.

Following are the key performance specifications that were the basis of the design:

?? Speeds up to 45 m/s (162 km/h, 101 mph)
?? Acceleration and braking up to 2 m/s^2 (4.4 mph/s)
?? Headways as short as 4 seconds when operated in platoons
?? Capacity up to 12,000 passengers per hour per direction (pphpd)
?? Horizontal turn radii of 18.3 m (60') and vertical radius of 300 m (984')
?? Target cost of $20 million per mile including vehicles
?? Minimum environmental impact with reduced noise and energy consumption

Figure 1.2 shows a cross-section of the guideway beam and the vehicle. The permanent magnets on the vehicle provide lift, guidance and act as the field for Linear Synchronous Motor (LSM) propulsion. Control coils wound around the magnets stabilize the suspension and adjust the nominal magnetic gap to the value that minimizes power requirements for the control. Windings in the guideway are excited by inverters located along the guideway and provide controllable thrust for acceleration, cruise and braking. The secondary suspension on the vehicle provides improved ride quality but can be omitted for lower speed operation.

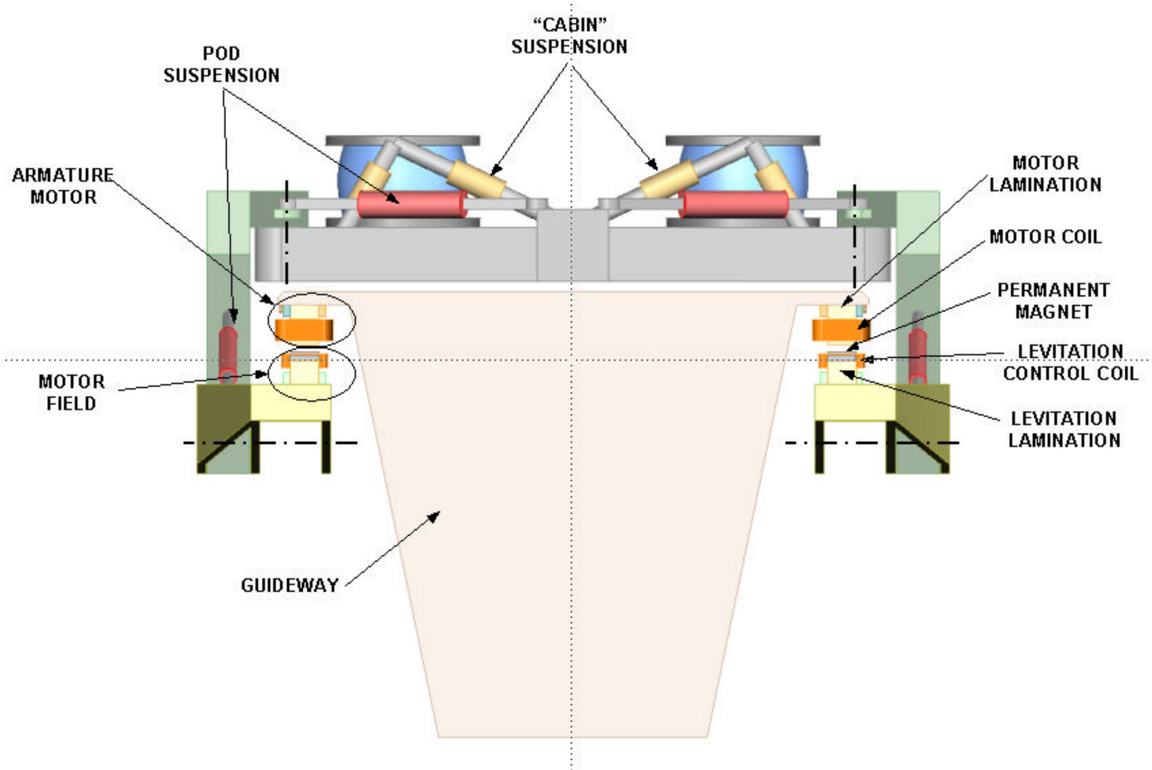


Fig. 1.2. Cross-section of guideway beam and preliminary vehicle suspension.
This is only a preliminary design and will be refined in the next phase of development.

The design of the M^3 system has focused on the components that contribute most to performance and cost with a particular focus on subsystems that have unique features: permanent magnet EMS suspension, LSM design and manufacture, guideway beams, vehicle suspension and control systems. In order to create confidence in the basic design a demonstration prototype has been constructed and tests to date are very encouraging. Future plans call for extending the test track and ultimately building a high-speed test loop as a prelude to installing a commercial system.

2 Electromagnetic suspension and guidance

A key design objective was to create a suspension that: is suitable for low to moderate speeds with frequent station stops, allows vehicles to make small radius turns in both the horizontal and vertical directions, and is suitable for use with small vehicles. Members of the MagneMotion maglev team have had considerable experience with both ElectroMagnetic Suspension (EMS) and ElectroDynamic Suspension (EDS). A careful review of the merits of each led us to pick the EMS design for the following reasons:

?? No need for an auxiliary suspension at low speeds;

?? No need to provide high propulsive force at low speeds to overcome magnetic drag;

?? No need to shield the passengers from unacceptably high magnetic fields;

?? Reduced cost for a complete system.

Following is a discussion of the M^3 features that contribute to decreasing cost and increasing performance.

2.1 Permanent magnet EMS

A key feature of the M^3 suspension is that every permanent magnet on the vehicle contributes to suspension, guidance and propulsion. This is analogous to the way every railroad wheel provides suspension and guidance and can play a key role in propulsion and braking. Without this 3-way combination there is added cost and complexity. For example, Transrapid uses one set of electromagnets to provide both lift and a field for an LSM but requires separate steel rails on the guideway and a separate set of feedback controlled electromagnets on the vehicle to provide guidance. The Japanese low speed HSST and Korean Maglev designs provide lift and guidance with a single electromagnetic structure but require a separate aluminum reaction rail on the guideway and Linear Induction Motor (LIM) primary on the vehicle to provide propulsion. For M^3 the integration of these three functions allows the vehicle magnet arrays to be mounted on pods that can rotate like wheel bogeys to allow sharp turns in both the horizontal and vertical directions.

Figure 2.1 shows a pod with permanent magnets attracted upward to a laminated steel suspension rail. Control coils around the magnets are used for stabilization and windings integrated into the suspension rails provide propulsion. Half-length magnets at the ends of the pod equalize magnetic flux and mitigate cogging. This drawing shows propulsion windings wound on teeth on a guideway rail and suspension control coils wound around permanent magnets on a vehicle pod.

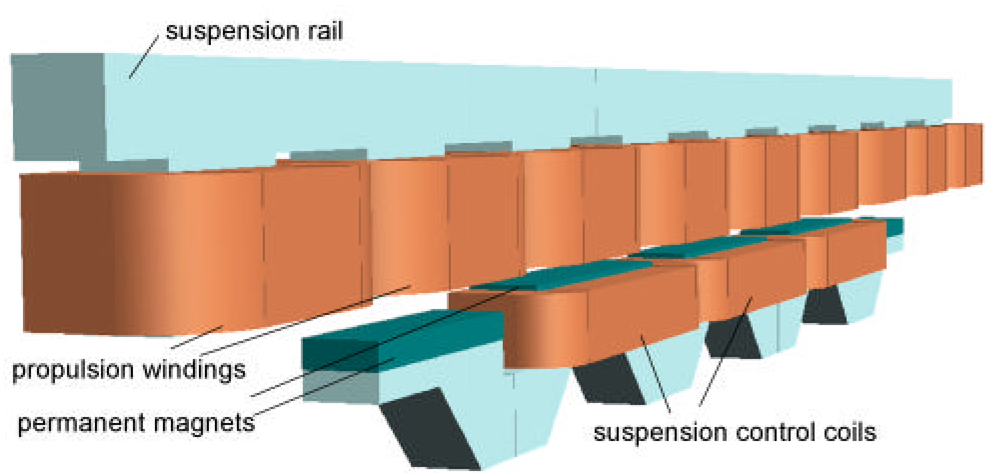


Fig. 2.1. A vehicle's magnet pod attracted upwards to a suspension rail.

Coils wound around the magnets are excited from a controller that uses gap and acceleration sensors to control current in these coils to stabilize the magnetic gap at that value which provides a match between vehicle weight and permanent magnet force. Ideally it would take negligible power to stabilize the suspension and in practice the power requirement is dramatically less than it would be if the entire suspension force were provided by electromagnets alone. When the vehicle is stationary the required control power will be only a few watts and at operational speeds it is expected to be on the order of 100 W per tonne of vehicle mass. For comparison, Transrapid uses electromagnets for suspension and they require 1,000 W per tonne of vehicle mass for a suspension with a magnetic gap of only 10 mm, and require additional power for guidance.

The use of permanent magnets allows the use of a magnetic gap of 20 mm with a corresponding reduction in guideway tolerance requirements. The vehicle mass is estimated to be 7±1.5 tonnes according to the number of passengers onboard. The suspension controller will adjust the magnetic gap to minimize control power and thus the gap will vary ±3 mm; a higher load will lead to a smaller gap and vice versa.

2.2 Lateral guidance and damping

The suspension system must also provide lateral forces to guide the vehicle and resist lateral forces due to turns and wind. An important feature of M^3 is the way the magnets that provide suspension forces also provide guidance forces. If the vehicle is displaced laterally there will be strong restoring forces created by the tendency of the magnets to align themselves with the steel suspension rails on the guideway. By using a magnetic gap that is ¼ the width of the suspension rails it is possible to provide passive guidance with a lateral guidance force up to 33 % of the vertical lift force. Figure 2.2 shows the results of a 3D Finite Element Analysis (FEA) of a 3.25 meter long pod (12 full size magnets and 2 half-magnets at the ends) designed to support ¼ of a baseline vehicle. The plot shows the magnetic gap and lateral guidance force F_z as a function of lateral displacement z_d for a nominal load. With a 20 mm gap there is 16.7 kN of lift force when there is no lateral displacement. With a lateral displacement of 40 mm the magnetic gap would drop to 14.7 mm (to maintain the vertical force) and there would be a lateral restoring force of 0.33 g = 5.5 kN. Vertical and lateral skid-pads will be provided to deal with extreme forces, such as might happen during an earthquake.

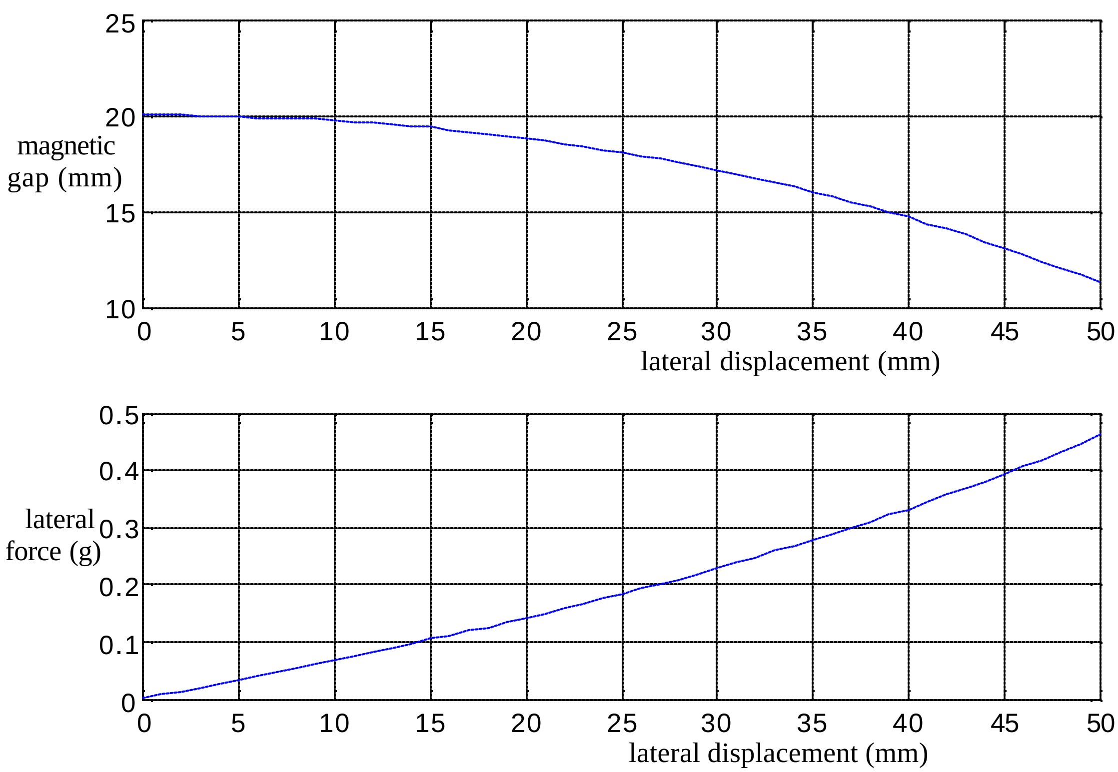


Fig. 2.2. Vertical gap and lateral force vs. lateral displacement.

Although the suspension is passively stable for lateral motion, there is very little damping so other means must be provided to prevent excessive lateral motion. The Japanese HSST and Korean maglev designs have both addressed this problem by using passive damping in a secondary suspension on the vehicle. The M^3 design can use this approach if needed, but an alternative is to use feedback control to achieve the same objective. Further development will determine the most effective way to provide lateral damping.

2.3 Horizontal and vertical turns

Creating a maglev system that can negotiate tight turns has been a challenge to all maglev designers. In a cost-effective design the magnetic force must be distributed over a large area but for making tight turns the suspension magnets must be articulated so that they follow the turn. The M^3 mechanism for doing this is shown in Fig 2.3-5. This preliminary design is for a 24-passenger vehicle that can negotiate horizontal turn radii of 18.3 m (60') and vertical turn radii of 300 m (984'). Improved designs are being studied.

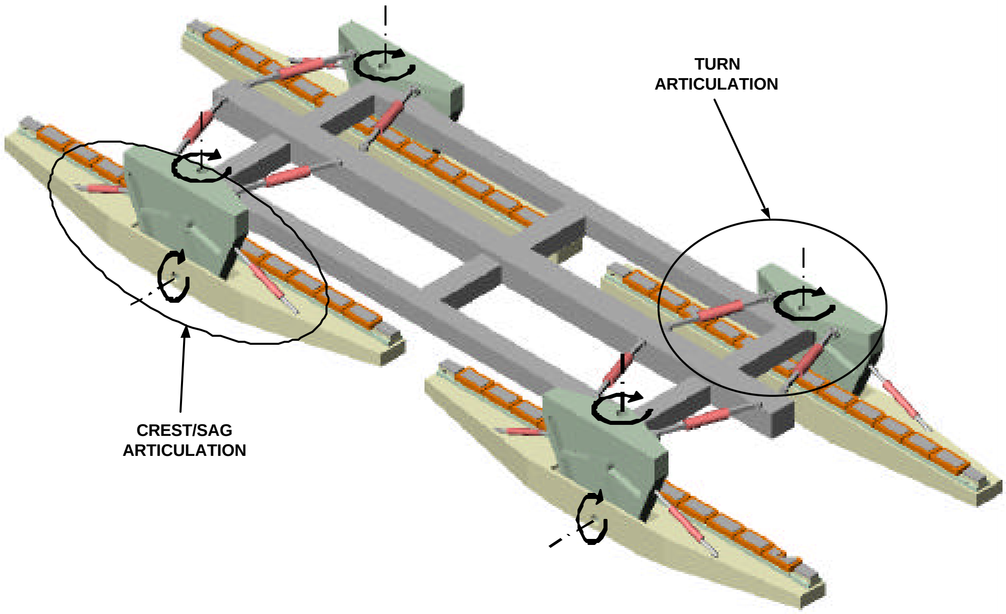


Fig. 2.3. Suspension mechanism showing pod pivoting for turns.

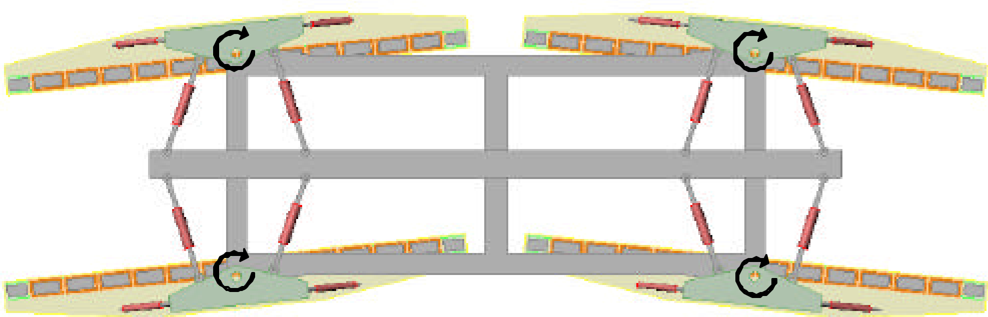


Fig. 2.4. Top view of suspension system.

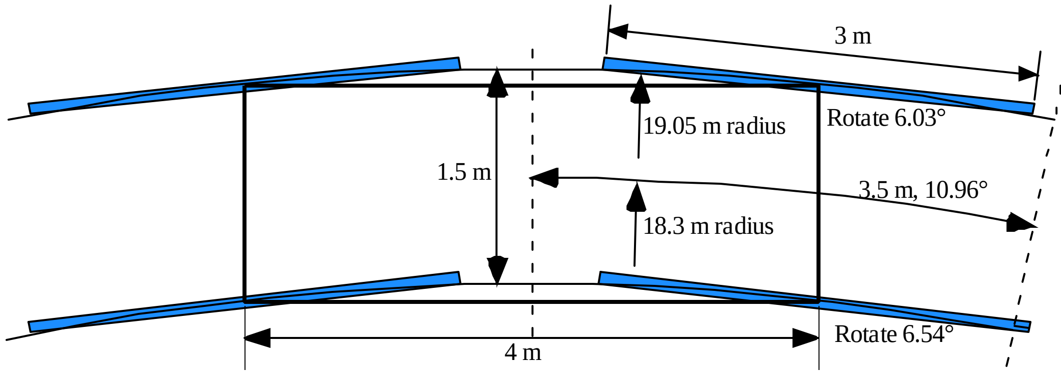


Fig. 2.5. Critical dimensions for pod pivoting for horizontal turns.

3 Linear Motor Propulsion

Maglev developers have universally adopted the linear electric motor as the propulsion system of choice for maglev. There are two types of linear motor that are currently being used for commercial designs: Linear Induction Motor (LIM) and Linear Synchronous Motor (LSM).

The only practical version of the LIM is one that has an onboard motor primary. This design has some advantages.

?? A power inverter is required for each vehicle motor, but the total cost of inverters for a complete system is reduced.

?? The guideway portion of the LIM consists of an aluminum sheet, sometimes on steel backing, and this is less expensive than an LSM stator.

But the LIM has major disadvantages.

?? The vehicle weight is increased by at least 20% because of the onboard propulsion equipment.

?? It is very costly in weight and efficiency to operate with a magnetic gap more than about 10 mm and thus guideway tolerances are more critical.

?? It is necessary to use sliding contacts to transfer all of the propulsion power to the vehicle or, at much greater cost, to use inductive power transfer.

?? The motor efficiency is reduced, both because the motor is less efficient and because the vehicle is heavier and requires more propulsive thrust.

The only practical version of an LSM is one that has the propulsion winding on the guideway, the so-called "long stator" design. This has a number of important advantages.

?? The motor can use the same magnets as the suspension and thereby reduce vehicle cost and weight and increase efficiency.

?? The magnetic gap can be larger.

?? The vehicles are lighter so less propulsive power is required.

?? No need to transmit propulsive power to vehicle.

?? The propulsion and control equipment is all on the guideway so communication is more robust, control is simplified and regenerative braking is easier to achieve.

The disadvantages of an LSM include:

?? Higher cost for guideway-mounted LSM motor windings and wayside power inverters.

?? Precise position sensing is required.

Virtually all high-speed maglev designs use an LSM for propulsion. Early versions of Transrapid used the LIM but starting with TR05 in 1975 they switched to the LSM. The Japanese high-speed maglev developers have always used an LSM. The Japanese HSST and Korean designs use a LIM but they have limited speed capability. A superficial analysis of cost might suggest that LIM propulsion is less expensive but when all of the costs associated with the negative aspects are considered it is likely to be more expensive for a complete system. The dramatic reduction in the onboard power requirements is also a strong incentive for using an LSM. For M^3 with a need for light vehicles and a 20 mm gap the LIM is not a viable alternative. Details of the M^3 LSM design are discussed in this section.

3.1 The tradeoff between cost and performance

An LSM can be designed to give almost any desired performance, but increased performance implies increased cost. The design problem is to find that level of performance that is most cost effective. For example, we could use a smaller LSM that produces less thrust and is less expensive, but then vehicle acceleration is reduced so travel time is increased and we lose many of the advantages of a higher top speed.

For standing passengers it has been generally accepted that an acceleration of 1.6 m/s^2 is an upper limit for safe operation. Since an urban vehicle stops frequently and often has standees it was decided to limit acceleration to this value. In order to be able to accelerate a fully loaded vehicle at 1.6 m/s^2 it is necessary to have more thrust than is necessary for the same acceleration for a nominal load. Thus the M^3 design calls for an acceleration capability of 2 m/s^{2}with a nominal load. This also allows a nominally loaded vehicle to maintain an acceleration of 1.6 m/s^2 up to a higher speed.

In many examples that have been considered there are sizable regions where it is not necessary to provide rapid acceleration or deceleration and in these regions it is possible to reduce the propulsive power with a resulting saving in cost. The reduced propulsive power also implies reduced braking capability from the LSM, but this can be made up by other means, as will be discussed later.

3.2 Block length

An LSM winding on the guideway is divided into sections called blocks and each block is excited by a wayside inverter to provide thrust. An important constraint is that only one vehicle can be in one block at one time. At low speeds and high acceleration we would like to have low winding resistance in order to have high efficiency with minimum inverter rating, but at high speeds and moderate acceleration the power loss in winding resistance is relatively low but the winding inductance plays a major role in limiting performance and leads to a higher VA rating on the inverters. In order to achieve acceptable values of winding resistance and inductance it is necessary to limit the length of propulsion winding that is excited at any time. For M^3 a good choice of block length is in the range 20 to 60 meters. In order to simplify installation it is convenient to match the block length to the guideway pier spacing. In a later section it will be shown that a good pier-to-pier spacing is 36 meters, so this has been chosen as the nominal block length. Near stations an 18-meter block length will be used and in regions where constant speed is the norm the block length may be as long as 72 meters. The combination of block length and inverter size should be carefully chosen so as to provide desired performance at the lowest cost.

3.3 Power distribution and control

Figure 3.1 shows a typical power distribution design. The electric utility provides 3-phase power to a rectifier station that then delivers DC power to a bus connecting the wayside inverters. Typically each rectifier station will provide 1.5 MW nominal power but with a potential for almost twice this value for short periods of time. The spacing between Rectifier Stations is determined by vehicle density and acceleration profiles but will typically be in the range 5 to 10 km (3.2 to 6.4 miles). For the baseline design a spacing of 8 km (4.97 miles) is used,

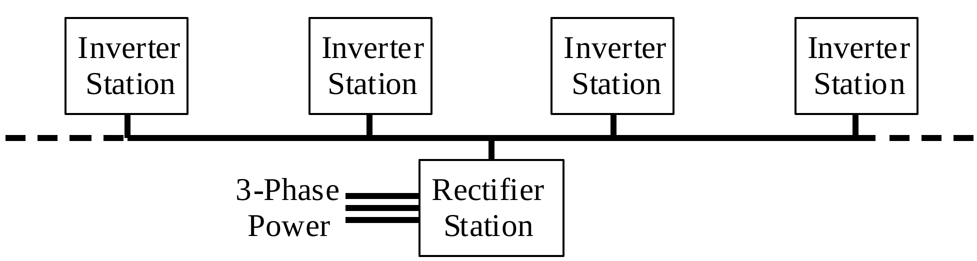


Fig. 3.1. Power distribution system.

The inverters not only provide power for accelerating vehicles, they are also used to decelerate the vehicles and deliver the vehicle kinetic energy back to the DC bus so it can be used elsewhere in the system. The use of regeneration can reduce total energy consumption by up to 40 % for a typical urban application, as will be seen in the next section.

Since only one vehicle can be present in a block at a time, inverter spacing must be short enough to deal with the minimum expected headway. For 4-second headway at 45 m/s we could, in principle, use one inverter to power a block that is almost 180 meters long. We would then use electronic switching to ensure that not more than 36 meters is excited at any one time. The choice between an inverter for every block and inverters that are switched to more than one block will be made on the basis of cost and vehicle headway requirements.

The baseline design uses two DC buses: +750 VDC and –750 VDC. The port and starboard motors are powered from separate buses so as to achieve redundancy against possible failures and to allow the majority of the power to be distributed at the 1,500 VDC level in order to allow longer distribution distances than are commonly used for rapid transit or light-rail. Relatively inexpensive IGBT power devices are now available for operation with a 750 VDC bus but the final choice of voltage will be based on minimizing the cost of inverters and power distribution components. The DC bus is designed to carry 750 kW up to 4 km (2.49 miles) in each direction with a typical efficiency of 97% at full load. The rectifier station will be designed to provide 50% over-capacity for several minutes in order to deal with fluctuations in power demand.

3.4 Performance simulation

Fig. 3.2 shows distance, velocity and power plots for a trip of 3.2 km (2 miles). It is assumed that the vehicle accelerates at a rate that is the minimum of 1.6 m/s^2 and a rate limited by the maximum available thrust from the motor for a nominal vehicle mass of 7 tonnes. For deceleration the LSM is able to sustain a uniform 1.6 m/s^2 for almost the entire stopping time. It is assumed that there are no grades that prevent the acceleration or speed from being sustained. The model used for the plots in Fig. 3.2.includes the effects of aerodynamic drag, winding resistance and power system inefficiency.

For the 3.2 km trip in Fig. 3.2 if the dwell time is 20 seconds the average speed is 27 m/s (60 mph). In order to estimate travel times for other trip lengths assume the speed is 45 m/s for the entire trip but with a time penalty of 30 seconds for every stop plus a dwell time, estimated to be 20 seconds, for every stop. If the trip length is less than 1.6 km (1 mile) then the vehicle never reaches maximum speed so extra time is required.

Power consumption is: 412 kW peak; 113 kW cruise; 65 kW average with full use of regenerated power; and 112 kW if braking energy is dumped in resistors without reuse. For this example regeneration provides a 42% saving in propulsion power cost. The savings would be less for a longer trip and more for a shorter trip.

In some cases more energy is being regenerated than can be used in a useful way and in this case the power must be dumped into resistors. It is possible to add a power dumping facility to each rectifier station, but this is unnecessary. There are at least 20 inverters not being used for every inverter that is being and these unused inverters can be used to dissipate power in the propulsion windings where there is no vehicle. This method of braking is particularly useful when, due to an emergency, it is desirable to stop every vehicle in the system in the shortest possible time. Preliminary calculations show that this can be done without the need for separate braking resistors.

All electrically propelled transit systems create problems for the electric utilities because of the large and rapid fluctuation in power consumption. One advantage of using small, closely spaced vehicles is that starting times can be controlled to minimize the peak excursions. Simulations show that with only minor control of when a vehicle leaves a station it is possible to make full use of regenerated energy and reduce the peak power excursions by a large factor. More detailed simulations are planned when the system design is complete.

A problem that all transit systems must address is the need to deal with electric power failures in a safe and effective way. Probably the least expensive way is to install a modest size standby power generator in every rectifier station. A 50 kW DC generator is adequate to move all vehicles, one by one, to a station where people can be unloaded. Such a generator would add very little to the system cost but provide an important safeguard.

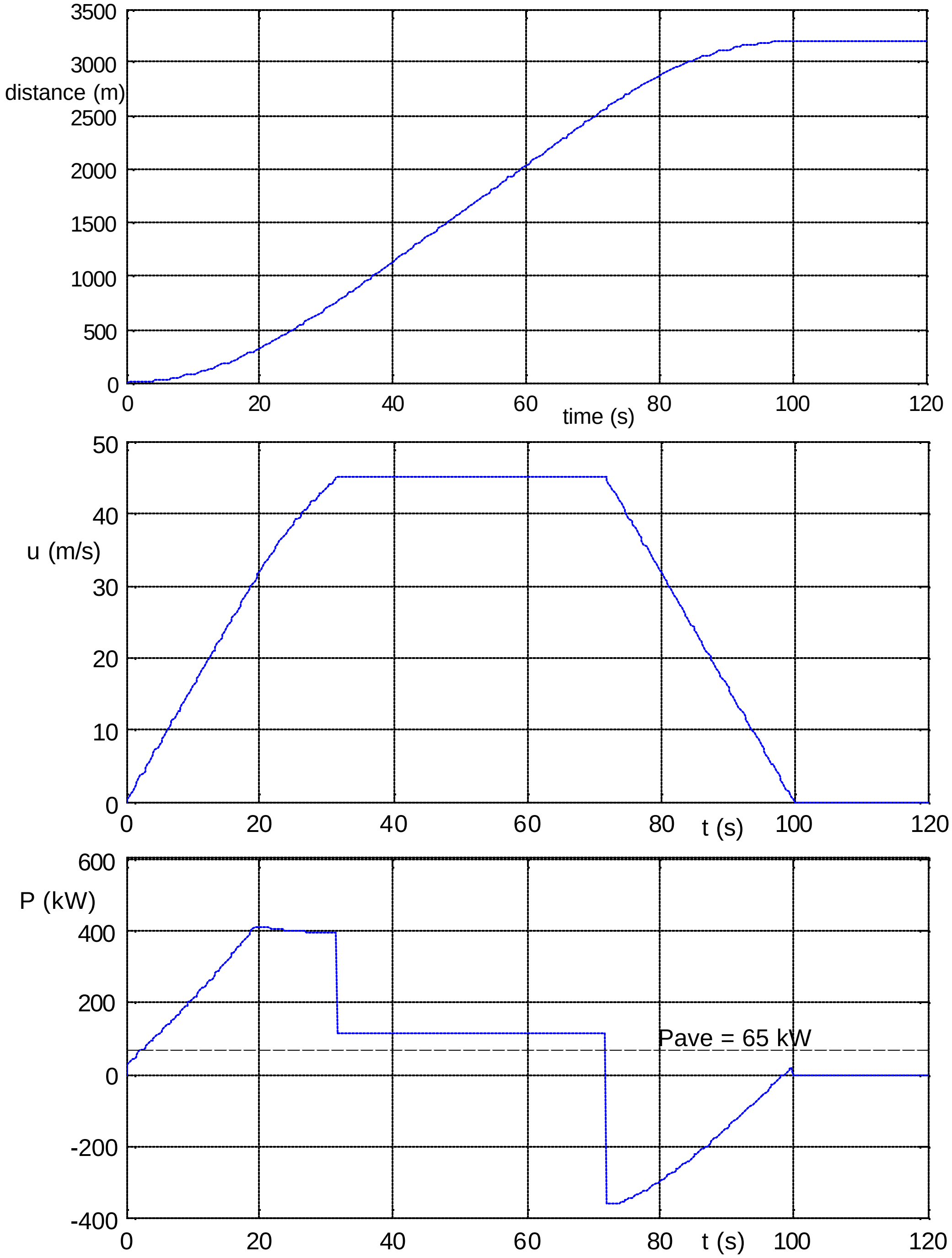


Fig. 3.2. Distance, speed and power profiles for a 3.2 km (2 mi) trip.

3.5 Efficiency and energy consumption

For a transit system energy cost are quite significant. For M^3 it is estimated that for typical usage the motor efficiency will average about 90%. This includes all loss in the stator, inverter and power distribution system. But in evaluating efficiency there are several points to keep in mind:

?? The efficiency of the motor is very dependent on speed and thrust.

?? The ability to use regenerated energy can reduce energy costs by a large factor.

?? For urban applications a large fraction of the energy consumed is related to acceleration and deceleration, not cruise at constant speed. This means that the use of a light vehicle and station-skipping control strategies can greatly reduce energy usage.

One of the best measures of efficiency is the energy usage per passenger-mile of travel. From the plots of Fig. 3.1 we see that the energy usage is 65 kW for an average speed of 60 mph or 3.9 MJ/mile. Assuming a nominal load of 18 passengers this implies a consumption of 217 kJ/pas-mi = 60 W-hr/pas-mi. In order to account for energy for HVAC power usage and other factors, assume the actual consumption is 100 Wh/mi. Assuming electric power cost of $0.12 per kWh, the energy cost is $0.012 per passenger mile. For continuous cruising at maximum speed the energy consumption is 62 W-hr/pas-mi, almost the same as with the stop.

In order to compare M^3 energy consumption with that of other transit systems we need to convert the energy to BTU/pas-mile. The theoretical conversion is 1055 J/BTU or 3.412 BTU/W-hr. For comparison with other modes we need to account for the 29% average efficiency of electricity generation and distribution (see Table B.3 in the reference given following Table 4.1) so the appropriate conversion factor is 11.8 BTU/W-hr. This example shows and energy intensity of 1180 BTU/pas-mile and Table 3.1 shows how this compares with energy consumption for various rail and bus modes.

Table 3.1. Comparison of energy usage of various transportation modes.

	Energy usage, 10^{12} BTU	*Average trip length, miles*	*Energy Intensity, BTU/pas-mi*
M^3			1180
Amtrak	16.2	243	2902
Commuter rail	25.9	22.1	2759
Rail Transit	47.2	5.1	3105
Intercity bus	33.4		964
Transit bus	101.4		4775
Dom. & Int. Air	2743.1	842	3952
Autos & lt. trucks	15680.0	9.1	5669

Data is taken from Tables 2.5-6,2.12-13, 8.12-13 and 12.11-13 in *Transportation Energy Data Book*, Edition 22, Sept. 2002, Oak Ridge National Laboratory (available at www-cta.ornl.gov/data). Data is for 2000 except intercity bus mode data is for 1999.

Care must be taken in interpreting Table 3.1 because of wide variations within any mode. For example, the energy intensity for light rail varies from less than 2,000 BTU/pas-mi for Newark to more than 8,000 BTU/pas-mi for Cleveland. But the conclusion is that maglev has the potential to reduce energy consumption below almost all other modes and, if people will use maglev instead of a car or airplane the savings are huge. If an M^3 system were operated with the same maximum speed and stopping frequency as intercity bus, M^3 would have essentially the same energy intensity. In summary, maglev can offer significant energy savings, particularly in comparison with the modes most used in the U.S. today.

4 Guideway

The focus of the M^3 design effort was to keep the guideway beams as small and light as possible without jeopardizing ride quality. The resulting design is based on deflection considerations, and the strength of the structures is far greater than is necessary so there is no compromise with safety. The relatively small size of the guideway is evident in the artist's rendition on the cover of this report. Note that the pier spacing is relatively large and the beam cross-section relatively small when compared with virtually all other elevated transit systems. For new installation it is believed that most urban maglev systems will use elevated guideways to avoid the right-of-way access and safety problems of at-grade guideways or the cost of tunnels. Maglev vehicles make no wheel or engine noise and very little wind noise at speeds suitable for urban transportation. Many of the objections to elevated guideways are ameliorated by the M^3 design.

In some cases Urban Maglev will operate at-grade or in tunnels and in these cases the beams can have a smaller height with more frequent supports, but the design principles are the same. For example, a reduced height beam could be mounted directly on concrete ties to replace rails in a rapid transit retrofit.

Guideway cost is a dominant item so considerable effort has been made to reduce cost by reducing size and weight. The following sections discuss some of the key details of the guideway design.

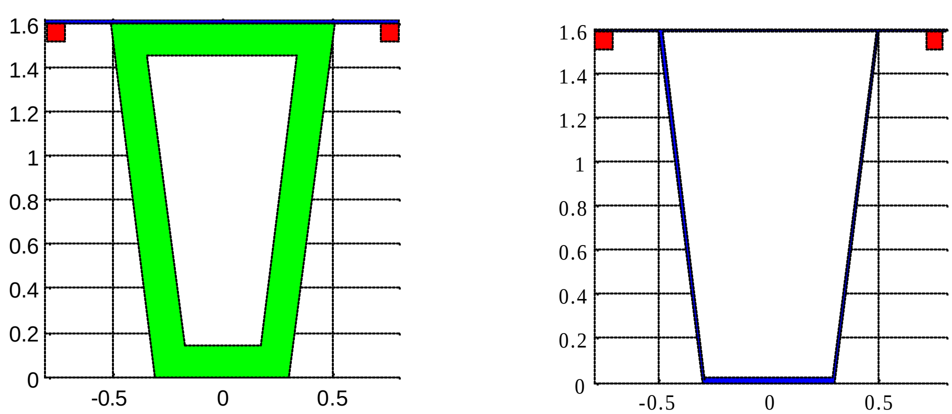
4.1 Beam design

With EMS designs the vehicles must either be supported by an overhead rail or use a monorail type of construction with the vehicle wrapped around the beam and magnets moving under the suspension rails. The overhead design could be useful for indoor use, but is not considered desirable for outdoor use because of the high cost of a support structure and poor ride quality in the presence of high winds.

The MagneMotion guideway consists of beams mounted on piers spaced 36 meters apart. This spacing was arrived at by an iterative process that considered the tradeoff in cost between using more piers and a lighter beam vs. fewer piers and a heavier beam. An additional consideration is a preference to use longer pier spacing because then there is less visual impact. For comparison the new Shanghai Transrapid installation uses a pier spacing of 24 meters but the beams are much heavier so a longer span would be very expensive. The New Millenium extension of the Vancouver Skytrain uses a 37 meter spacing.

It would be possible to make the beam length equal to the pier spacing, but there are major advantages of using a double-span beam. In this case a double-length beam is supported in the middle with a rigid mount and at the ends with a sliding mount. When the temperature changes the beam will change length and slide on the end mounts and enough space is allowed so that adjacent beams never touch. The distributed nature of the suspension magnets allows gaps of 20 mm to be easily bridged. As compared with a single-span beam with the same pier spacing, the double-span beam offers a 30% reduction in static deflection as well as a reduction in dynamic deflection, even though the lowest resonant frequency is the same. In some cases it may be necessary to use single-span beams and then a somewhat large section will be used to maintain adequate stiffness.

Three alternate sections have been studied for the guideway beams: a steel box girder, a concrete box girder, and a hybrid design that uses a concrete box girder with a composite steel top plate. The sections for concrete and steel are shown in Figure 4.1. The hybrid design is similar to the concrete design except that steel crossties used to support the suspension rail are replaced by a solid steel top plate that is bonded to the concrete beam. With the hybrid design the steel that supports the rails also contributes to reducing guideway deflection and increasing the resonant frequencies.



(a) Concrete (b) Steel

Fig. 4.1. Alternate beam section with dimensions in meters.

For all of the alternates a two-span continuous girder configuration is chosen. Horizontal restraint is provided at the interior pier with fixed bearings in the case of the steel alternate, and with a monolithic connection in the case of the concrete alternate. The monolithic connection will use the additional stiffness of the pier to increase the overall stiffness somewhat, and is an economical means of making the connection.

These sections were incorporated into single and double guideway designs. The geometry of the design is dictated by dimensional constraints on the beam, and its connection at the column, which are imposed by the attractive maglev system. A relatively narrow girder is required because of the necessity of the magnetic pods to wrap around and under the edge of the girder with the motor laminations attached to the underside of a plate protruding from the top of the girder. In addition, ride-quality considerations and deflection tolerances suggest a relatively deep girder. Together these two requirements result in a fairly deep narrow girder for which stability must be provided by external diaphragms. Since 4 meters (i.e. from beam center to beam center) will separate the two double-track guideway beams, intermediate diaphragms between the girders are not desirable (though they may be necessary in seismic zones). Stability is therefore provided by "outrigger" diaphragms at the bearings, or by a monolithic connection to the column. Diaphragms must be kept out of a zone of roughly half a meter below the top of the girders in order to allow the magnetic pods to pass.

4.2 Beam statics and dynamics

Guideway beams are designed on the basis of stiffness, not strength. Almost any design that gives good ride quality will be capable of carrying much higher loads then the maglev vehicles will create. The extra strength means, for example, that heavy maintenance or rescue vehicles could safely operate on the guideway if they operated at reduced speed. Since the key issue is ride quality, the important parameters are the guideway deflection under static and dynamic loads and due to thermal deflection and creep. Since beam cost is very nearly proportional to weight, the problem is to design a beam that is as light as possible but provides good ride quality.

For this discussion static deflection is defined as the deflection of the center of the beam when a vehicles move across it at a low speed. Dynamic deflection is defined to be the extra deflection that occurs because of resonances in the beam. Although the beam has an infinite number of resonant frequencies, only the first one or two contribute significantly to vehicle ride quality. The peak dynamic deflection can never exceed the peak static deflection but it can have a major effect on ride quality. We can use precamber of the beam to compensate for nominal vehicle mass but can not use it too compensate for dynamic deflection.

Table 4.1 Properties of the three beams shown in Fig. 4.1.

	Concrete	Hybrid	Steel
Density (kg/m^3)	2,400		7,860
Elasticity (E, Gpa)	30		207
Top thickness (mm)	145	15	15
Side wall thickness (mm)	145	145	13
Bottom wall thickness (mm)	145	45	19
Mass (kg/m)	1,767	1,804	751
EI (N-m^2)	5280	7140	5480
Area (m^2)	0.6149	0.6345	0.0765
I (m^4)	0.1755	0.2421	0.0293
Static deflection (mm)	8.84	6.3	8.51
Thermal gradient deflection (mm)	3	7	9
Creep deflection (mm)	2	2	0
f_1 (anti-symmetrical, Hz)	2.09	2.43	3.44
f_2 (symmetrical, Hz)	3.27	3.80	5.38

All beams have the following properties: double-span 72 m (236') long; 1.6 m (58") high; suspension rails have a 1.5 m (59") spacing between rail centers. For a single span beam the static deflection is 30 % higher.

4.3 Comparison of steel and concrete beams

4.3.1 Live Load Deflections

Deflection and ride-quality considerations, rather than strength, governed the design of both the steel and concrete alternates. Both are operating well below their safe load-carrying capacity. The quantity EI (elasticity times moment of inertia) for the steel alternate is 5500 MN·m^2, while that for the concrete alternate is very similar at 5300 MN·m^2. The live load deflections for the two are 10 mm and 9 mm respectively. The live load deflection of the concrete alternate is slightly lower, even though it has smaller section stiffness, because of the monolithic connection at the interior pier. Preliminary estimates for the dynamic amplification of the vehicle loading were about 20%. A value of 20% has been used in these deflection calculations, and that value will be updated as the design of the system progresses. Structural damping for either alternate will be very small, on the order of 1 or 2%, and will do little to reduce the immediate dynamic effects of vehicle loading, though it will have an important effect on the time the guideway continues to vibrate after the vehicle has passed.

The hybrid section is envisaged as the concrete section with a steel plate attached at the top with sufficient shear-flow capacity to make the plate act compositely with the concrete. The plate would be made thick enough to support the vertical load from the vehicle and windings in transverse bending to transfer it to the girder. It would not be considered for the strength design for longitudinal bending. The increase in stiffness would only be considered for the reduction in deflection that it would provide. The section stiffness EI for the hybrid section is about 7140 $MN{\cdot}m^2$, which would reduce the live load deflection to about 7mm.

The live load performance of the steel and concrete alternates is very similar. The steel alternate exhibits a lower dynamic response because it has a lower mass for the same stiffness, which results in a fundamental period that is significantly shorter than the transit time of the vehicle. The monolithic connection that is possible for the concrete alternate helps to increase it's stiffness and compensate for the fact that it's fundamental period is closer to the transit time and therefore increases its dynamic response. That is, even though its dynamic deflection is greater, its static deflection is less, such that the total deflection is about the same. It is important to note that it is the vertical acceleration of the vehicle that is important, and not the dynamic deflection of the guideway. The total live load deflection, static plus dynamic, is a good proxy for vehicle acceleration, since the vehicle has to travel vertically from zero to the full deflection and back in the time it takes to cross the span. Since the total live load deflections are very similar, the ride quality will be similar as well. The hybrid alternate will have the best live load performance because it has the smallest total live load deflection.

The live load deflections in curved spans will be greater than those in tangent spans because of the additional component from twisting. Moreover, the twist itself will be undesirable if it becomes too great. Deflections were computed for a 20 m span on an 18.3 m radius to determine the possible extent of this problem. A vertical deflection of about 6 mm was found, which is less than that for the typical tangent span, owing to the reduced span length. The maximum twist results in a difference in elevation between the inner and outer suspension rail of about 8mm, which is within acceptable limits. For comparison, the difference in elevation from a 6? superelevation will be 157 mm.

4.3.2 Thermal Deflections

The deflection under live load is not the only consideration for ride quality. Thermal gradients will also contribute to the total deflection. At this stage only vertical thermal gradients have been studied. The effects of horizontal thermal gradients will be considered at a later stage of the study. The thermal gradient for the steel cross section was taken from the Federal Railroad Administration Report No. DOT/FRA/ORD-94/10, *Safety of High Speed Magnetic Levitation Transportation Systems*. The thermal gradient for the concrete alternate was taken from the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications, 2002.

Analyses of the sections for thermal gradients show that the steel alternate exhibits significantly higher deflections under this effect, with an upward deflection of about 9 mm. The upward thermal gradient deflection for the concrete alternate is about 3 mm. The peak temperature for the thermal gradient for the steel structure is higher than that for the concrete, as would be expected. However it is only slightly higher, and the differences in temperature alone cannot explain the large difference in the thermal gradient deflection. The principal cause of the difference is the difference in section geometry. Since the temperature gradient is very steep at the top slab, the thickness of the top slab of the concrete alternate results in an average temperature in the slab much less than the peak temperature at the extreme fiber. In contrast, the entire thickness of the top plate of the steel alternate is effectively at the peak temperature, and therefore tends to cause a much greater curvature in the steel section.

Reflective coatings and/or insulation may be used to reduce the temperature peaks at the surface of the section to reduce deflections. Such treatment would be effective for both concrete and steel alternates, but would obviously be more worthwhile for the steel alternate. Of course the addition of insulation will have cost implications, and perhaps maintenance implications as well.

The situation for the hybrid alternate is not as clear. The temperature in the top plate of this section will probably be higher than what was found for a hollow steel girder, since it will tend to be insulated below by the concrete. However it is probably also safe to assume that the average temperature in the concrete top slab will be less than it is in the concrete alternate. In the absence of any data on the temperatures in such a structure, we have assumed that the steel plate will see the same temperature as the top plate of the steel alternate, and that the temperature changes in the concrete portion of the section will be negligible. In response to such a loading, the deflection of the hybrid alternate is midway between those for the concrete and steel alternates.

4.3.3 Long Term Deflections

The effect of long-term concrete deformations must also be added to the deflections from thermal gradients in order to get a meaningful comparison of the deflections affecting ride quality for the three alternates.

The long-term deflections of concrete can be separated into two components: shrinkage and creep. Shrinkage occurs independently of the applied loads and it does not tend to cause deflections in the superstructure, except for the secondary effect that it has on prestressing loss and the effect it has on column shortening. Creep occurs in response to a sustained applied load and tends to increase deflections that exist in the structure from those loads.

Both steel and concrete alternates will experience deflections due to shrinkage shortening of the concrete column over time. The magnitude of the deflection will depend on the ambient humidity, curing practices and the height of the column. Strains can vary from about 200 to 500 microstrain. For “average” conditions, shrinkage strains that occur after erection of the superstructure on the order of 200 microstrain can be expected. For a 15m high column (column + foundation shaft), a deflection of about 3mm results. Column shortening, however, will not affect the ride quality except at abrupt changes in column height, such as stations and abutments where the difference in deflections between adjacent columns is large. Shrinkage will not otherwise affect the deflections in the superstructure, except that it will contribute to the loss of prestress in the concrete alternate, which will have some small effect of the prestressing deflection.

The creep strain is proportional to the stress in the structure under permanent loading. Permanent loading includes the girder self weight, the superimposed loads from the windings and their supports, and prestressing. Since prestressing will tend to cause curvatures in the opposite direction from dead load bending, the creep deflection from prestressing will counteract creep deflection from dead loads, just as elastic deflections from prestressing will counteract elastic deflections from dead load. Since the creep curvature will depend on the total moment on the section over time, it is convenient to think about a “creep-inducing moment” which is the difference between the prestressing moment and the dead load moment. If the prestressing moment is identically equal and opposite to the dead load moment along the entire structure, the creep-inducing moment will be zero and therefore the vertical creep deflection will be zero. A prestressing design that creates moments equal and opposite to the dead load moments is generally referred to as a “balanced” design, in other words the prestressing balances the dead load.

It is generally not practical or economical to exactly balance the dead load with prestressing. However, in the case of the M^3 system the unusually light live load and girder make it possible to design prestressing that is very close to balanced without an excessive economic impact.

4.3.4 Total Deflections and Camber

For both the steel and concrete alternates, it is possible – and necessary – to camber the girders in anticipation of service deflections. Both alternates will have to be cambered for dead load deflections. The concrete alternate would also have to be cambered for creep so that, with time, those deflections will tend to bring the riding surface closer to flat and level instead of tending to increase the deflections.

Typically for roadway, and even light rail bridges, the girders are cambered to end up “flat” under permanent load deflections. It is also possible, however, to consider cambering the beams for live and thermal deflections. This is especially interesting in the case of M^3, since cambering to counteract live load deflections would reduce the vertical acceleration of the vehicle as it crosses a span and improve ride quality. Though such camber would doubtlessly be beneficial, it will take careful study to determine what the actual optimum camber would be, since it would be necessary to consider the transient nature of thermal deflections, and the fact that the weight of the vehicle is not constant.

The worst-case deflection for ride quality could be some combination of all of the above-mentioned deflections – or no net deflection at all. For example, in the case of the steel alternate, the thermal gradient deflection is a positive 9 mm, while the live load deflection is about equal and opposite to that value. If the vehicle should pass at a time when the full thermal deflection is present, the net result would be that the total deflection due to live load and thermal gradients would be zero, which would be beneficial to ride quality. In this scenario, it is clear that cambering the girder upward to completely counteract live load deflections would be counterproductive.

It should be noted, however, that negative thermal gradients exist in bridge girders as well. Such negative gradients for concrete bridges are presented in the National Cooperative Highway Research Program (NCHRP) Report 276, *Thermal Effects in Concrete Bridge Structures*. Though there is no similar report for all steel box girders to the authors' knowledge, certainly such gradients exist, and present a topic for further study.

Assuming for the moment that the deflection due to a negative thermal gradient is equal to the opposite of half the deflection from positive gradient, it may be that the optimum camber for the steel alternate is some compromise value. A value of about half of the live load deflection (plus the dead load deflection) would be appropriate as a first estimate. This value should be adjusted based on the expected fraction of the time that the thermal gradient deflections exist and their correlation with the operating hours of the system and the expected total vehicle weight during those hours.

In the case of the concrete alternate, creep and thermal deflections would have to be considered as well when figuring live load camber. The creep deflection should be considered from the time that the suspension rail is installed, because the installation will account for creep occurring before that time. In our study this so-called "service creep" results in sag, though that would not necessarily always be the case. Typically the girder would be cambered to arrive at a "flat" condition late in service when creep has run its course. However since the creep deflection could potentially be positive or negative, and it has to be considered in conjunction with the thermal deflections, it is not immediately clear that the same approach would be appropriate for the M^3 system, and the question needs further study. Assuming that service creep results in a sag of 3 mm, and positive thermal gradients result in a hogging that is roughly equal and opposite, something close to full camber to compensate for live load deflections would be appropriate. Table 4.2 shows deflections due to creep, temperature and live loads.

Table 4.2. Deflection Summary

	Creep Deflection	*Peak Temperature*	*Thermal Gradient Peak Deflection*	*Live Load Deflection*
Concrete	-3 mm	23 ?C	3 mm	-9 mm
Steel	N/A	30 ?C	9 mm	-10 mm
Hybrid	-2 mm	30 ?C	7 mm	-7 mm

4.3.5 Horizontal Deflections

The guideway will be subject to horizontal deflections during operations from wind, live loads and thermal loads, which will also affect the ride quality. Horizontal thermal gradients require further study, as discussed above. Horizontal deflections from wind and live loads can be broken down into a guideway-beam component, which comes from horizontal bending in the beams, and a pier component, which is the result of bending in the pier and rotations in the foundation.

In the case of wind, there will be a dynamic structure response, and it will depend on the wind speed, gust characteristics, and the geometry (drag coefficient and natural frequencies) of the guideway. A complete analysis that considers all of these factors is beyond the scope of the current work; however, as a first approximation it is possible to calculate static deflection based on the wind loads given in the AASHTO code. For a 100 mph wind, AASHTO gives a net total pressure of 50 psf (2.4 kPa). Applying this load to the windward beam only, a total deflection of 60 mm is found. Approximately 40mm of that deflection comes from column bending. There will also be a load on the leeward beam, which is not considered in the above numbers. AASHTO stipulates a value of half that for the windward chord for leeward truss chords. If that loading is used for the leeward beam, the pier deflection will increase by about 50% to 60 mm. This is a relatively large deflection, and it may dictate the use of stiffer substructure elements, though horizontal deflections at the top of the pier of up to 100 mm have been allowed for some light rail systems.

Assuming that the vehicle will only operate at full speed in winds of 50 mph or less, the deflection used for assessing the ride quality can be reduced. Since the wind pressure is proportional to the square of the wind velocity, the deflections will be one quarter of those given above, i.e. 15 mm for the piers and 5 mm for the beam.

4.4 Ride quality

The static and dynamic deflection under live load are major considerations for ride quality, but they are not the only ones. Thermal gradients and long-term material deformations (creep and shrinkage) will also contribute to the total deflection. At this stage only vertical thermal gradients have been studied. The effects of horizontal thermal gradients will be considered at a later stage of the study. The thermal gradient for the steel cross section was taken from the Federal Railroad Administration Report No. DOT/FRA/ORD-94/10, "Safety of High Speed Magnetic Levitation Transportation Systems…" and is given in the appendix. The thermal gradient for the concrete alternate was taken from the AASHTO LRFD Bridge Design Specifications, 2002.

In the concrete alternate, the combination of deflections that would cause the worst ride quality is probably creep and live load deflection. The total deflection of live load alone is greater than the combination, since the creep deflection is positive at the point of maximum live load deflection; however, the creep deflection causes double curvature in the span, which would be more unfavorable from a ride-quality perspective. The maximum change in deflection for this combination is about 6 mm and it occurs over about half a span length. Again, efforts would be made to camber the girder to help reduce this effect. A reduction of half of the creep deflection can be reasonably expected.

For both the steel and concrete alternates, it is possible to camber the girders in anticipation of shrinkage and creep deflections. That way with time those deflections will tend to bring the riding surface closer to flat and level instead of tending to increase the deflections. Precamber can also be used to compensate for normal live load, but variations in load and dynamic behavior cannot be compensated.

The seismic design requirements for the guideway for the M^3 system are not fundamentally different from those for other bridge structures. Ideally the foundation and superstructure will be designed to remain elastic, and the columns detailed to respond in a ductile manner, though that philosophy may change depending on the location of the site and the local seismic risks. Further requirements unique to the M^3 system could include maximum tolerable deflection limits during seismic response (for example angle deviations at expansion joints) or buffers to prevent the vehicle from locking up and stopping too suddenly if it bumps up against the guideway. Such additional safety considerations will have to be addressed as the mechanical systems for the vehicle and suspension rail are developed further.

Ride quality is often measured by plotting a spectrum of vertical acceleration vs. frequency (for a vehicle moving along the guideways) and comparing that with an empirically derived limit, such as the International Standards Organization ride quality standard shown in Fig. 4.2.

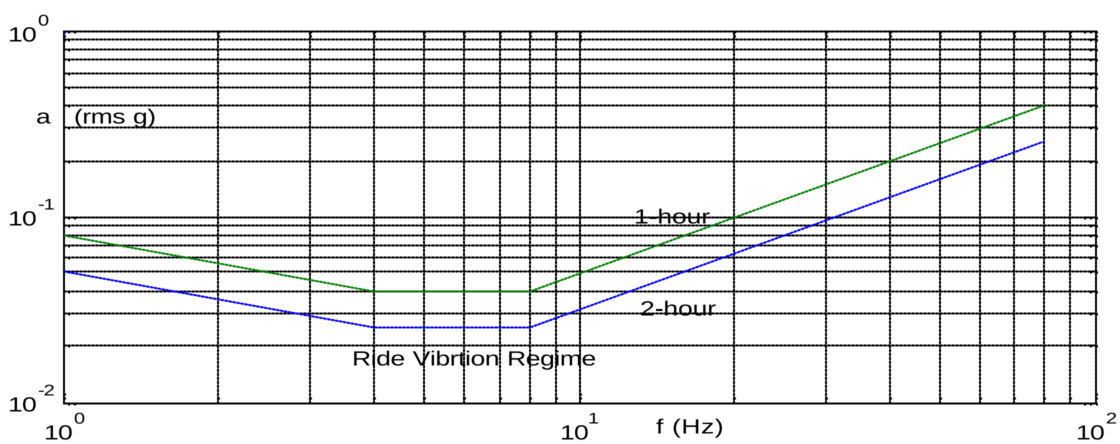


Fig. 4.2. ISO Standard for acceptable vertical acceleration for good ride quality.

. The problem of achieving good ride quality is particularly difficult at high speed because the vertical acceleration tends to increase as the square of the speed. Figure 4.3 shows the computed vertical acceleration spectrum for the baseline vehicle traveling along the hybrid guideway at 45 m/s. This simulation assumes full live load deflection with no precamber and no deflection reduction due to the attachment of the beam to the middle pier, but it neglects deflection due to creep and thermal effects.

The vertical spectrum is dominated by the pier-crossing frequency, 1.25 Hz, and the lowest resonant frequency of the beam, 2.4 Hz, modulated by the beam crossing frequency. There is also some response near the higher frequency beam resonances: 3.8 and 9.8 Hz. Particularly noteworthy is the low amplitude of high frequency components, a result of the distributed nature of the magnetic suspension. More detailed and accurate simulations will be done in later phases of this project, but it appears that the M^3 vehicle can have dramatically better ride quality than the ISO limits given in Fig. 4.2.

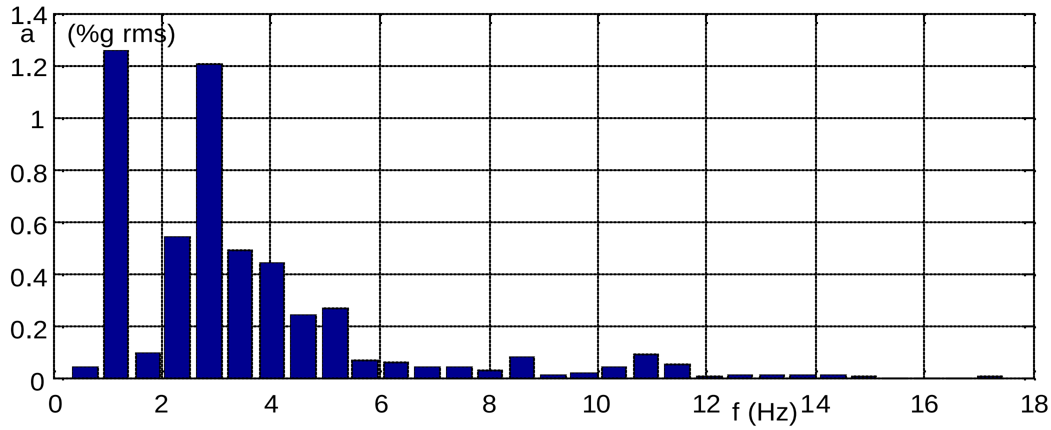


Fig. 4.3. Vertical acceleration spectrum for a baseline vehicle going 45 m/s on a hybrid guideway.

4.5 Structural Issues

4.5.1 Longitudinal Design

Because the guideway design is controlled by deflections, the stresses from service loads are very minor. In the steel alternate the total service stress is less than 20% of yield, and the live load stresses are almost insignificant. The situation is much the same for the concrete alternate, though the stresses are somewhat higher in relation to allowable limits, at least for shear. In the case of a guideway on an 18m horizontal curve, the shear stresses from shear and torsion are still well within acceptable limits. For example, in the case of the concrete alternate the principal tensile stress in the web during service loading is less than one MPa (a value of about 1.5 would be acceptable). The shear stress in the steel alternate is even less compared with the allowable value.

4.5.2 Seismic Design

A seismic analysis of the system following the AASHTO LRFD specifications was performed on the two alternates to verify the preliminary member sizes. A peak rock acceleration of 0.4g and a soil coefficient of 1.0 were assumed, indicating a high seismic zone on firm soil or rock. The foundation was assumed to be a 1.8-meter-diameter single drilled shaft. This foundation type has been gaining popularity in California because of its excellent seismic performance and simplicity of construction. Because continuous girders are restrained longitudinally at the center column and left free to expand at the outer columns, a single column resists the longitudinal seismic actions. During transverse seismic response, the girders span horizontally between columns so that all columns are acting. Therefore the longitudinal response controls the design of the column. At some point it may be worthwhile to consider pinning the superstructure at one outer column in high seismic zones to allow all of the columns to participate in the longitudinal seismic response, however it is beyond the scope of this report to develop the special details required for such a connection.

A 1.0-meter diameter column was chosen for the steel alternate. This alternates lightweight results in lower seismic demands and allows for the use of a smaller foundation and substructure elements. The results of the preliminary seismic analyses indicate that this column and foundation are adequate for the loads suggested by the AASHTO specification.

The key point to consider for the steel alternate superstructure with regards to seismic performance is that it will be supported on bearings. The tall narrow cross section will have to be stabilized either by providing tie-down bearings, diaphragms between the girders at the piers, or by devising a continuous connection between the girders and the hammerhead. Adequate bearing-seat width and restrainers will be provided to prevent loss-of-support failures.

A 1.2-meter diameter column was used for the concrete alternate. With the greater mass of this alternate, the larger stiffness keeps the displacement at acceptable levels. The same diameter drilled shaft is used, though it will require a greater steel content and penetration into the founding rock or soil.

Stability is provided by the monolithic connection at the interior pier. As with the steel alternate, shear keys, adequate seat width and restrainer cables will be required to maintain support at the expansion piers.

4.6 Conclusions and Recommendations

All of the three alternates developed in this preliminary study would be acceptable for the guideway for the M^3 system. An effort was made to achieve approximately equal performance between the three alternates so that the cost comparisons would be meaningful. The authors believe that this has been achieved more or less, though the different characteristics of concrete and steel have made exact equality impossible. The one that could possibly be called an outlier is the hybrid alternate, which has significantly greater stiffness and therefore lower live load deflections. It was necessary to develop it in this way, however, due to the nature of the construction technique envisaged.

It is difficult to decide which alternate is would be preferred, and probably impossible without knowing the site, length of the project, and local construction conditions. In general, though, it is reasonable to conclude that the concrete alternate will be the least expensive by a significant margin. It is also likely that it will require the least maintenance and have the lowest lifecycle cost. This will be borne out in most locations in the United States, though there may be some places where steel may be less expensive because of local contractor experience and availability of the materials.

It is difficult to say which alternate will perform the best in terms of ride-quality. The live load deflection response is similar for steel and concrete, with the concrete having a slightly greater dynamic response but a smaller static response. The total deflection of the hybrid is the lowest, giving it the best live load behavior. The price premium of the hybrid alternate over the concrete alternate is essentially paying for improved ride quality.

The thermal deflection of the steel alternate causes its greatest performance problem. Though the vertical gradient causes a significant deflection, the deflections from horizontal gradients are likely to be a worse problem and need further study. We believe that insulation and reflective coatings will solve this problem, but at some as yet unknown increased cost.

Creep deflections are the greatest concern for the concrete alternate, and although they could theoretically be limited to acceptable levels, uncertainties about actually being able to correctly predict them add a greater risk to this alternate. The hybrid alternate faces the same construction risk from creep, and the additional uncertainty about our ability to attach the top plate with sufficient stiffness and strength. It is expected that it will be possible to construct all of the alternates within adequate dimensional tolerances. Although past experience has shown that the tolerances actually achieved for both steel and concrete may be at the limit of what is needed, it should also be recognized that the current technology has been developed to deliver only the tolerances that have been required by road and rail bridges, and it should be expected that improvements for both materials can be realized if required for the M^3 system.

Based on our findings to date, there are potentially considerable advantages to the concrete alternate for its lower cost and its thermal-deflection characteristics. Its principal detractions are the uncertainties involved with creep deflections and the attendant construction risk. The advantages are significant enough though that it is advisable to construct a test segment to quantify and understand the risks. We recommend therefore that a prototype system of limited scale be built using concrete. Depending on the scale and end use of the system, it may be appropriate to build all of it, or only a portion of it in concrete, and the rest in steel. A cast-in-place structure would probably be the best choice, as it would be the most appropriate for a guideway of limited length and would still allow us to study the dimensional stability of concrete.

Several other important issues remain to be studied at this stage. Horizontal deflections from thermal gradients will likely cause deflections equal to or even larger than the deflections from vertical gradients. Since horizontal accelerations are more disturbing to passengers than vertical accelerations, this is an important area to study. Work needs to be done to determine the horizontal gradients that will exist in concrete and steel structures, and change the cross sections if necessary, to limit the deflections set up by these gradients. We recommend that both the steel and the concrete alternates be advanced through this next stage.

Likewise, it will be important to consider horizontal accelerations from wind and live loads. The effect on those accelerations from deformations in the substructure should be considered in evaluating these effects. Work to be done includes determining the aerodynamic properties of the cross section, the response of the structure to a generic wind climate, and the effect of wind oscillations on vehicle performance. For live loads, additional rolling-stock type analyses should be performed for various guideway parameters to determine acceptable limits for foundation stiffness, pier height, etc. Work to optimize the span lengths for curves of various radii would also be warranted.

The mounting hardware for the suspension rails is probably the most important item to develop. It needs to allow for easy adjustment both horizontally and vertically. If it were possible to develop hardware that allows for rapid and economical readjustment, then it would be possible to assume more risk in the dimensional stability of the initial construction, and would help greatly in eventually developing the lowest cost guideway.

5 Vehicle

MagneMotion is working with vehicle manufacturers to estimate the cost and weight of a vehicle. Figure 1.1 shows an initial vehicle design with articulated magnet pods for suspension on a guideway with LSM propulsion. An improved design will be developed in a future phase of this project.

The lack of any onboard propulsion equipment simplifies the interior design and makes it possible to put HVAC and other equipment in the nose and tail where streamlining prevents use for passengers. This reduces drag and lowers the center of gravity, both important for this application.

The primary suspension is provided by the magnets but there may be a secondary suspension that has two components: the magnet pods have pivots with dampers so as to allow tight turning radii in both horizontal and vertical directions, and pneumatic springs allow improved ride quality and can, if desired, provide active control of ride quality, including tilting.

Ride quality is often measured by determining the frequency profile of the vertical acceleration and comparing this with desired limits based on subjective experiments with passengers. The amplitude of most of the terms in the spectrum will increase at least as fast as the speed and in some cases they vary as the square of the speed. Hence reducing speed will almost always improve ride quality so the magnetic suspension by itself is adequate for lower speed applications. The maximum speed for which a secondary suspension can be omitted will be determined in a later phase of this project.

Preliminary estimates indicate that a 24-passenger vehicle will weigh about 5.5 tonnes empty and cost about 330 k$. For comparison, a typical articulated light rail vehicle weights 40 tonnes empty and costs about 2,500 k$. The light rail vehicle has a crush load capacity of about 200 passengers, but in typical operation it only takes 3 24-passenger maglev vehicles to provide the same capacity as one light rail vehicle because of the higher average speed. Thus maglev vehicle cost less than half as much as for light rail and maintenance cost should also be much less. The improved comfort for passengers is a bonus.

5.1 Issues involved in choosing vehicle size

European and Japanese maglev developers have always viewed maglev as a modern form of train travel with the potential for higher speeds, lower maintenance cost, etc. The German Transrapid and the Japanese high-speed designs all use multicar trains with each train carrying several hundred passengers and train spacing of several minutes. In contrast, U.S. maglev developers have always thought of maglev as form of bus or airplane with a preference for smaller vehicles operating more frequently. All 4 designs that resulted from the U.S. 1992 National Maglev Initiative recommended the use of individual vehicles with capacities less than a 100 passengers. Following are some of the advantages of each approach.

Advantages of using larger vehicles or trains:

?? Lower labor cost when operated manually
?? Higher capacity is possible
?? Lower aerodynamic drag per passenger
?? Vehicles are less expensive per passenger

Advantages of using smaller vehicles:

?? High vehicle frequency
?? Reduced propulsion power per vehicle
?? Platoons are more versatile than trains
?? Fewer stops per vehicle
?? Easier to reuse regenerated energy

For automated operation at speeds up to 45 m/s (101 mph) the advantages of using smaller vehicles are substantial. The use of a linear motor that does not depend on friction for braking makes it possible to operate with very short headway and hence the capacity advantage of a train is eliminated. At these speeds and for urban use the aerodynamic drag is not the major power consumer. The vehicle cost advantage disappears if the vehicles operate with higher top speeds so that fewer vehicles are required. If the operating speed were to increase by a factor of 2 to 3 there would be merit in some increase in size but there does not appear to be any operational advantage of using a long train for maglev.

5.2 Vehicle design for the M^3 system

For urban use at speeds up to 45 m/s the M^3 design is based on a vehicle that can carry 24 passengers seated and another 12 standing. When operated with platoons and 4-second headway within a platoon this size vehicle can transport up to 12,000 pphpd.

For lower speeds and capacities a smaller vehicle can be used. Our baseline design for a smaller vehicle is one that carries half as many people as the high speed version.

5.3 Secondary suspension

The magnetic suspension can, by itself, provide good ride quality at low speeds but for operation at the maximum speed there are advantages in having a secondary suspension to improve ride quality. The secondary suspension design will be addressed in a later phase of this project.

6 Control System

6.1 Introduction

For any modern mass transit system a digital control system is required. There are many ways to implement such a control system, and one concept is presented in this chapter. Only the high level concept of a control system is described here – there are many details of implementation that are left out for the sake of a concise, readable document.

6.1.1 Goals

Any control system for people movers should be designed with the following goals in mind:

?? Safety
?? Reliability
?? Efficiency
?? Flexibility (Expandability)
?? Effective Fault Handling

The most important goal of the control system must be safety. According to USDOT 2001 highway fatality statistics, more than 40,000 people died last year in automobile crashes (a fatality rate of 1.52 people per 100 million vehicle miles traveled). While the general public accepts this rate, they hold mass transit to a much higher standard, with outrage at any deaths on a public transit system. Thus, safety must be the primary goal of the control system.

The transit system should also be reliable, such that avoidable traveler delays are minimized, and should be efficient, so that the transport resource is used to near its full potential (and not significantly limited by the control system). This ensures maximum return on investment.

The control system should also be flexible, to be easily used for transit systems of differing types (shuttle vs. network) and variations in demand. At the same time, it should be expandable so that the system can be upgraded with additional guideway with minimal impact on existing routes. Finally, the system should have carefully planned fault handling to deal with problems as they occur, of both expected and unexpected types.

6.1.2 Experience

The control system concept proposed in this document is based, in part, upon a concept implemented successfully in an installation of a material handling system in an industrial factory carrying sensitive parts. The installation is capable of carrying more than 1000 vehicles per hour per lane. Note that while the concept will work for a transportation system carrying people, the actual implementation would be different due to more stringent safety standards for people movers. Nevertheless, the proposed preliminary control scheme concept is valid and based upon proven methods.

6.2 Architecture

The architecture for the proposed control system is a hierarchical one. A hierarchical control system has benefit of expandability. As the system grows, more modules are added at each of the lower levels (at some point it may be necessary to add another layer). The hierarchical system also minimized communication and required processing power, as each function can be implemented at the appropriate level. Fig. 6.1 illustrates a concept of such a hierarchical control system. Note that a control system for a simple shuttle may be significantly simpler (2-layer). The control architecture here is designed to implement the control strategies of Section 6.3.

In this concept, the block controller performs the following functions:

?? Constantly tracks position of vehicle
?? Closed-loop control of vehicle according to order from zone controller
?? Drives the linear motor
?? Keeps track of vehicle state information, vehicle ID, position, velocity, etc.
?? Communicates with adjacent block controllers & Zone (& Possibly vehicle)
?? Motor Synchronization / Vehicle Handoff / Liftoff, Estop, etc.
?? Monitors status of block and inverter

The zone controller performs the following functions:

?? Constantly tracks position of vehicle
?? Monitors Status of Power System, Block and Switch controllers
?? Vehicle Coordination (multiple vehicles)
    o Grants movement permissions to vehicles (& blocks)
    o Ensures adequate vehicle spacing
    o Implements safe merge strategies
    o Responsible for vehicle protection functions
?? Reports Errors to Central Controller
?? Interfaces to station controllers
?? Tracks vehicle information (ID, routing, etc.)

The Central controller performs the following functions:

?? Performs global optimizations
    o Vehicle selection and routing
    o Manages vehicles
    o Performs switching decisions (vehicle routing)
?? Displays system condition to operator
?? Records/reports fault conditions
?? Tracks network statistics
?? Communicates with all controllers

- o Uploads software updates to entire control system
- o Diagnose system problems

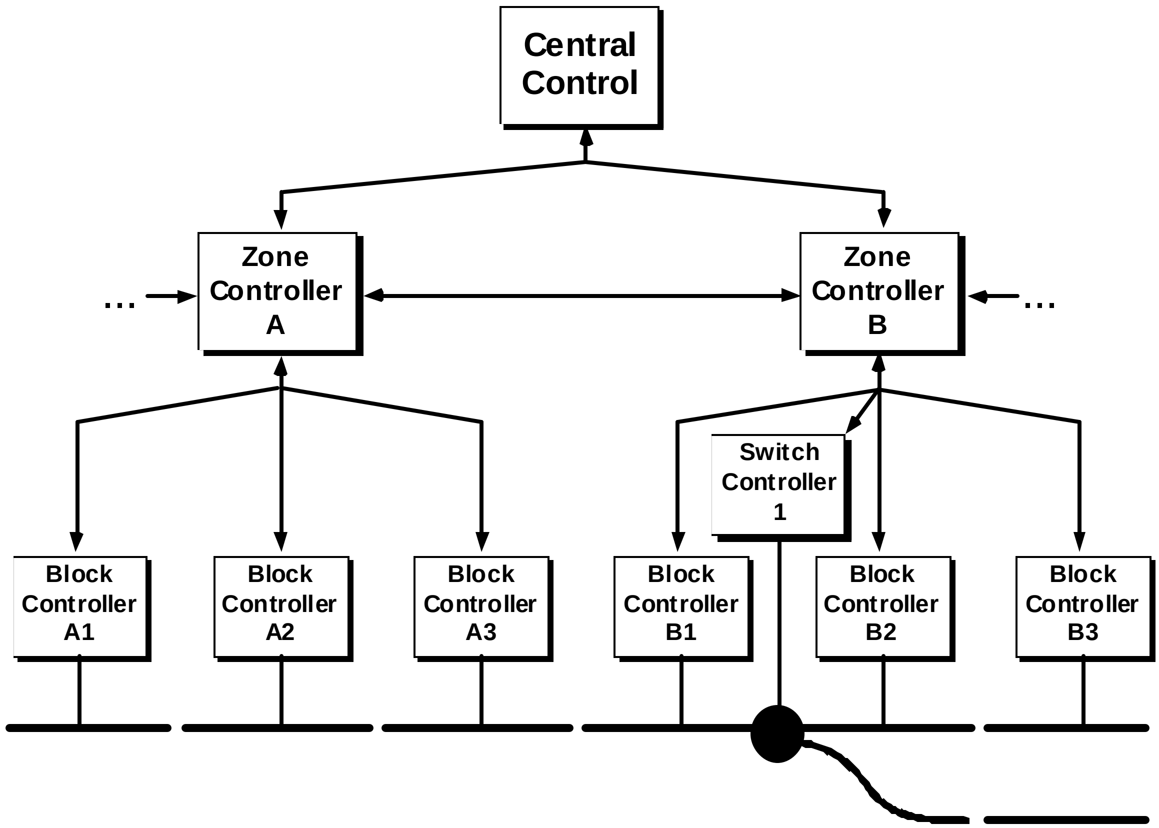


Fig. 6.1. An example of a hierarchical control system.

6.3 Preliminary proposed control scheme

The following control scheme is based upon a previous control scheme implemented by MagneMotion. It is only a preliminary concept and needs to be fully adapted to a people-mover application. It is designed to match the one-vehicle-per-block constraint of a linear motor based system.

6.3.1 Constraints

The design of the proposed control scheme was strongly influenced by the system constraints. The limitation of one vehicle per LSM block in the system imposes a significant constraint on how the system is operated. The system must ensure that under any normal set of operational circumstances, each vehicle must be in a separate block. In addition, due to the fact that the stopping distance for a vehicle may be several blocks, each vehicle must at all times have a dedicated block for the vehicle to stop, where no other vehicles are allowed.

Other constraints include the headway criteria, emergency egress points, stop exclusion areas (in switches, etc.), and emergency stop capabilities. A variety of headway constraints may be imposed on the system, including “brick-wall”, slightly less conservative “safe” headways, and “platoon” headways.

“Brick wall” headway is defined as the minimum headway between vehicles such that if a vehicle comes to an immediate stop (e.g., hits a brick wall), the following vehicle will be able to stop in the intervening distance. A “safe” headway is defined as the minimum headway between vehicles such that if a vehicle applies maximum braking, the following vehicle will be able to stop without collision. “Platoon” headway is a specified headway between vehicles, which may be significantly shorter than the other two types, with the inter-vehicle spacing tightly controlled (with the assumption that if a vehicle operates incorrectly, other vehicles within the platoon will have only a small difference in velocity, minimizing damage in a collision). In this system, these definitions are further amended to mean that a following vehicle will stop in the block before the preceding vehicle.

Finally, there are the ride quality and performance constraints of the system, described as acceleration and velocity limits.

6.3.2 Waypoint (target) concept

The topology of the track, from the standpoint of the control system, consists of a set of LSM blocks and an ordered set of locations in those blocks called 'waypoints.'

Several types of waypoints are defined:

?? Target Waypoint
?? Diverge Waypoint
?? Merge Waypoint
?? Junction Waypoint
?? Speed Sign Waypoint

The proposed system is based on a 'target' waypoint concept. A target waypoint is a location on a track where a vehicle is given permission to stop. Each target may be 'held' by a single vehicle only. The basic system operation is based on the granting and relinquishing of targets to vehicles. The movement of the vehicle is based upon the requirement of a vehicle to stop at the last target it was granted. Ideally the vehicle will move at maximum velocity and acceleration consistent with stopping at the target location, resulting in the shortest possible transit time. In actuality, some margin must be allowed for dealing with unexpected contingencies.

A diverge waypoint is the location at which the track bifurcates. A merge waypoint is the location at which two tracks converge. A junction waypoint is the boundary between two zones. When a vehicle crosses this boundary, one zone hands responsibility for the vehicle over to the next zone.

A speed sign waypoint indicates the allowed speed on a section of track. A vehicle must not move faster than the limit of the last speed sign passed, and must also move no faster than the limit of the next speed sign at the time the vehicle arrives at its location. Thus, each vehicle obeys the limits of both the last speed sign passed, and the next one in front. When a speed sign is passed, the next speed sign is acquired.

6.3.3 Target placement

Targets would typically be placed at the end of each block. When a vehicle stops at such a location, as soon as it is allowed to move again, it clears the block in the least amount of time relative to other possible target positions in the block. Thus, other vehicles may gain entry to the cleared block quickly. When several vehicles are queued up (one per block), they will move out most quickly with this placement. Fig. 6.2 shows placement of several waypoints along with velocity profiles for three of the targets. Each vehicle must plan on stopping at the last acquired target until it acquires a new target. The dashed lines represent the planned velocity profile (verses time) stopping at each of three targets. The vehicle will only follow the dashed stopping profile in the case that the following target is not free to be acquired.

Another possible location for targets on high-speed portions of a guideway layout would be at emergency egress points near supports. Thus, in the case of a system stop, vehicles would already stop at the egress points and not have to move later, and would prevent the necessity to walk on the guideway to get to an egress point.

Targets would also be placed at station stops, and any offline parking locations.

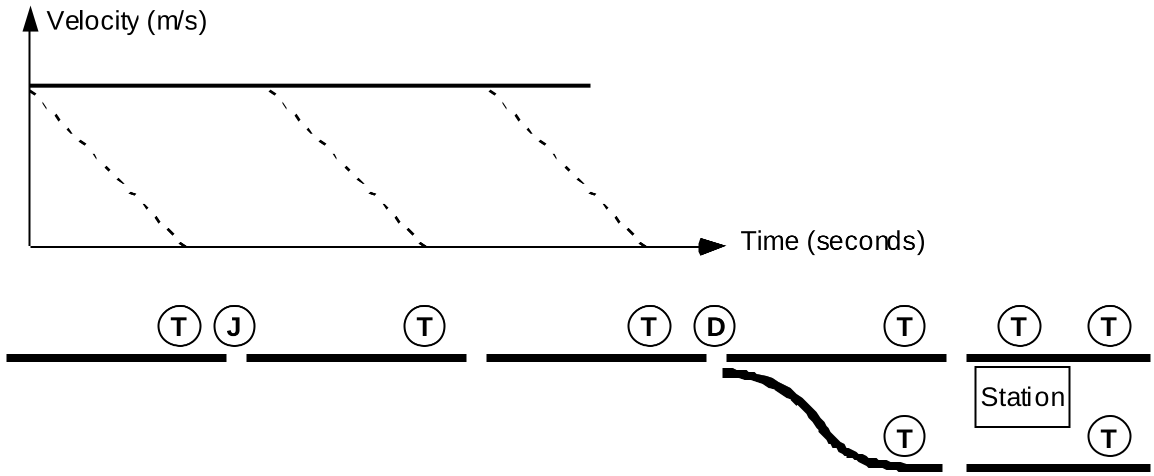


Fig. 6.2. Waypoint placement and velocity profiles.

6.3.4 Target acquisition

In the proposed control concept, a new target is requested for a vehicle when:

?? The current target is not the destination of the vehicle, and

?? The vehicles speed is impacted by the location of the current target

If the vehicle's current destination is the target, then the vehicle should stop at that location, and thus does not request a new target. A short time before a target location begins to impact vehicle movement (when a vehicle must start slowing down, or limit its acceleration due to the target position), a new target is requested for the vehicle.

One benefit of requesting a target only when necessary is that in the case of a system shut down of some type, the vehicles come to a stop as quickly as possible at their assigned targets (which may be egress points and station bays). This is also a type of fail-safe mechanism, such that if a higher-level control is inoperable or not communicating, no new targets are granted and the vehicles come to a quick stop. Also, an emergency stop can be implemented by means of denying all new target requests, and the vehicles all stop at predictable locations outside of exclusion zones (and again, often at station bays or egress points (in the small chance that they need to be used)).

When a new target is requested for a vehicle, the control system parses the list of waypoints in search of a new target. As the system parses the list, it performs certain checks at each waypoint to ensure that it is safe to grant a new target at or beyond the waypoint.

As the control system searches the ordered list for a new target, and comes across a diverge, the system checks to see if the diverge is operational and in the correct position. If operational and in the correct position, the system searches along the correct path (according to the switch settings of the vehicle's order) for the next waypoint. If not operational, the target request is rejected (no new target granted). If the switch is operational, but not in the correct position, the switch is commanded to move to the correct position (if not already) and the target request is rejected. Upon a subsequent request, when the switch is in the correct position, the system searches for the next waypoint along the correct route. A merge waypoint operates in a similar manner to a diverge waypoint. Thus, a vehicle must be prepared to stop at the target before a switch until the switch is operational and in the correct position.

A junction waypoint on the path indicates that the target request should be forwarded to the zone adjacent to the boundary (no new target is granted until a response is received from the adjacent zone). The adjacent zone then continues with the target search, parsing its own list starting with the junction.

When a target search reaches a new target, further checks are made before the target is assigned. If the block that contains the target is not operational, the target is not granted. If the target is assigned to another vehicle, the target is not granted. Otherwise, the vehicle is granted the new target.

6.3.5 Target release

The target release criteria can be used to implement different headway strategies. The release mechanism used must ensure that two vehicles are never assigned targets in the same block, and that each vehicle always has an assigned target.

One possible strategy is to release the targets in a block when a vehicle has completely exited the block (the entire vehicle is in the following block). This strategy results in "brick wall" headways between vehicles, since a vehicle must be tasked to stop at a target in a block prior to the preceding vehicle. As previously stated, a vehicle is moved in such a fashion that it is always able to stop at the last target granted to the vehicle, and in this case no target will be granted in a block which already contains a vehicle.

Another strategy is to release the targets in a block when a vehicle is, at maximum deceleration, no longer able to stop in the block. Thus, targets may be released for a vehicle in a block before the vehicle passes the block (and to do so, the vehicle must have been granted a separate target downstream at which to stop). This strategy results in "safe" headways.

Finally, for platooning, one several strategies may be used. If the platoon spacing is always at least a block length, then one of the above strategies may be applied to each platoon, as opposed to each vehicle. The releasing of targets must be based upon the location of the last vehicle in a platoon. In another possible platooning strategy, one of the first two prior strategies is again used for releasing targets by the last vehicle within a platoon. A target held by a preceding vehicle within a platoon may be released to the immediately following vehicle as long as the preceding vehicle has acquired a target in another block. This strategy will easily allow for non-standard sizing of blocks, and each vehicle will still have a dedicated block in which to stop. To summarize, one of the first two methods is used for spacing platoons rather than vehicles, and another layer of control is added to ensure adequate spacing between vehicles within a platoon.

6.3.6 Benefits

The proposed scheme is able to meet high throughputs in a safe manner while respecting the one vehicle per block limitation. It is flexible in terms of the headway strategy used, and easily expandable. Through proper target placement, the algorithm supports such design goals as sub-block switching and can limit the loading of support structures by limiting the number of vehicles on a particular track section. The scheme, through proper placement of targets, can also support stopping only at egress points along the guideway

This system is fail-safe in the sense that when a controller or a communication link is not operational, new targets are not granted and the vehicles come to a stop at their last acquired target.

6.3.7 Operational strategies

To exploit the full capability of the transport system, certain strategies may be used. In a high speed urban system with on-line stations, it will likely be necessary to use multi-bay stations to achieve desired throughput, as shown in section 6.4.2.

High-level control strategies may be layered on top of an existing control system by the central controller or at the track layout stage of design. For instance, greater throughput may be acquired by using strategies such as selective station servicing, where every vehicle does not stop at every station. Each vehicle may, for instance, service two out of every three stations, with different vehicles serving different sets. A passenger can still move from his origin to his chosen destination by selecting the correct vehicle or by changing vehicles. Since fewer stops are required, greater throughput may be achieved. Also, demand-based station servicing may be used. For instance, vehicles may skip stations where there is no demand (which would require knowledge of the destination of each passenger). Platooning strategies may also be used to improve throughput. These topics will be the subject of future work.

6.4 Preliminary simulation

Preliminary simulations were performed to examine the basic limitations of the system. One such limitation is line throughput – the maximum capacity of the line. Using some basic assumptions, it was discovered that with a 'safe' headway, the line has a capacity beyond the goal of 12,000 passengers per hour per direction (pphpd). The next most significant limitation investigated was throughput limitations of the stations, as they were assumed to reside on-line. The simulations described below focus on the limitations presented by the necessity to stop at on-line stations. With certain operational strategies, the simulations showed that the target throughput could be met with on-line stations.

6.4.1 Assumptions

The simulations were performed using the assumptions for performance and operational strategies given in Table 6.1.

Table 6.1. Simulation Assumptions

Item	*Value*
Max Acceleration	1.6 m/s^2
Station Type	On-line
Headway Type	“Safe”
Dwell Time	15 s
Block Length at stations	18 m
Max Velocity	45 m/s
Vehicle Occupants	36

The simulations were performed based upon a crude model of the control system previously described. The stopping point for each vehicle (station bay) was assumed to be at the end of each block within the station. The assumed acceleration was based upon passengers standing in the vehicle to achieve maximum capacity.

It should also be noted that the throughput improves when shortening blocks, due to the constraint of one vehicle per block. Most of the benefit of shortening blocks is achieved by 18 meters, but additional capacity may be gained by shortening the blocks within stations further.

6.4.2 Results

Preliminary simulations were performed with a range of one to five bays per station. It was assumed that for multi-bay stations, a fleet of vehicles would move into the station, dwell, and leave the station. A fleet of vehicles is made up of the number vehicles that fit in the station at once (the number of bays in the station). To calculate throughput, the time was calculated from the start of the exit of one fleet of vehicles to the arrival of the next. This time was added to the station dwell time to realize the total time that the fleet occupied the station. From this value, the average throughput may be calculated. Fig. 6.3 illustrates a scenario with 4 bays and 6 vehicles. As the first fleet of four exits, the next vehicles enter and stop at the first two bays in the station.

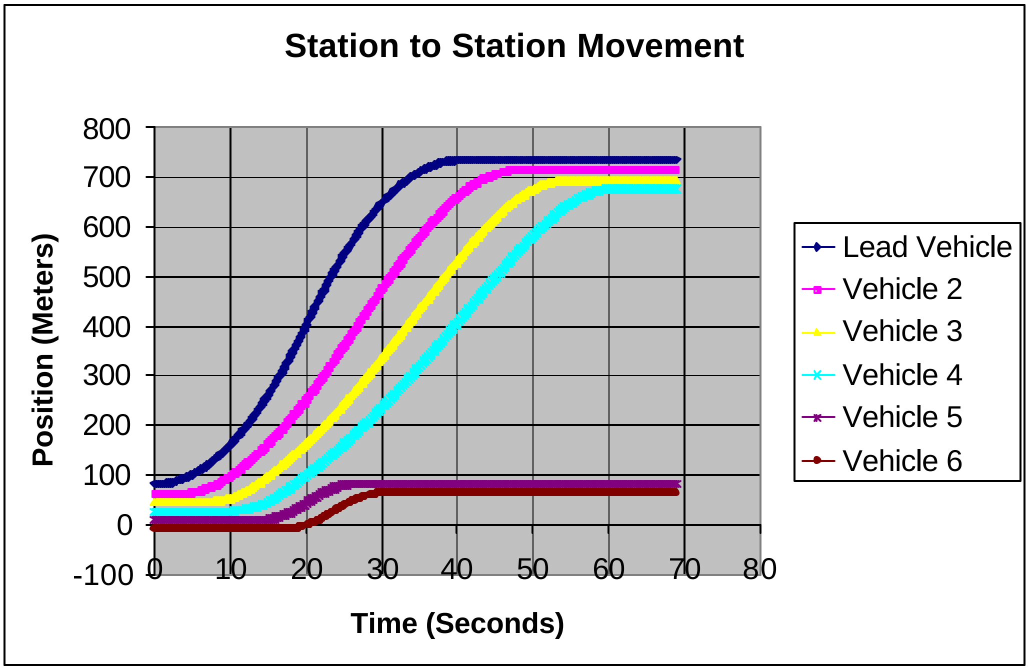


Fig. 6.3. Typical Simulation of a 4 bay station with 6 vehicles

A summary of the results illustrated in Fig. 6.4. Note that a minimum of four bays is required to achieve the desired metric of 12,000 pphpd. Selective stopping strategies may further enhance throughput, or reduce the required number of bays.

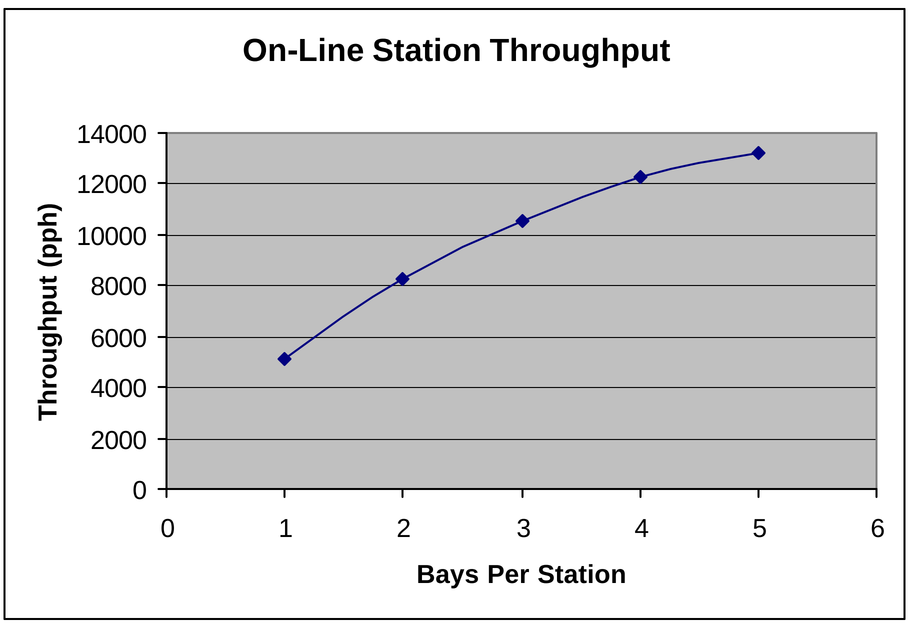


Fig. 6.4. Station throughput as a function of the number of bays.

6.5 Conclusions

The primary conclusion is that a throughput of 12,000 pphpd is achievable under certain assumptions using the control system concept described. The line is able to meet the capacity when using a "safe" headway strategy, as previously defined. The stations are able to meet this throughput through the use of multiple sequential bays per station. Although a basic framework exists, additional work is required to further tailor the control scheme to the people mover application and perform more detailed simulation of the control strategies.

6.6 Future work

The following tasks should be pursued in the near future:

?? Define Requirements: functionality, performance, nominal safety, benchmarks;
?? Develop Control Algorithms based on several headway criteria;
?? Simulate Control Algorithm(s);
?? Develop Control Architecture;
?? Investigate high level operational strategies.

Additional tasks are required further in the future in the implementation of final design to carry people. The near term tasks are detailed below.

1. Define Requirements

The appropriate requirements for a control system will be defined, appropriate for this stage of development. These requirements include performance (throughput), functionality, headway constraint, a virtual track definition for purpose of benchmarking, and safety insofar as collision avoidance in the control algorithms is concerned. The virtual track definition will include a representative section of track with stations, dwell times, etc., that can be used to measure the relative performance of control algorithms. Requirements for safety regulations, reliability, and redundancy are important, but will be examined and considered in a later stage of development, and will not be included in this stage. This will allow for the most progress, appropriate to this stage of development, to be attained.

2. Development of Control Algorithms

A set of control algorithms will be developed, appropriate to the system constraints (one vehicle per block, etc.) and requirements. A variety of related algorithms will be developed based upon different headway criteria.

3. Simulation of Control Algorithms

A simulation of the control algorithm on the benchmark track will be performed. This simulation will be performed based upon ideal vehicle behavior to give nominal throughput performance. Optionally, a variety of stopping strategies (vehicles not stopping at every station) may also be simulated to calculate the effect on performance.

4. Develop Control System Architecture

Based upon the control algorithms of task 2, an appropriate control system architecture will be designed at a high level. The functionality of each component of the architecture will be determined and described, in relation to the control algorithm.

5. Investigate high-level operational strategies

High-level control strategies may be layered on top of an existing control system by the central controller or at the track layout stage of design. For instance, greater throughput may be acquired by using strategies such as selective station servicing, where every vehicle does not stop at every station. Each vehicle may, for instance, service two out of every three stations, with different vehicles serving different sets. A passenger can still move from his origin to his chosen destination by selecting the correct vehicle or by changing vehicles. Since fewer stops are required, greater throughput may be achieved. Also, demand-based station servicing may be used. For instance, vehicles may skip stations where there is no demand.

7 Typical applications

In Section 3.1 it was shown that, for a simple model, the travel time is 30 seconds more than it would be if the acceleration and braking were instantaneous. This time estimation method has been used in the following discussions of applications. In the next phase of this project more accurate estimates will be made for specific examples.

7.1 Short shuttle

There are many practical applications for a shuttle to move people a distance of a mile or two with few if any intermediate stops. A common example is to provide transportation from an airport, university campus or medical center to a remote parking lot. The best approach is to have a loop at each end so that the vehicles always operate in the same direction and vehicle headway can be kept low. With an 18.3 m (60') radius turn it does not require much space for the vehicle to reverse direction. With a complete 3.22 km (2 mile) loop it is possible for vehicles to make a round trip every 3 minutes. Six vehicles operating with 30 second headway would provide a capacity of 4,320 pphpd. By using 6 platoons of 4 vehicles each and operating with 40 seconds between platoons, each vehicle makes 15 round trips per hour for a capacity of 12,960 pphpd. The same capacity can be maintained for longer loops by increasing the number of vehicles.

In some cases a single guideway will suffice with one or more vehicles shuttling back and forth, but this severely limits capacity and increases average wait time. For example, 2 vehicles operating as a platoon with 4-second headway could make a 1-mile round trip every 3 minutes for a capacity of 1,440 pphpd. In off-peak times a single vehicle could make a round trip every 5 minutes for a capacity of 432 pphpd.

7.2 An alternative to light rail and rapid transit

Light rail and rapid transit normally operate without a precise schedule but with an average time between trains that is a function of the time of day. For this mode of operation any reduction in wait time is equivalent to increasing average speed. The example for a shuttle loop showed that a capacity of over 12,000 pphpd is possible with an average wait time of only 20 seconds. As an example, a trip of 12 km (7.5 mi) with 5 intermediate stops requires 8.6 minutes, including an average dwell time of 20 seconds per stop, for an average speed of 23 m/s (52 mph). This is twice the average speed of typical rail based transit systems.

The advantages of M^3 are even more significant when the mode of operation takes advantage of station skipping strategies. As a simple example, assume that the vehicles are operated in platoons of 3 with each vehicle skipping every third station but synchronized so that it is possible to go from any one station to any other station without changing vehicles. For the preceding example this eliminates 2 stops thereby saving 110 seconds so the average speed is increased to 29 m/s (64 mph).

In some cases, such as during rush hours, it may be preferable to not guarantee that a rider can go from any station to any other station as long as average travel time is short. There are several ways to reduce the number of stops by more than a factor of 2 with a net decrease in travel time for the average rider. In these more complex scenarios it is desirable to adapt the stopping strategy to the demand with a suitable central control system. The important idea is that creative scheduling can increase average speed without reducing capacity.

7.3 An alternative to commuter rail

In the U.S. most commuter rail systems uses diesel locomotives to push and pull 5 to 10 car trains. They tend to have high peak demand but low average demand. However, part of the reason for low off-peak demand is that the usual mode of operation is to keep train length long enough for peak load and simply decrease the frequency of service in off-peak, a passenger-unfriendly strategy. For these applications the use of small vehicles allows higher frequency off-peak service and this will almost certainly increase demand. But there are other strategies that take advantage of the high speed of maglev.

Commuter rail systems usually operate on a schedule, and this allows a number of operational strategies for maglev. In the morning there is usually a high demand for trips from urban areas to city center stations and the opposite is true in the evening. In this case we can create express service without the need for express tracks. Consider the example of a 40 km long commuter rail line. In order to provide faster service it is common to restrict the number of stations that receive good service but this has the bad effect of creating traffic congestion at the stations with good service.

A better strategy is to have more stations and a better scheduling algorithm. Assume, for example, that there is a station every 2 km (1.2 mi) so there are 19 intermediate stops. Without station skipping the complete trip would take 30.6 minutes at an average speed of 22 m/s (49 mph), fast compared with any mode, including a car in urban areas. But suppose a 16 minute period was dedicated to having all vehicles making express trips from each urban station to the city center or the reverse. The 40 km trip would then take 15.3 minutes for an average speed of over 40 m/s (88 mph) and all trips would be completed in 16 minutes. As soon as a vehicle deposits its load in the city it returns so that the vehicles are returned to urban stations. The process can then be reversed by reversing the direction of travel on the guideway. A few intermediate stops can be provided to facilitate shorter trips but some passengers may have to change to make a desired trip. The key idea is to provide express service for the majority of riders and adequate service for the rest.

The outer extremities of commuter rail lines often have only single-lane guideway. In this case it may be desirable to have off-line loading and unloading so that vehicle passing is possible. Offline loading will require switch activation, and this reduces capacity, but for most commuter rail lines the resulting capacity will be more than adequate. As people move further from city centers, commuter rail could be one of the most cost effective ways to eliminate congestion on the highways at rush hour.

8 Cost estimates

This section itemizes system components and estimates the cost per mile for the M^3 Urban System. Costs are compiled from information supplied by component designers and manufacturers and have been confirmed by a second source where possible. In a few instances there is not enough information to make an accurate estimate, but all of the primary costs have been determined after consultation with appropriate manufacturers and vendors. MagneMotion will continue to refine the cost estimates as the design evolves.

The cost estimates for all guideway related items are computed on a per-unit-beam-length basis. The baseline design calls for double-span beams that are 72 meters long. Each 72-meter length of guideway contains the following:

?? 2 72-meter long beams
?? 2 piers
?? 8 36-meter long LSM stators
?? 1 inverter station containing 8 inverters and associated controllers
?? 1 hub controller and communication module
?? 4 power cables for distributing DC power, 2 in each beam

The DC power is provided by a rectifier station located every 8 km (4.97 miles), and each station contains a power transformer and rectifiers that provide separate +750 and –750 VDC power with a total power rating of 1.5 MW. The rectifier station may include a source of emergency power, but this cost has not been included; a rough estimate is $50,000 added cost for every rectifier station for a 50 kW generator.

Power station rating and spacing is consistent with operating 4 vehicles per mile of dual guideway, so this is used as the nominal vehicle requirement. For different applications the number of vehicles per mile could vary substantially. If smaller and lower speed vehicles are used the cost of the vehicles and power system will be somewhat lower.

The order of the costing section follows highest to lowest cost components.

1. Power distribution and control
2. Guideway
3. LSM stator
4. Vehicles

8.1 Power distribution and propulsion control

Key components of the propulsion system are the inverters that transfer power between a DC bus that distributes power along the guideway and the LSM windings. For the baseline design it is assumed that there is an inverter station at every other pier and it contains inverters for driving the port and starboard motors for each lane of a dual guideway with different inverters for different directions from the inverter station. Later studies may show it feasible to reduce cost by using fewer inverters that are multiplexed to drive more than one block, but the baseline design is based on separate inverters for each motor block.

Cost estimates are based on the following assumptions:

?? There is an inverter station every 72 meters and it contains 8 inverters.
?? Each inverter has a rating of 400 kVA and operates off of a 750 VDC bus.
?? Inverter pricing includes control, power sections and filtering.
?? Inverters will have regeneration capability but no braking resistors.
?? Inverter cooling and heating capabilities are suitable for any urban environment.

The baseline design uses two DC buses: +750 VDC and –750 VDC. The port and starboard motors are powered from separate buses so as to achieve redundancy against possible failures and to allow the majority of the power to be distributed at the 1,500 VDC level in order to allow longer distribution distances than are commonly used for rapid transit or light-rail. Relatively inexpensive IGBT power devices are now available for operation with a 750 VDC bus but the final choice of voltage will be based on minimizing the cost of inverters and power distribution components. The DC bus is designed to carry 750 kW up to 4 km (2.49 miles) in each direction with a typical efficiency of 97% at full load. The rectifier station can provide 50% over capacity for several minutes in order to deal with power fluctuations.

System communication and wayside electronics are anticipated to require 1 node at each rectifier station.

8.1.1 Cost basis:

MagneMotion designed LSM control systems are currently operating in material handling applications. These cost estimates are based on scaling the cost based on higher power levels and greater requirements for safety and redundancy.

Costs for the rectifier station and power cables are based on discussions with Massachusetts Electric Construction Co. and inverter cost estimates are based on discussion with Yaskawa Co.

8.1.2 Cost estimate

Table 8.2. Cost estimate for power distribution and propulsion control.

Item\Costing	*Unit cost*		*Usage/72m*		*$/72m*	*$/mile*
Controller module including cabling	4,000	$	8		32,000	715,264
Hub control	4,000	$	1		4,000	89,408
Installation	60	$/hr	512	hrs	30,720	686,653
Inverters	30,000	$	8		240,000	5,364,480
Inductive power transfer modules	20,000	$	1		20,000	447,040
Power cable	26	$/m	288	m	7,488	167,372
Rectifier station, 1.5 MW	1,000,000	$/recsta	0.009	recsta	9,000	201,168
Total before contingency					343,208	7,671,385
Total with 25% contingency					429,010	**9,589,232**

8.2 Guideway

Guideway cost is based on our baseline design: a dual guideway with double-span 72-meter long guideway beams and pier construction. The cost estimate includes provisions for mounting the LSM and labor hours for anchoring and aligning the LSM stator to the guideway beam. Pricing assumes piers for both concrete and steel guideway configurations are of concrete construction. Steel reinforcement is included in concrete and hybrid configurations.

A 50% contingency factor has been added in the expectation that additional expenses will be necessary to meet installation and operational requirements. Structural requirements have been met in the preliminary investigations of guideway designs using both concrete and steel but operational dynamics may dictate refinements to these designs. When a site is chosen and beam materials are selected for that site, guideway optimization simulations will dictate full beam requirements.

8.2.1 Cost basis

Cost estimates are based on information supplied by Earth Tech of Long Beach CA, and are based on their recent experience with installation of the Vancouver Skytrain, and Bankok Transit system. For a more detailed breakdown of guideway component costs see the Supplemental Report, M3 *Guideway Design and Analysis*. This includes a report by EarthTech that contains tradeoff studies of concrete, steel and hybrid beams and also contains cost backup based on the Vancouver Skytrain construction costs.

8.2.2 Cost estimate

Table 8.1 is from M^3 *Guideway Design and Analysis*, a MagneMotion document.

Tables 8.1. Guideway cost in $ per mile including 50% contingency.

Steel alternate	*Unit Rate*	*Unit*	*Quantity*	*$/72m*	*$/mile*
Steel superstructure	$3.00	kg	98,267	294,801	6,589,392
Bent cap concrete	$400.00	m^3	11.5	4,600	102,819
Column concrete	$300.00	m^3	9.5	2,850	63,703
Drilled shaft	$1,500.00	m	24	36,000	804,672
Bar reinforcement	$1.35	kg	16,500	22,275	497,891
Bearings	$1,500.00	EA	12	18,000	402,336
Total				378,526	8,460,813
Total with contingency.	50%			567,789	**12,691,220**

Concrete alternate	*Unit Rate*	*Unit*	*Quantity*	*$/72m*	*$/mile*
Concrete superstructure	$700.00	m^3	93	65,100	1,455,115
Bent cap concrete	$400.00	m^3	11.5	4,600	102,819
Column concrete	$300.00	m^3	13.6	4,080	91,196
Drilled shaft	$1,500.00	m	24	36,000	804,672
Bar reinforcement	$1.35	kg	30,630	41,351	924,278
Post-tensioning steel	$4.00	kg	3,800	15,200	339,750
LSM support ties	$2.75	kg	4,307	11,844	264,737
Bearings	$1,500.00	EA	8	12,000	268,224
Total				190,175	4,250,792
Total with contingency	50%			285,263	**6,376,187**

Hybrid alternate	*Unit Rate*	*Unit*	*Quantity*	*$/72m*	*$/mile*
Concrete superstructure	$700.00	m^3	93	65,100	1,455,115
Bent cap concrete	$400.00	m^3	11.5	4,600	102,819
Column concrete	$300.00	m^3	13.6	4,080	91,196
Drilled shaft	$1,500.00	m	24	36,000	804,672
Bar reinforcement	$1.35	kg	30,630	41,351	924,278
Post-tensioning steel	$4.00	kg	3,800	15,200	339,750
Top Plate	$2.75	kg	28,700	78,925	1,764,132
Bearings	$1,500.00	EA	8	12,000	268,224
Total				257,256	5,750,186
Total with contingency	50%			385,884	**8,625,279**

8.3 LSM stator

The LSM stator is made up of two major components: laminations and windings. Included in the LSM costs are the costs for mounting and aligning the stator laminations and installing the windings.

8.3.1 Cost basis

Lamination estimates are by Tempel Steel assuming that the lamination stacks are fabricated on site from stamped and spooled M19 24-gauge electrical steel. Winding estimates are based on corporate experience with producing and installing LSM windings. Although manufacturing methods for the 3- phase windings have not been determined, wound on or off site cost estimates are expected to be similar.

8.3.2 Cost estimate

Table 8.3. Cost estimates for LSM stator per 72 m of guideway.

Item\Costing	*Unit cost*		*Usage/72m*		*$/72m*	*$/mile*
Laminations (44.7 kg/m x 288 m)	1.90	$/kg	12874	kg	24,460	546,726
Lamination mounting hardware	33	$/m	288	m	9,504	212,433
Windings (28.2 kg/m x 288 m)	4.95	$/kg	8122	kg	40,202	898,593
Winding mounting hardware	33	$/m	288	m	9,504	212,433
Labor to assemble & align laminations	60	$/hr	512	hrs	30,720	686,653
Labor to wind & assemble windings	60	$/hr	512	hrs	30,720	686,653
Total before contingency					145,110	3,243,493
Total with 25% contingency					181,387	**4,054,367**

8.4 Vehicle

Two vehicle configurations will be considered: a baseline 45m/s vehicle with secondary suspension and a smaller 30 m/s, vehicle with minimal if any secondary suspension.

A secondary eddy current brake is planned for emergency use and a tertiary mechanical brake is planned as an added safeguard but with the expectation that it will never be used. No detailed designs have been completed so only rough estimates are used for budgeting purposes.

8.4.1 Cost basis

The vehicle body estimates are based on discussion with Hall Industries, TPI, CWA and others. The suspension component costs are based on discussions with MagneMotion magnet and structural component vendors.

8.4.2 Cost estimate

The baseline vehicle has seats for 24 and room for 12 standees. It has 4 magnet pods that include a secondary suspension suitable for speeds to 45 m/s (101 mph). The smaller vehicle has seats for 12 and room for 6 standees. It has 2 magnet pods and no secondary suspension and is suitable for speeds up to 30 m/s (67 mph).

Table 8.4. Vehicle cost itemization in k$ per vehicle.

	12 pas	*24 pas*
Shell	40	60
Suspension struts	16	32
Levitation pods		
Laminations	4	8
Magnets	7	14
Assembly	1.2	2
Power electronics	20	30
Batteries, power pickup, etc.	20	30
Communications	8	8
HVAC, seats, etc.	40	80
Total before contingency	156	264
Total with 25% contingency	195	**331**

8.5 Cost summaries

Table 8.5 summarizes costs, in 2002 dollars, of each major component. It is assumed that the installation is at least 10 miles long with the expectation that costs will be somewhat higher for shorter installations. The extended price includes the contingency factors for component parts, but does not include civil works, shipping, or land acquisition costs

Component contingencies account for uncertainties in our cost estimates and are based on discussions we have had with various vendors regarding the relative risk associated with the estimates. Even with the 25% to 50% contingencies added, M^3 costs are well below those of competing transit systems.

Table 8.5. Total cost in M$/mile for three guideway alternates and baseline vehicles.

	Concrete	*Hybrid*	*Steel*
Power & control	9.589	9.589	9.589
Guideway	6.376	8.625	12.691
LSM stator	4.054	4.054	4.054
Total excluding vehicles	19.779	22.260	26.351
4 Vehicles	1.322	1,322	1.322
Total with 4 24-pasenger vehicles/mile	**21.101**	23.582	27.673

For a system using the smaller vehicles the power system cost will be reduced because of the reduced power demand. The fact that winding inductance plays such an important role limits the reduction in inverter rating that is possible, so the reduction is not as great as might be expected. A detailed analysis has not been done, but it is estimated that the cost of the power and propulsion control components will be reduced by 20%. This leads to the cost summary in Table 8.6.

Table 8.6. Cost summary in M$/mile for three guideway alternates and small vehicles.

	Concrete	*Hybrid*	*Steel*
Power & control	7.671	7.671	7.671
Guideway	6.136	8,617	12.707
LSM stator	4.054	4.054	4.054
Total excluding vehicles	17.861	20,342	24.433
4 Vehicles	781	781	781
Total with 4 12-pasenger vehicles/mile	**19.183**	21.664	25.755

The cost objective of $20M per mile is clearly achievable if we can improve the design further and reduce the need for large contingencies.

9 Demonstration prototype and future plans

The design concepts described in this document have been tested by constructing the demonstration prototype shown in Fig. 9.1. This prototype uses full-scale magnets but the vehicle is shorter and narrower than the vehicles described in Section 5. The prototype is fully functional, and has met its design objectives. The agreement between predicted and measured quantities ranged from fair to very good. The computer models used to design the demonstration system correctly predict the system behavior with good accuracy so it is reasonable to expect similar validity for the models of the full-size system.

Table 9.1 gives data that is exemplary of the many measurements made; it shows the relatively good agreement with predictions. Prototype testing involved a much wider range of load than is planned for a full-scale vehicle, so in normal operation the gap will only vary about ±3 mm from a nominal value. The levitation power is very small, but this is for static tests and does not include power consumed by position sensing and other overhead functions.

Table 9.1. Static performance of demonstration prototype.

	Gap (design)	*Gap (actual)*	*Mass (design)*	*Mass (actual)*	*Lev power*
Light	25 mm	24.6 mm	734 kg	777 kg	2.0 W
Nominal	20 mm	20.6 mm	958 kg	981 kg	2.0 W
Heavy	15 mm	15.8 mm	1284 kg	1229 kg	2.3 W

The guideway is 6 m long and allows a vehicle move of 3.9 m. With a nominal load of 981 kg the maximum test speed was 1.74 m/s (3.8 mph) with an acceleration of 2 m/s^2.

Fig. 9.1. Photograph of prototype vehicle and guideway.

This prototype test track will be extended and modified to allow more complete testing of the suspension, guidance and propulsion subsystems for a full-scale small vehicle.

Future plans call for developing an outdoor test track that will allow full speed testing of a passenger-carrying vehicle and, ultimately, a commercial installation.

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As the project continues we expect to expand the Team to include representatives from companies that contribute to the design and construction of a full-scale prototype and, hopefully, a commercial system.