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Compendium of Executive Summaries from the Maglev System Concept Definition Final Reports

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16. Abstract

This report contains the Executive Summaries from the four System Concept Definition (SCD) studies awarded under the National Maglev Initiative. These summaries present the technical feasibility, performance, capital, operating and maintenance costs for a maglev system that would be available by the year 2000. Performance on a hypothetical route, provided to test these concepts in order for the NMI to make performance and cost comparisons, is briefly discussed. This compendium constitutes the principle publication of those SCD reports on technical matters.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in.) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

$[(x - 32)(5/9)]°F = y°C$

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (kn^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

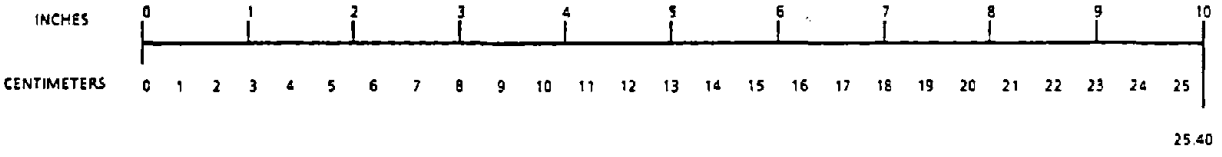
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

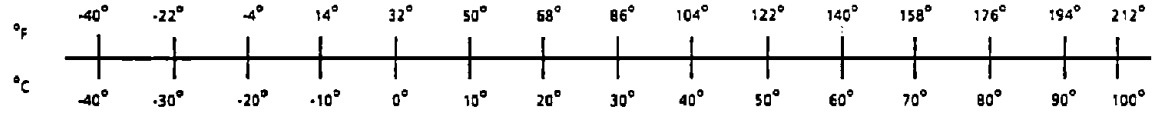
$[(9/5)y + 32]°C = x °F$

QUICK INCH-CENTIMETER LENGTH CONVERSION



25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

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PREFACE

Compendium of Executive Summaries from the Maglev System Concept Definition Final Reports

Four 11-month system concept definition (SCD) studies, totaling more than $8.6 million, were awarded in late October 1991 to determine the technical feasibility, performance, capital, operating and maintenance costs for a maglev system that would be available by the year 2000. Due to the extensive nature of the final reports, the limitations on distribution of proprietary information and the difficulty of presenting consistent detailed cost and performance information it was decided not to publish all of the material delivered under these SCD contracts. This compendium of Executive Summaries of the SCD Final Reports presents the essence of the studies representing the information supplied to the US Government as part of its evaluation of the potential of maglev as a future transportation system. The four industry teams were:

Bechtel (San Francisco, CA) with Hughes Aircraft; EMD Division of General Motors; Massachusetts Institute of Technology (MIT); and Draper Labs. The concept features repulsive superconducting levitation, tilting vehicle, a ladder track, and a box beam girder guideway partially reinforced with Fiber Reinforced Plastics (FRP).

Foster-Miller, Inc. (Waltham, MA) with DeLeuw Cather; Boeing Aerospace and Electronics; Morrison Knudsen; Bombardier; General Dynamics; General Atomics and AYA & Associates. Concept features repulsive superconducting levitation which integrates lift, guidance and a locally commutated linear synchronous motor (LCLSM) propulsion in a tilting vehicle. The guideway employs null flux levitation coils and a unique vertical switch with no moving structure.

Grumman Corporation (Bethpage, NY); with Parsons, Brinckerhoff Inc.; Gibbs & Hill; Battelle Labs; Intermagnetics General; PSM Technologies; Honeywell; and NY State University at Buffalo. Concept features attractive levitation using controlled superconducting magnets, tilting vehicle, and V-shaped guideway supported by a central spline girder with outriggers.

Magneplane International (Wayland, MA) with MIT Plasma Fusion Center; MIT Lincoln Labs; Raytheon; Bromwell and Carrier; Failure Analysis Associates; and Koch Process Systems. Concept features repulsive superconducting magnets with a semi-circular sheet guideway which permits self banking. Stability is provided by a "magnetic keel".

These projects were jointly funded by the US Army Corps of Engineers and the Department of Transportation with support from the Department of Energy.

Under Contract
DTFR 53-92-C-00003

BECHTEL MAGLEV SYSTEM CONCEPT DEFINITION

FINAL REPORT — SYSTEM OVERVIEW

Prepared for

U.S. Department of Transportation
Federal Railroad Administration

A. GENERAL SYSTEM OVERVIEW

This section provides an overview of the operation of the entire system, with later sections used to elaborate on details of the design and operation. All technical issues mentioned here are discussed in more detail elsewhere in this report.

1. INTRODUCTION

Maglev is a transportation system that uses vehicles which are levitated a short distance from a dedicated guideway by magnetic forces. These vehicles also use magnetic forces for non-contacting guidance and propulsion, and will travel safely at speeds greater than 150 m/s (540 km/h or 336 mph).

Maglev has many similarities to high speed rail. It depends upon mechanical guidance from a guideway, and can carry people directly into regions of high population density. It employs electric propulsion and is capable of operating in almost all weather conditions. It can provide comfortable travel with greater safety than either air or highway modes. But unlike high speed rail, the vehicles can accelerate and decelerate rapidly and bank steeply for turns. This allows the route to have much steeper grades and follow the interstate highway right-of-way where appropriate. The proposed maglev design uses smaller vehicles and off-line loading and unloading so that passengers do not need to make many unnecessary stops. This necessitates short headways and demands completely automated control.

Maglev also has many similarities with air travel. The suspension system is non-contacting and the proposed operating mode uses airline size vehicles and point-to-point scheduling. Unlike air travel, the operation is not as sensitive to weather conditions, and vehicle control is completely automated. It is expected to be as safe as high speed rail, which is safer than any other passenger carrying system, because there is no guideway encroachment and much less chance for human error.

In this section we present an overview of the principal concept characteristics of the maglev system being developed by the Bechtel Team. Some features are based on requirements imposed by our statement of work, and others have been created by members of the Team based on studies conducted before and during this project. Important innovative features of the concept include:

- A high efficiency electrodynamic suspension system that can suspend the vehicle down to very low speeds and thereby reduce power consumption

- A box-beam guideway that reduces structural cost and environmental impact while providing a high degree of safety and longevity
- A linear motor propulsion system that provides high acceleration and braking and can operate at reduced speed in the presence of many types of failure
- An automated and fault tolerant control system that allows highly reliable fail-safe operation with short headway and high availability
- Use of air bearings for low speed stop/start in lieu of wheels, for emergency situations

This overview emphasizes *what* the system does rather than *how* it does it. Subsequent sections describe the technical details of how we expect to achieve these objectives.

2. SYSTEM PARAMETERS

2.1 SPEED

The maximum design speed is 150 m/s (540 km/h or 336 mph), but in most cases the top operational speed will be 135 m/s (486 km/h or 302 mph). By providing safe operation at higher than normal speeds, we help ensure outstanding safety at normal speeds. In addition, we allow full speed operation against head winds of 18 m/s (40 mph) and in the presence of minor variations in the performance of subsystems.

At times of high demand the maximum operational speed may be reduced somewhat. A reduced speed allows shorter headway and higher system capacity, with no reduction in safety margins or increase in total system power consumption. The operational speed that provides maximum system capacity will be determined by simulation for each section of guideway, and the Central Control will never reduce speed below this point unless required for safe operation in the face of unusual conditions.

2.2 ACCELERATION

Acceleration is limited by the thrust available from the linear motor, but it is also limited by passenger comfort and safety constraints. For U. S. applications it is expected that major sections of the guideway will follow interstate highway rights-of-way, and vehicles will frequently have to slow in order to negotiate turns with acceptable banking angles. Without relatively high rates of acceleration there will be considerable time lost negotiating turns, but it is not practical to require passengers to be seated during numerous speed changes. Hence, it is necessary to limit vehicle acceleration to values that are compatible with passengers standing and walking.

There is some uncertainty as to what steady acceleration limits are acceptable to standing passengers, but the upper limit for normal operation seems to be about 2.0 m/s^2 (0.2 g). We believe that the advantages of uniformity of design and flexibility of control make it worth the cost of providing sufficient thrust to achieve 2.0 m/s^2 acceleration almost everywhere on the guideway and at almost all speeds. The maximum thrust is the maximum motor thrust reduced by the drag produced by aerodynamic and magnetic forces. Aerodynamic drag force increases as the square of the speed, and magnetic drag force decreases inversely as the speed, so over a wide speed range the drag force is surprisingly constant. For the baseline vehicle the deceleration from these forces is about 0.4 m/s^2. In order to achieve a net acceleration of 1.6 m/s^2 we need about 2 N of motor thrust for every kilogram of vehicle mass.

For comparison, the proposed maximum acceleration is more than three times the value that can be achieved by a Transrapid maglev vehicle or any existing high speed train when they are operating near the top of their speed range. It is also less than half the accelerations commonly encountered in automobiles and rapid transit vehicles.

2.3 DECELERATION AND BRAKING

Under normal conditions, and allowing standing passengers, the deceleration limits are the same as those for acceleration, or 1.6 m/s^2. Normal braking is regenerative with most of the vehicle's kinetic energy being converted to electric energy that is made available for propulsion of nearby vehicles.

For mild emergency conditions the vehicle is regeneratively braked with reverse thrust up to the motor limits, or 2.0 m/s^2 deceleration. The regenerative braking, coupled with aerodynamic and magnetic drag, provides about 2.4 m/s^2 of net deceleration. This exceeds normal comfort levels but is not considered hazardous to standing passengers. This mode will be used whenever unexpected events require rapid but not extreme stopping action.

For extreme emergency conditions it is imperative to stop rapidly and even limited injury is preferable to a low deceleration rate which would result in a more damaging situation. For this "hard stop" condition the linear motor is capable of providing 2.0 m/s^2 deceleration, and when the aerodynamic and magnetic drag is added, the total deceleration can exceed 2.5 m/s^2. Where possible the passengers would be given a few seconds warning before being subjected to this level of deceleration, but the hard braking is assumed to be acceptable where necessary to avoid catastrophic accidents.

Still faster braking is possible with the use of aerodynamic forces, such as from speed brakes or a drag chute. These have been added to ensure the highest possible levels of redundancy and safety.

2.4 HEADWAY AND CAPACITY

The minimum allowed headway is a function of speed, with guideway capacity determined by this minimum headway. There are three possible limits to headway: a headway distance minimum due to linear motor zone length; a headway time minimum due to control related issues; and a safety limit determined by the ability to stop in the clear distance ahead, the so-called "brick wall" criteria. These are shown graphically in Figure A-1.

The nominal maximum speed is 135 m/s, but many routes will require turn negotiations at substantially slower speeds. Extreme weather or minor malfunctions may also dictate a need for slower speeds. The design is based on the ability to handle 100 vehicles per hour at an average speed of 125 m/s (450 km/h or 280 mph), and 90 vehicles per hour at average speeds from 100 m/s (360 km/h or 224 mph) to 135 m/s (386 km/h or 302 mph). The 100-vehicle per hour limit implies a minimum headway time of 36 seconds, while the 90-vehicle per hour limit implies a minimum of 40 seconds; both of these limits are shown in Figure A-1.

At low speeds the minimum headway distance is controlled by the electronic inverter spacing because an inverter can only propel a single vehicle. Our design allows a vehicle headway of 40 seconds at an average speed of 100 m/s, so the inverter spacing must be no more than 4 km. The nominal inverter spacing is 4 km, but this is reduced in regions where an average speed of 100 m/s is not possible, such as when there are frequent tight turns or unusually steep grades. Longer zones may be preferable on routes with much lower traffic density where acceleration and deceleration are less important and cost reduction is more important.

At the highest speeds the minimum headway is imposed by safety considerations. Assuming a "brick wall" stopping criteria with a 2.0 m/s^2 deceleration limit and a 2-second reaction time, the

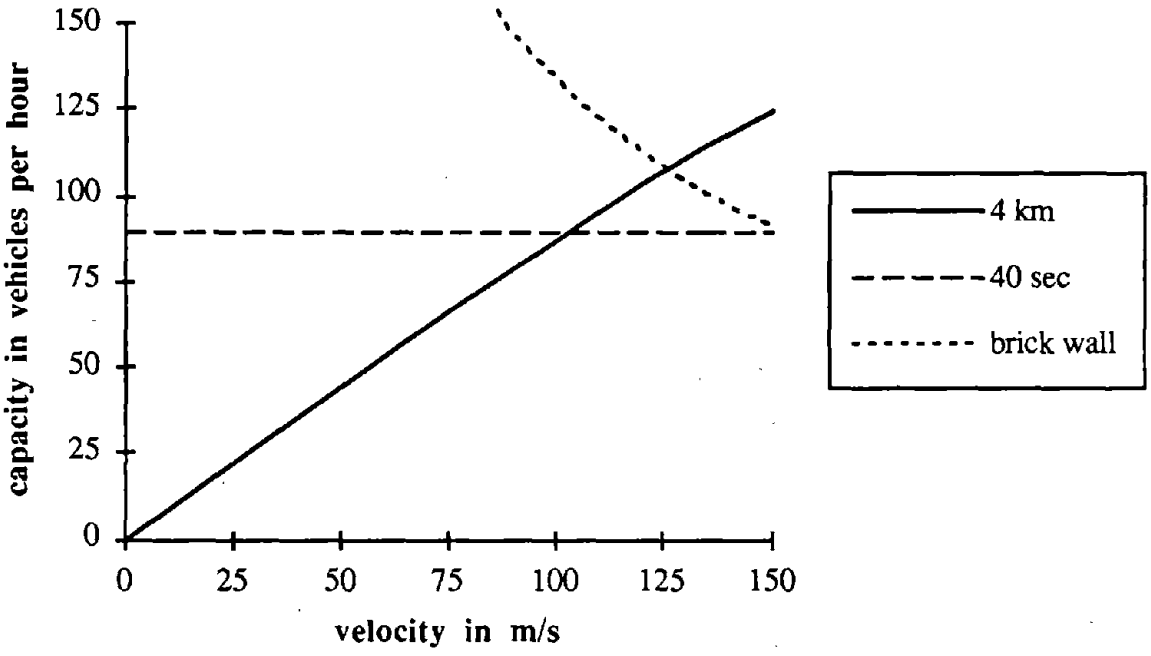


Figure A-1 Headway limitations

required stopping distance varies from 5 km at 150 m/s to 2 km at 75 m/s, as shown in Figure A-1.

There are additional headway restrictions imposed by switches, and these will be discussed later. The actual required stopping distance would be determined by extensive simulation prior to actual operation, and a required headway set accordingly. If desired, we can provide somewhat greater deceleration to allow shorter headway.

With a 4 km headway requirement, a capacity of 90 vehicles per hour can only be sustained for speeds in excess of 100 m/s. If vehicles in a particular section of guideway must reduce speed below this value to satisfy an abnormal safety or failure constraint, then the reduced capacity would cause serious constraints on system scheduling. To mitigate this problem, the propulsion system has a unique capability to operate with a spacing of 2 km at speeds from 50 to 100 m/s. The details of the method are described later, and the corresponding capacity limit is shown in Figure A-1.

With a 36-second headway limit the capacity limit is 100 vehicles per hour. With 120-passenger vehicles there is a theoretical capacity of 12,000 people per hour, but statistical variations in headway and restrictions on maximum switching speed limit the capacity to about 9,000 people per hour. Increases in capacity beyond this value will require an increase in braking rate or vehicle size or a decrease in speed or headway margin.

In the proposed design the minimum headway will initially be 60 seconds. Reductions will be allowed only as the system matures and operational experience indicates shorter headway is safe. Thus, the initial capacity will be 60 vehicles per hour. Considering statistical variations and extra headway requirements for switching we expect a practical limit of about 45 vehicles per hour, or 4,770 passengers per hour in 106-passenger vehicles.

2.5 SWITCHING

A specialized section of the guideway, called a switch, allows a vehicle to be diverted from the main guideway to a deceleration lane, or from an acceleration lane to the main guideway. In the interest of safety, it is assumed that all vehicles leaving a guideway will stop, even if their objective is to immediately reenter a guideway going in a different direction. This stop allows the scheduling of the two sections of guideway to be handled independently. Later implementations may allow faster transfer between two different guideways.

Switching can be accomplished in two ways, referred to as active or passive according to whether or not the guideway is required to perform an "active" part of the switching action. With passive switching the guideway has an alternate path that can be selected using movable mechanisms or electromagnetic actuators that are on the vehicle. The active switch uses a mechanical change in the guideway to force the vehicle to take an alternate path. The only proven switch designs are active: the flexible beam switch used by Transrapid in Germany and the articulated beam switch used by JNR in Japan. Both active and passive switches are being considered as alternates for use with our design.

In order to achieve good system capacity at a reasonable cost, the nominal switching speed for vehicles entering or exiting the guideway will be in the range 30 to 60 m/s (67 to 134 mph). Switching speeds of 30 to 60 m/s imply the need for 230- to 920-meter-long acceleration and deceleration lanes. These lanes are specially designed to allow continuous acceleration and deceleration rates of 0.2 g between standstill and the designed switching speed. Since passengers can stand while the vehicle is stopping and starting, it is expected that only about one or two minutes are required for passenger and baggage transfer before the vehicle accelerates back up to the switching speed and then merges back into the main guideway.

Although vehicles continuing through a switch do not need to reduce their speed, vehicles following a stopping vehicle must allow sufficient spacing to stop in the clear distance ahead. This "brick wall" criteria implies that a vehicle which is following a stopping vehicle may have to slow down somewhat. With our alternate passive switch the time penalty is small but with our baseline active switch it is necessary for a guideway mechanism to change position after the exiting vehicle traverses the switch, so headway capacity is reduced considerably. Our flexible beam switch requires 15 s to operate so there must be 72 s headway between a stopping vehicle and a following non-stopping vehicle assuming a 40 m/s switching speed.

2.6 STATIONS

With on-line stations the minimum headway is 3 or 4 minutes, as with present high speed trains, so it is necessary to use a long train with frequent stops to maintain a reasonable passenger capacity. To compensate for the 3 or 4 minutes lost for more frequent stops, it is necessary to increase operating speed to maintain the same travel time; this increased speed results in a net increase in energy and power consumption and requires a more expensive propulsion system. From both a cost and efficiency standpoint, it is better to use lower guideway speeds and off-line stations. This also allows the more comfortable option of fewer stops.

With off-line stations there are two switches for each direction of travel, and each switch has an associated acceleration or deceleration lane. There is also an area where vehicles can load and unload. Some stations will have the capability to turn a vehicle around so that it can be dispatched in the direction from which it arrived.

Stations may be located several kilometers from the main guideway with lower speed guideways used for vehicles to travel into regions of high population density where high speeds are not suitable. This is analogous to the use of circumferential highways to carry traffic around cities with special radial feeders used to access city centers, airports, and lower speed highways. Stations may also be located at intersections of major highways or at airports in order to facilitate intermodal passenger transfer.

2.7 SCHEDULING

All transportation systems experience periods of peak travel demand when the system capacity is stressed to the limit. For both existing systems and our proposed maglev system, it is appropriate to reduce maximum speed somewhat to accommodate more vehicles when demand exceeds the full speed capacity. From Figure A-1 we see that the maximum capacity occurs at about 125 m/s (280 mph). For speeds above 125 m/s, reducing vehicle speed will increase capacity because slower speeds allow shorter safe headway. During peak operating hours we will limit the maximum operating speed to 125 m/s and allow vehicles to depart with headways as short as 36 seconds. This slower operation at times of peak demand is preferable to restricting the number of vehicles that can use the guideway. The lower operating speed also reduces peak power consumption and therefore reduces electric utility demand charges.

Between about 6:00 AM and 9:00 PM, but with the exception of the hours of peak demand, the headway will be limited to 40 seconds and the maximum speed set at 135 m/s. This higher speed provides some encouragement for passengers to travel at off peak times. Exclusive passenger service is maintained only during peak periods, and freight service is interspersed with passenger departures at other times.

It may be desirable to operate at reduced speed before 6:00 AM and after 9:00 PM. The use of reduced fares and the carrying of high priority freight may be the norm for these less popular travel times, so somewhat lower speeds may be acceptable. Lower speed operation during night hours will also cause less noise and therefore be more acceptable to people living near the guideway.

Note that at speeds above about 120 m/s the noise power increases as the sixth power of speed, so a modest speed reduction creates major noise reduction.

The shutdown period for maintenance of the guideway and wayside facilities is about two hours at the time of lowest demand. This time may be shortened if demand warrants and the required service can be done in a shorter period.

Although scheduled departures provide basic service along a given route, it is also expected that dynamic scheduling will be used to accommodate the actual demand. This allows extra vehicles to be added when needed at times of unexpectedly high demand.

It is important to avoid the consequences of having frequent through vehicles blocking access to local vehicles, and also important to minimize wasted guideway capacity due to excessive slowing for stopping or starting vehicles. Real time simulation by the central controller will allow it to dispatch vehicles from stations in such a way as to optimize guideway usage while still offering fair access to vehicles entering from any station.

The reduced capacity which results from switching can be mitigated by the use of a scheduling strategy called platooning. This might be done, for example, when two vehicles are traveling the same route at the same time to simulate the effect of a single larger vehicle. In this manner the guideway capacity is not reduced as much as with random scheduling. With the combination of platooning and a passive switch, capacity is reduced about 10 percent due to switching, but with an active switch the capacity may be reduced by as much as 30 percent. Optimized scheduling will allow non-stop express service between major transportation centers and local service with more frequent stops. Note that platooning does not create a safety problem because any vehicle in a platoon can still stop if nearby trailing vehicles slow down.

2.8 RIDE QUALITY

Ride comfort is expected to be an important determinant of public acceptance of maglev. Ride quality which is better than our design goals may not attract passengers from alternative modes, but significantly poorer ride quality will deter use of a maglev system. The design of the vehicle, the primary and secondary suspensions, the guideway, and the propulsion system are carefully integrated to assure superior passenger ride quality, and to attract passengers from competing modes.

The guideway curve transitions and banking, vehicle tilting, and the vehicle speed profile are designed to maintain the horizontal and vertical passenger accelerations to levels that are acceptable for standing passengers and comfortable for seated passengers. Acceptable ride quality levels have been calculated and are described in the body of the report.

3. VEHICLE

3.1 BASIC DESIGN

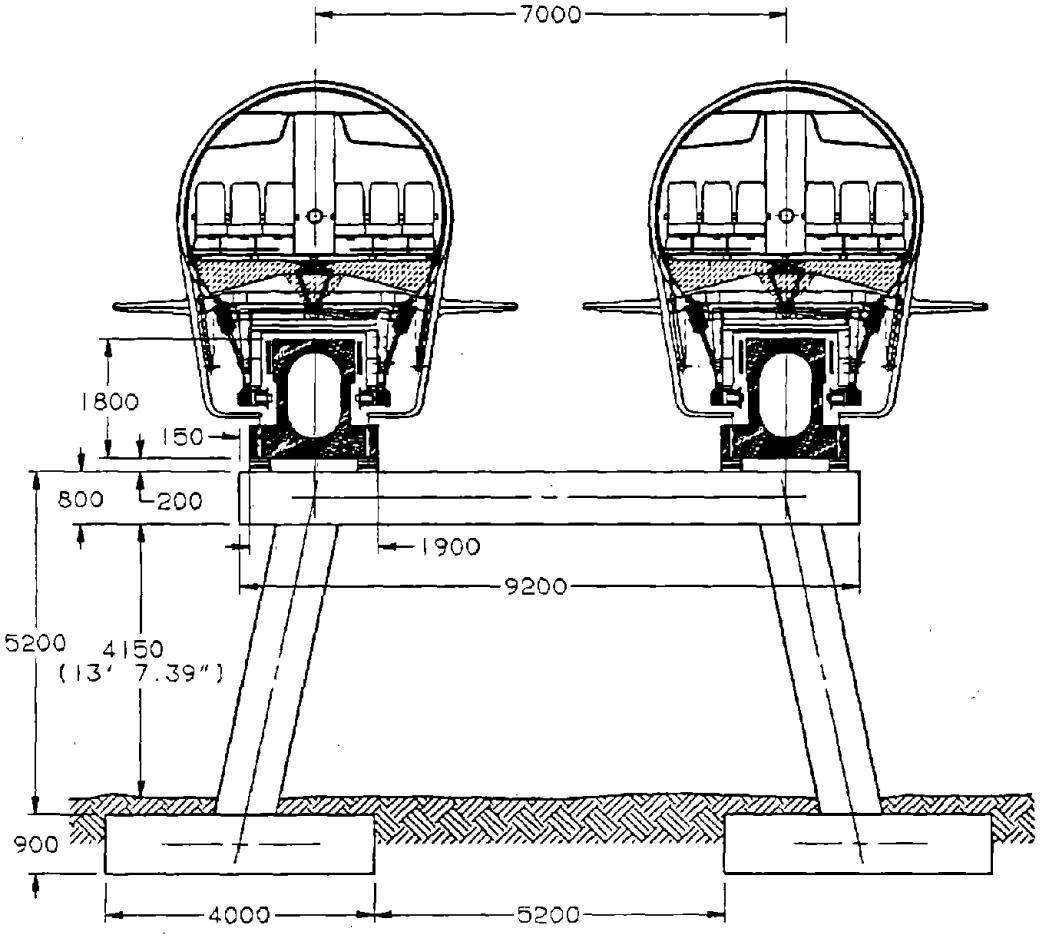
The baseline vehicle and guideway are shown in Figure A-2 (more detailed drawings are provided in later sections). The vehicle resembles the passenger compartment of a Boeing 737 with the important exceptions of more doors and larger aisles to facilitate more rapid loading and unloading. The slightly wider body provides more passenger comfort as an inducement to attract more riders. The passenger capacity is 120 in six abreast seating with adequate luggage capacity on the same level as the passengers, and additional space for high priority freight. Some four abreast business or first class seating is used, and this results in a 106-passenger single vehicle. This vehicle is 36.1 meters (118.4 feet) long, 4.1 meters (13.5 feet) wide, 5.08 meters (16.7 feet) high, and has a mass between 48.5 and 63.3 Mg (53.5 and 69.8 tons) depending on load. In normal operation the vehicle can negotiate a 400-meter turn and operates in a unidirectional mode. In some cases the guideway can be built with a wider gap to allow a shorter radius turn. When desired, the vehicles can operate in reverse at reduced speed.

3.2 PRIMARY SUSPENSION

The vehicle uses a proprietary "flux canceling" electrodynamic suspension (EDS) in which superconducting coils on the vehicle interact with a ladder-like structure on the guideway, with the latter providing suspension and some guidance forces. This design produces less magnetic drag than any other EDS system, and has the ability to provide full magnetic levitation and guidance down to 10 m/s (22 mph). The guidance is provided by figure-of-eight coils on the guideway which are cross-connected to provide no guidance force when the vehicle is centered, but a strong restoring force if the vehicle deviates from the symmetrical position. This suspension and guidance system is totally passive so that as long as the vehicle is above the takeoff speed it is suspended and guided independent of the successful operation of any power source or active control system.

Estimated power loss for the suspension and guidance is 10 kW/Mg, or 0.64 MW for a 64 Mg vehicle, essentially independent of speed for speeds greater than 50 m/s (112 mph).

At stations there will be several places for vehicles to stop and special coils in the guideway provide suspension and propulsion down to zero speed, so the vehicle will be able to stop without the use of wheels. For stopping on the guideway there are air bearings that provide suspension



GUIDEWAY CROSS-SECTION
ON GIRDERS

below 10 m/s. At preferred stopping points on the guideway there is space for two vehicles to stop and facilities that allow people to transfer between stopped vehicles or between vehicles on the guideway and the ground.

3.3 SECONDARY SUSPENSION

The secondary suspension transfers force from the superconducting magnets to the vehicle. At high speeds any imperfections in the guideway will cause substantial vibration forces on the magnetic suspension and the secondary suspension must reduce the impact of these forces on the passengers. The cost of constructing a guideway without these minor imperfections would be prohibitive and a passive secondary suspension does not give the best possible ride quality, so the vehicles use an actively controlled secondary suspension.

The active suspension creates forces between the magnetic suspension and the passenger-carrying part of the vehicle body. Additional control is provided by small winglets at the bow and stern. These surfaces are actively controlled to provide additional improvements in ride quality with only modest increase in aerodynamic drag. The direction and magnitude of secondary suspension forces is controlled on the basis of sensors on the vehicle. For example, there are inertial sensors that measure absolute acceleration. The control is also based, in part, on prerecorded data concerning the dynamic aspects of the guideway, so some amount of anticipatory control is possible.

3.4 TILTING

A secondary suspension mechanism allows the vehicle to tilt up to 15 degrees relative to the guideway, but the guideway itself may also be banked up to 15 degrees. Thus, the total vehicle bank angle can be as great as 30 degrees. This banking is used primarily for turns in order to minimize the amount of speed change required to negotiate a turn. With a 30 degree bank angle, a vehicle traveling 135 m/s can negotiate a coordinated turn, in which there is no lateral acceleration on the passenger, with a minimum radius of 3.2 km. At 125 m/s the minimum radius coordinated turn is 2.8 km. If lateral acceleration is allowed the radius can be smaller, but there is debate as to whether lateral acceleration is acceptable in light of other forces, such as those due to wind and guideway roughness.

3.5 CRYOGENIC COOLING

The cost of cryocooling is not very significant, so the main objective is to decrease the impact of the cooling system on vehicle weight and availability. Our baseline design uses liquid helium that is recycled once each day during stops at special stations located about every 400 km along the guideway. No helium is lost, and the recycled helium is recooled at wayside refrigeration plants. The cooling requires only a small amount of power for operating pumps.

We explored an alternate design using on-board cryocooling. This method is clearly possible, but with the best available superconductors and cooling technology, this approach is not currently as attractive as the use of wayside cryocooling. However, the cooling system is not part of a standard, so it is possible for vehicles to operate with on-board cooling equipment in cases where the economics favor this mode.

3.6 ON-BOARD POWER

On-board power is provided by a pair of methanol-powered fuel cells that can deliver a total of 186 kW of power. This is enough to power the heating, ventilating and air conditioning equipment, the hydraulic actuators, the on-board computer and vehicle lighting. There are also 2 NiCd battery banks that provide peak power and can provide emergency power for up to one hour in the event of failure in both fuel cells.

3.7 MAGNETIC FIELDS

The dc magnetic fields due to superconducting windings are focused in the vicinity of the guideway, and fall off rapidly with distance from the source. A number of relatively low-cost mitigation options can be used to reduce the dc fields in the vehicle to 1 gauss or less.

3.8 EMERGENCY OPERATION

The suspension, guidance, and propulsion all depend on a set of independent superconducting magnets on the vehicle. These coils are operated in the persistent current mode and are designed to be sufficiently robust so that they can operate for many minutes without any external input, so total loss of on-board power will not cause the loss of suspension and guidance. Our baseline concept vehicle uses 12 separate magnet modules, so a failure in one or two modules will not produce a serious problem. Sensors will be used to warn of failure of any one module, and the vehicle will be required to slow down and stop at the nearest station whenever a single failed module is

detected. Hence, there is no need to provide backup high speed suspension or braking systems of the type required for electromagnetic suspension systems. Note that the suspension system provides more than 1 g of pull-down force to prevent derailing in the case of very strong winds or major guideway misalignment.

Total power failures are expected to be extremely rare, but when they do occur the vehicles will normally be able to coast to a stop at a preferred stopping point. This is true because the inverters have battery backup for their control system, so they are able to provide regenerative braking even in the case of total power failure. Moreover, vehicles that are braking can provide power to vehicles that are not braking in order to extend the range for coasting.

When the vehicle is required to land other than at a station, it will land on an air bearing that allows a graceful stop and restart. An air bearing landing is expected to be very infrequent, but is provided in the interest of safe landing anywhere on the guideway in the presence of unexpected catastrophic failure.

3.9 COLLISION MITIGATION

The system is designed with collision avoidance as the highest safety priority. The automated control system will be validated to ensure that the probability of a collision will be less than 10^{-9} per hour of operation of the guideway, or virtually nonexistent. However, during low speed maneuvers human error is a possibility. At these reduced speeds the vehicle is designed to protect the passenger compartment by absorbing the impact from collisions up to at least 5 m/s (11 mph).

4. PROPULSION SYSTEM

4.1 OVERVIEW

The propulsion system is shown schematically in Figure A-3. Utility substations are located at approximately 20 to 30 km intervals, normally in the vicinity of existing high voltage power transmission lines. At the substation the ac power is transformed and rectified to produce lower voltage dc which is fed to underground dc transmission lines along the entire length of the guideway. Inverters spaced at about 4 km intervals tap this dc transmission line and create variable voltage, variable frequency ac power for exciting the linear synchronous motor (LSM). This variable voltage power is applied to the LSM windings on the guideway and creates a traveling magnetic wave that propels the vehicle in synchronism with the motion of the magnetic field.

For safety and availability, a separate guideway is used for each direction of travel. However, the LSM is capable of moving vehicles equally well in either direction along the same section of guideway. In case of failure in one guideway lane, the opposite direction lane can be used for two-way travel, although with severely reduced capacity.

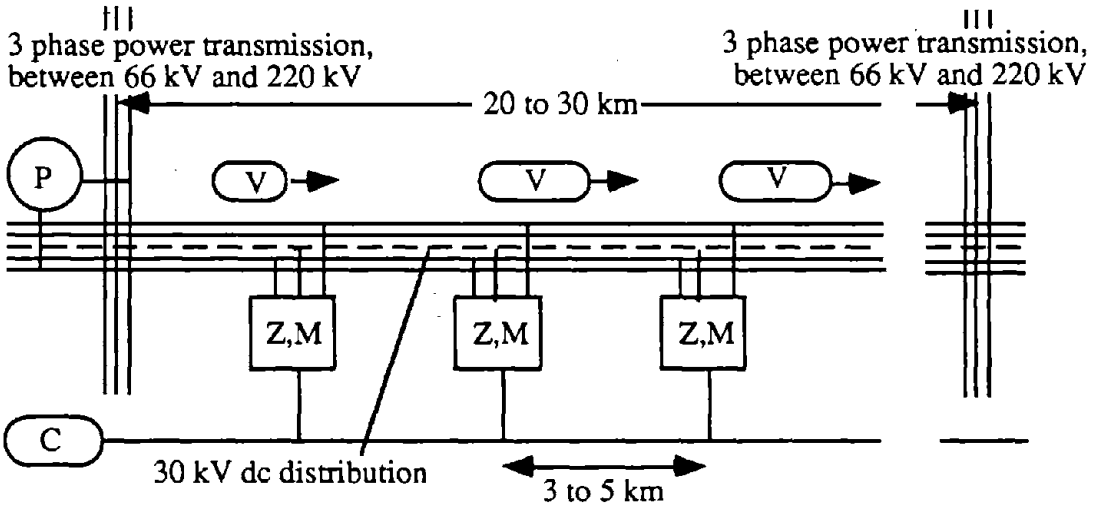


Figure A-3 Propulsion system

4.2 UTILITY SUBSTATIONS AND DC POWER DISTRIBUTION

Modern high speed rail systems use a single phase catenary voltage of 25 kV at the local power line frequency of 50 or 60 Hz. Typical maximum power requirements for a train are on the order of 20 MW, and this 25 kV voltage allows power feeder spacing on the order of 30 km. We have adopted

a similar strategy, but use underground dc power transmission from the utility substations to wayside power converters which power the LSM.

Studies of several routes, and experience with rail electrification, show that electric utility transmission lines usually cross or come near projected guideway routes at spacing of 30 km or less. The design objective is to build a utility substation about every 20 to 30 km and then transmit lower voltage dc power along the guideway. Because of the magnitude and nature of the load, the guideway power must come from transmission lines operating at 66 kV or higher voltages. Voltages near 66 kV are preferred because this reduces substation cost. Where necessary the substation can be located a few kilometers from the guideway or a short extension of transmission lines can be used to bring ac power to the guideway.

We anticipate a maximum load of 3MW/km of dual guideway. This maximum power level and normal utility spacing led to the choice of 30 kV for the dc bus voltage. This is a compromise between a higher voltage which would reduce cable cost and a lower voltage which would reduce inverter cost.

The transmission of power along the guideway reduces the need for new utility substations and allows propulsion power to be shared between adjacent power substations. When a vehicle travels down the guideway the load is gradually transferred from one utility substation to the next. In normal operation there would be several vehicles supplied from each substation at any given time.

The dc power is transmitted in underground cables with cable size chosen on the basis of substation spacing and expected maximum power requirement. For normal operation it is expected that the efficiency of the substations and the dc power distribution system will be about 95 percent at full power load with higher efficiency at reduced power levels.

4.3 ELECTRONIC POWER CONTROL

The guideway is divided into zones with an inverter station located near the center of each zone. There is at least one electronic power inverter for each zone for each lane of travel, but there will be additional inverters in some cases. For example, there will be extra inverters at stations so that acceleration and deceleration lanes can be operated independently.

The inverter uses series connected phases powered by a current source inverter with variable voltage input. The power switching is done with conventional thyristors, although gate turn off

thyristors can be used if there is a cost advantage. The variable voltage is developed from the dc bus by means of a two-phase chopper that provides protection as well as voltage control. When regenerative braking is desired the chopper regenerates power back into the dc bus. The inverter has a standby power system for its control circuitry so that this regenerative mode can be used even when there is a total loss of power from the utility power grid. The chopper plus inverter efficiency is expected to be about 94 percent at maximum power output and somewhat higher under normal cruise conditions.

The inverter controller has an accurate position sensor which allows the motor to provide controllable forces over the entire speed and power range, including reverse direction operation and regenerative braking. The position sensing is done by means of a 20 kHz signal injected into the motor winding by a coil on the vehicle. This 20 kHz frequency is high enough that it can be separated from the propulsion power frequencies on the guideway winding, and the inverter can then use the phasing of this signal to sense the vehicle position without any external communication link. There are two position sensors, one on each side of the vehicle, in order to provide redundancy. Additional position sensing is provided by guideway mounted sensors that generate an identifying signal whenever a vehicle enters or leaves a control zone.

Each zone is divided into blocks, and a block is the shortest length of guideway that can be excited by the linear motor propulsion unit. In most locations there will be one inverter and two blocks in each zone for each direction of travel. With a nominal zone length of 4 km, the active and inactive blocks would each be 2 km long. Special overlapped windings are used to allow smooth transition from one block to the next.

Semiconductor switches are used to determine which block is excited by the inverter, and the unexcited block is short-circuited to provide the maximum allowable dynamic braking. There is always an unexcited block between two active blocks, and any vehicle that enters an unexcited block will be subject to strong deceleration forces. The switches which connect resistors to an inactive block are powered by a control system with battery backup facilities so that the dynamic braking can be applied when the power system fails.

A vehicle is propelled by two independent six-phase inverters driving the separate port and starboard motor windings. One inverter is powered from the positive dc bus while the other is powered from the negative bus. In the event of failure in either the port or starboard motor systems the other system can provide enough thrust to allow full speed operation, although with reduced

acceleration capability. This redundancy entails little added cost and provides highly available, safe operation in the presence of many types of failure.

4.4 MOTOR WINDINGS

The inverter power is delivered to port and starboard motor windings, each with six phases of meander windings. The use of six phases allows considerable fault tolerance since a failure of any one phase will allow power in the remaining phases to provide continued operation. Acceleration and deceleration will be slightly reduced, but the system will be able to operate safely and at full guideway capacity for many hours until repairs can be effected.

The motor winding is one of the few guideway components that is subject to failure over time periods of less than about 50 years. Since we can expect some failures to occur, it is necessary to have a method of replacing the winding. A special mounting scheme allows replacement of sections of the windings in a relatively short time.

4.5 PROPULSION POWER REQUIREMENTS

Estimated propulsion power demand at 135 m/s is: 10 kW per Mg for suspension and guidance, 150 kW for eddy current loss in the guideway. The aerodynamic drag force varies as the square of speed with a drag of 40 kN at 135 m/s. The linear motor is designed to be 90 percent efficient when propelling the vehicle at the design speed of 135 m/s. The total power loss for a 64 Mg vehicle is then about 6 MW at 135 m/s and 4.9 MW at 120 m/s. This power must be provided by the electronic inverters to the motor windings in the guideway.

The LSM requires about 6 MW for constant speed cruise, but it is necessary for the motor to produce substantially higher thrust. A good design rule is to specify a thrust of 0.2 g, so a 64 Mg vehicle requires 125 kN of thrust. In order to provide this much thrust at 135 m/s, and considering LSM winding resistance loss, the inverter should be rated at about 21 MW peak. This rating will provide thrust capability to allow the vehicle to achieve its speed potential in the face of the frequent speed changes that are necessary if the vehicle is to follow the curves of a highway based right of way. In sections of the guideway where the vehicle can operate at nearly constant speed, a 10 to 15 MW inverter may be adequate and inverter spacing can be increased to 6 km.

4.6 ENERGY CONSUMPTION AND COST

When power is purchased in bulk from high voltage transmission lines, the cost is only about half of the cost for residential power, typically in the range $0.04 to $0.07 per kWh. In order to buy power at this rate the user must install and operate the power substations. Utilities are willing to purchase and operate a substation for a customer, with a monthly charge commensurate with the cost of the service. It is an economic decision as to whether it is better to pay less for the electricity or to reduce capital expenditures. The difference in energy cost is typically about $0.02 to $0.03 per kwh.

At a steady speed of 135 m/s the power load is estimated to be 6 MW, or 100 Watt-hours per seat-km. At a speed of 125 m/s the power requirement is about 4.7 MW, or 92 Watt-hours per seat-km. Assuming an electricity cost of $0.055 per kWh and a passenger load factor of 60 percent, the estimated energy cost is about 1.0¢ per passenger-km at 135 m/s and 0.84¢ per passenger-km at 120 m/s.

4.7 FAULT TOLERANT PROPULSION

Sometimes it is necessary to operate at reduced speed because of extreme environmental conditions or system malfunctions. If the vehicles slow down too much, the guideway capacity is reduced because of the restriction of no more than one vehicle per zone. For this special reduced speed condition the port inverter can be connected to one block and the starboard inverter connected to the other block in the same zone. With this mode a 40 s headway is possible at a speed of 50 m/s (112 mph), albeit with only 50 percent as much thrust capability. There is no longer a dead block between operating vehicles, but the stopping distance is also reduced so the probability of a collision can be made extremely low.

Adequate fault coverage is provided within each inverter as well as for each power substation to allow normal operation, or operation at reduced speeds which still maintain system capacity during the repair of a failed component.

The multiple feed guideway power distribution provides a large measure of fault tolerance because an outage on one transmission line can be compensated by power from adjacent substations. When one power station outage is detected all affected vehicles will slow down enough to limit power to that available from adjacent substations. It is rarely necessary to operate at speeds below about 100

m/s because of failure of a single power station, thus guideway capacity is not reduced and no major service interruption will be created.

Transmission line failure is much less common than power distribution line failure, so power availability will be very high. In regions where outages are more common it will be possible to use a battery bank to provide power for emergency operation, but it is not expected that a battery backup system will be necessary to achieve an acceptable level of availability.

Protection is provided by circuit breakers in the high voltage ac line, and electrical disconnects are used to allow isolating any portion of the dc bus that experiences a fault. No dc circuit breakers are required.

4.8 SAFETY FEATURES

In the event of total power loss from the utilities it is desirable to be able to dynamically brake all vehicles simultaneously. This is done with a resistor bank located near each substation, and these resistors will be switched in as necessary to dissipate energy generated by the decelerating vehicles without allowing the dc bus voltage to rise too high. The inverter controllers will all have a standby power source that can provide control power in the event of power system failure. The control system would endeavor to stop each vehicle at a station or in a preferred stopping area on the guideway. Note that if some vehicles are braking the power generated can be used to power other vehicles, so most vehicles should be able to reach a station or preferred stopping area.

Each station will have an emergency battery backup power source that can provide reduced dc voltage and enough power to propel a vehicle that has been forced to stop near the station but not at a safe stopping place. This battery operation is desirable because near a station it is common for vehicles to be operating at relatively low speeds, and thus they are more vulnerable to a failure in the power system. In this way total power failure will not strand any vehicle at an inaccessible point. In most cases power failures are local, so the multiplicity of power substations will allow utility-generated power to provide controlled stopping of all vehicles at a station.

In a truly catastrophic failure, such as loss of guideway integrity, all linear motor windings would be connected to dynamic braking resistors to provide fail safe braking.

5. GUIDEWAY

5.1 GUIDEWAY GIRDER AND SUPPORT STRUCTURE

The guideway structure consists of girders and support frames as columns and foundations. The propulsion/levitation/guidance system is mounted on both sides of the upper girder section. The vehicle straddles the guideway girder and its magnets interact with the girder mounted equipment providing propulsion, levitation and guidance. The guideway may typically be elevated, but when possible will be constructed at grade. Figure A-4 shows a frame elevation with basic dimensions.

The girder is a hollow box-beam with dimensions as shown in Figure A-5. The upper half of the girder section is exposed to magnetic fields generated by the vehicle magnets. This necessitates the use of FRP reinforcement in this part of the girder section. Steel reinforcement is used in the lower girder section. Both reinforcement types cover shear and torsional stresses. Bending stresses are taken by conventional prestressing steel located in the lower half of the girder.

At-grade girders are conventionally reinforced but utilize FRP rods in the upper section.

The use of FRP reinforcement allows the construction of a full strength, nonmagnetic beam at cost acceptable for maglev application.

Support structures consist of single columns and foundations (single track) or in the case of double track systems of frames and foundations. Typically, support structures are poured in place but prefabrication and subsequent erection of columns is possible. Standard steel reinforcement is used in all support structures.

5.2 SUSPENSION AND PROPULSION MOUNTING

The suspension, guidance and propulsion systems require the mounting of substantial amounts of aluminum and copper conductors on the guideway. These components are all exposed to significant pulsating forces, and these forces must be transferred to the guideway. Among the problems addressed in the baseline design are: the potential for corrosion and vibration to loosen the mountings, the necessity of using non-magnetic and non-conducting mounting hardware, the need for high voltage insulation on the propulsion windings, and the tendency for structures like these to create excessive acoustical noise. The baseline design uses the mounting system shown in Figure A-6, although alternate approaches have been explored.

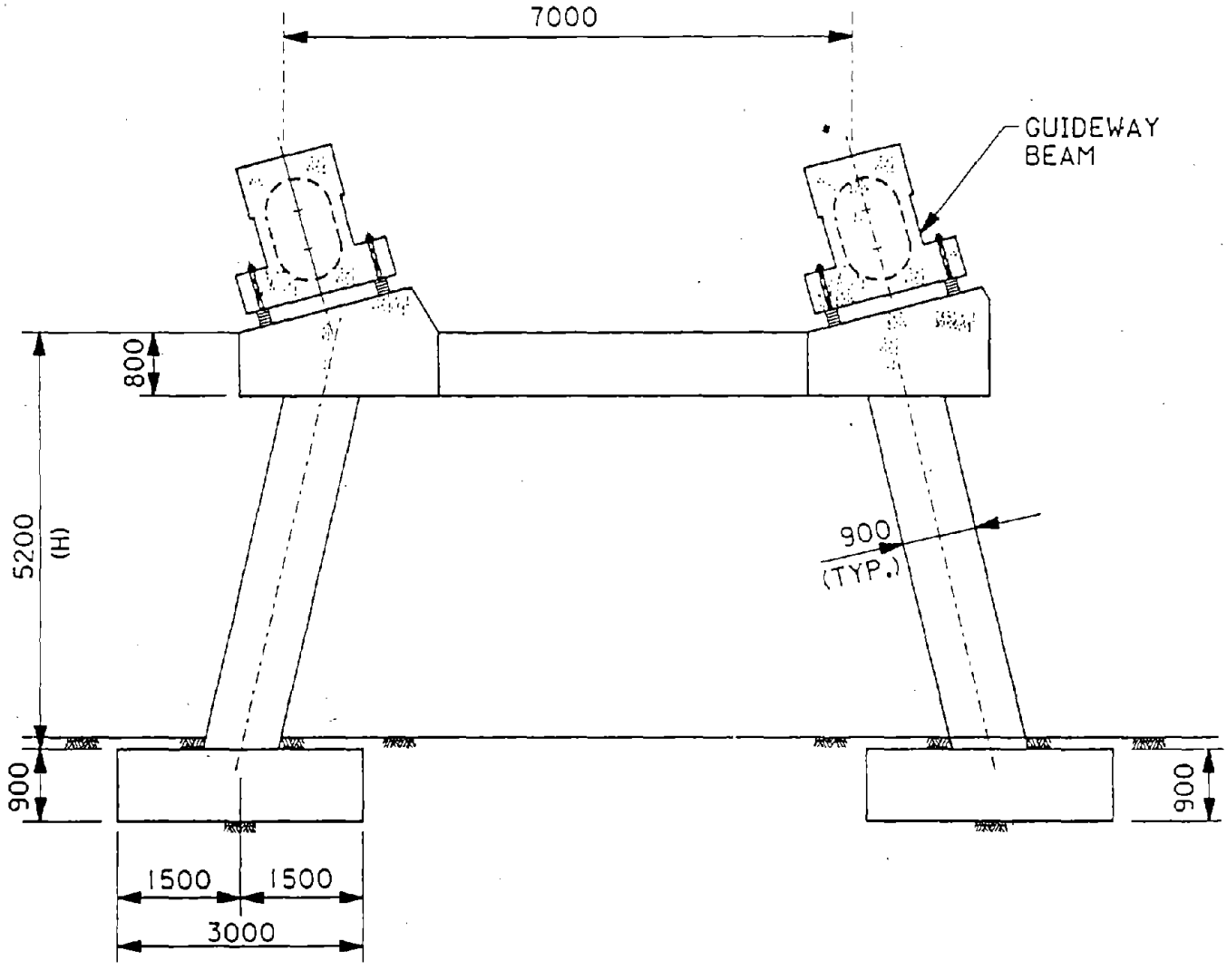


Figure A-4 Guideway frame elevation

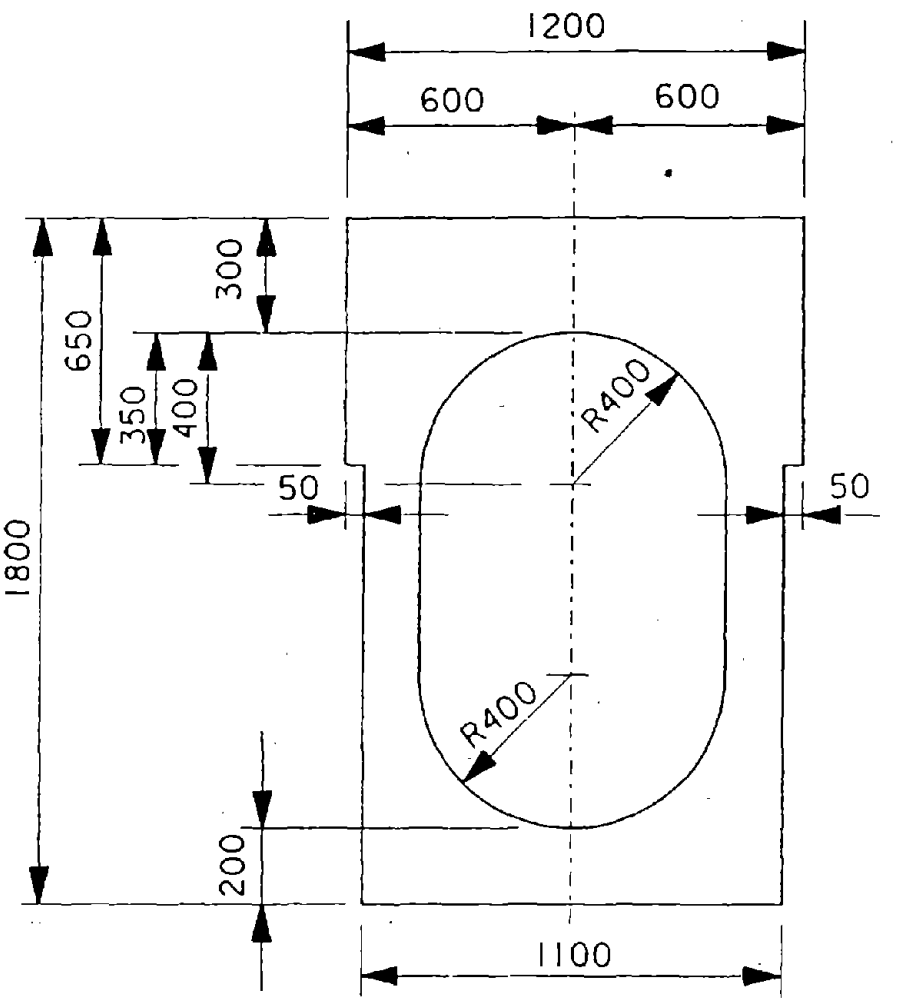


Figure A-5 Girder cross-section

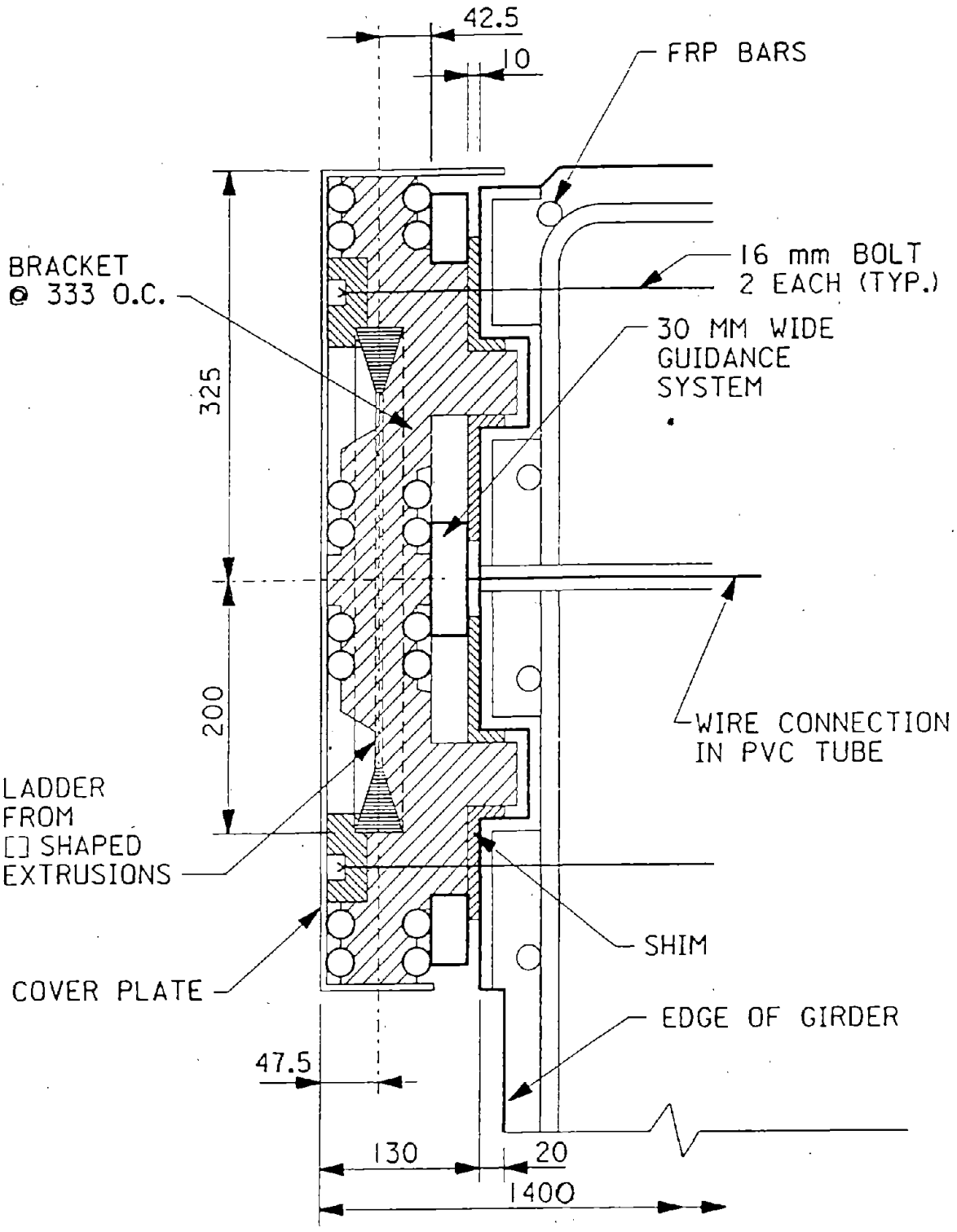


Figure A-6 Propulsion/levitation/guidance mounting bracket

Our baseline propulsion//levitation/guidance system consists of:

Two six-phase cable windings
The guidance system
The levitation ladder

The six-phase cable windings are supported by the mounting bracket and provide propulsion and braking forces.

The guidance system consists of aluminum coils supported within FRP frames 666 mm long and 610 mm high. These frames are attached to the rear side (girder) of the mounting bracket which also provides vertical support.

The levitation ladder is fabricated out of high strength aluminum alloy of good conductivity. Individual sections are extruded and then bonded together to form the ladder. The propulsion ladder is mounted to the front of the bracket. The entire system is covered by a cover plate to reduce aerodynamic drag and noise.

The mounting bracket is adjustable in vertical and lateral direction to permit precision alignment of the levitation, guidance and propulsion system. Variable dimension FRP shims, achor bolts and shear keys provide lateral, vertical and horizontal support.

5.3 SWITCHES

The proposed baseline switch features a flexible FRP girder which can be laterally deformed to line up with an alternate section of the guideway. The technology of flexible switches was developed and tested for monorails in the late 1950s and has been successfully operated at Japanese test sites and most extensively at the site in Emsland, Germany by Transrapid. These switches permit operating speeds for 200 km/h with lateral acceleration limits of 0.1 g.

For low operating speeds of 20 to 30 km/h in storage and maintenance yards and at crossovers, standard 25.0 m long straight girders can be used. These girders are supported by undercarriages permitting lateral movements such that the girders form a polygon in curved track position.

Our Team also is proposing two alternate switch concepts; our preferred alternate concept is structurally passive with no movement of guideway components and is described in detail in the body of the report.

An alternate switch concept is described in Section D4-2. This is a passive switch from the standpoint that there are no moving parts on the guideway. It is also true that there are no moving parts on the vehicle. Switching is accomplished by the setting of electrical switches on the guideway prior to the arrival of the vehicle.

This alternate concept removes the potentially hazardous situation which might be created if a vehicle encounters an open or partially open switch. It also increases the throughput of the system by removing the need to maintain increased separations to guard against this hazard. The concept is not part of the baseline from the standpoint that it would require modifications to the baseline vehicle. Also, some additional development would be required to verify that there are no problems which would render the design impractical.

5.4 PREFERRED STOPPING AREAS

At every inverter station there is a preferred stopping area where vehicles can make unscheduled stops in relative safety. Each preferred stopping area can accommodate at least two vehicles and provide zero speed levitation for smooth starting and stopping. When two vehicles are stopped it is possible to transfer passengers from one to the other which can then go either forward or backward to transport the passengers to a nearby station. There is also a means for passengers to walk down a stairway to the ground where buses can transport them to a convenient location. Preferred stopping areas can provide on-board power to vehicles so that passengers can stay in the vehicle in comfort with all on-board equipment operative.

The 4 km spacing of the inverter stations is short enough that in almost all cases a vehicle will be able to reach to a preferred stopping area. For example, a vehicle which starts coasting to a stop from a speed of 80 m/s will stop in about 6 km, and with dynamic braking it can stop in 2 km; as long as this difference in stopping distances is greater than the zone length we can ensure that a vehicle will reach a safe stopping point. Vehicles traveling at low speeds when the power fails would be accelerated using power generated by other decelerating vehicles. In this way it is expected that most vehicles would reach a preferred stopping area.

Preferred stopping areas can also be used as temporary on-line stations whenever it is desirable to shut down portions of the guideway, such as when an earthquake occurs.

5.5 RESCUE AND MAINTENANCE VEHICLES

A vehicle might stop at other than a preferred stopping point for several reasons. If the reason is a temporary power outage, then the vehicle can be restarted when power is reapplied. If the stop is due to a major failure and the vehicle cannot go forward or back, then a rescue operation may be appropriate.

Rescue can often be accomplished by transferring people to another vehicle traveling in the opposite direction using special transfer facilities. If this is not possible, the preferred rescue mode is to use internal combustion powered vehicles to drive down the guideway and either drag the disabled vehicle to a safe stopping area or remove the passengers. The objective is to design the system in such a way that this type of event occurs with extremely low probability, e.g., when there is a massive earthquake with no advance warning.

Every station will be manned around the clock, and will have a rescue vehicle that can be dispatched at any time. This vehicle can also be used to carry personnel along the guideway to effect inspections or minor repairs. This type of vehicle has been used for many years by Transrapid on a routine basis.

6. COMMUNICATION AND CONTROL

6.1 OVERVIEW

Maglev vehicles will travel significantly faster than any existing ground transportation vehicles. The higher speed, coupled with short headway and off-line stations, implies more serious consequences for control failure. The conflict between capacity and safety requires the use of a fully automated and validated control system, and human operators are unable to perform the required real-time control.

Our LSM propulsion system uses very precise position sensors and maintains absolute synchronism between the vehicle position and a traveling magnetic wave created by the propulsion system. There are physically distinct blocks of guideway, and if a vehicle enters a block unexpectedly it will be exposed to high dynamic braking forces, giving a high degree of safety due to the inherent attributes of the LSM.

The proposed communication and control system is shown schematically in Figure A-7. The guideway is shown divided into successive zones with the vehicles traveling along the guideway from zone to zone. There are communication and control systems for each direction of travel. The two directions share common facilities, but are functionally independent, so Figure A-7 and the following discussion are focused on communication and control for a single direction of travel.

6.2 ZONE CONTROL

The zone is a physically distinct section of guideway that is typically about 4 km long, but may be longer or shorter depending upon terrain and other design factors. The zone control is the lowest level of control and is located physically and functionally in an unmanned facility near the center of a zone. The zone control's principal function is to control a vehicle that is traversing the zone. The zone control is located on the guideway because of the greater availability of communication facilities, electric power, space, and the immediate proximity to the propulsion system. But the zone control is in continuous communication with, and always acts in the best interest of, the vehicle.

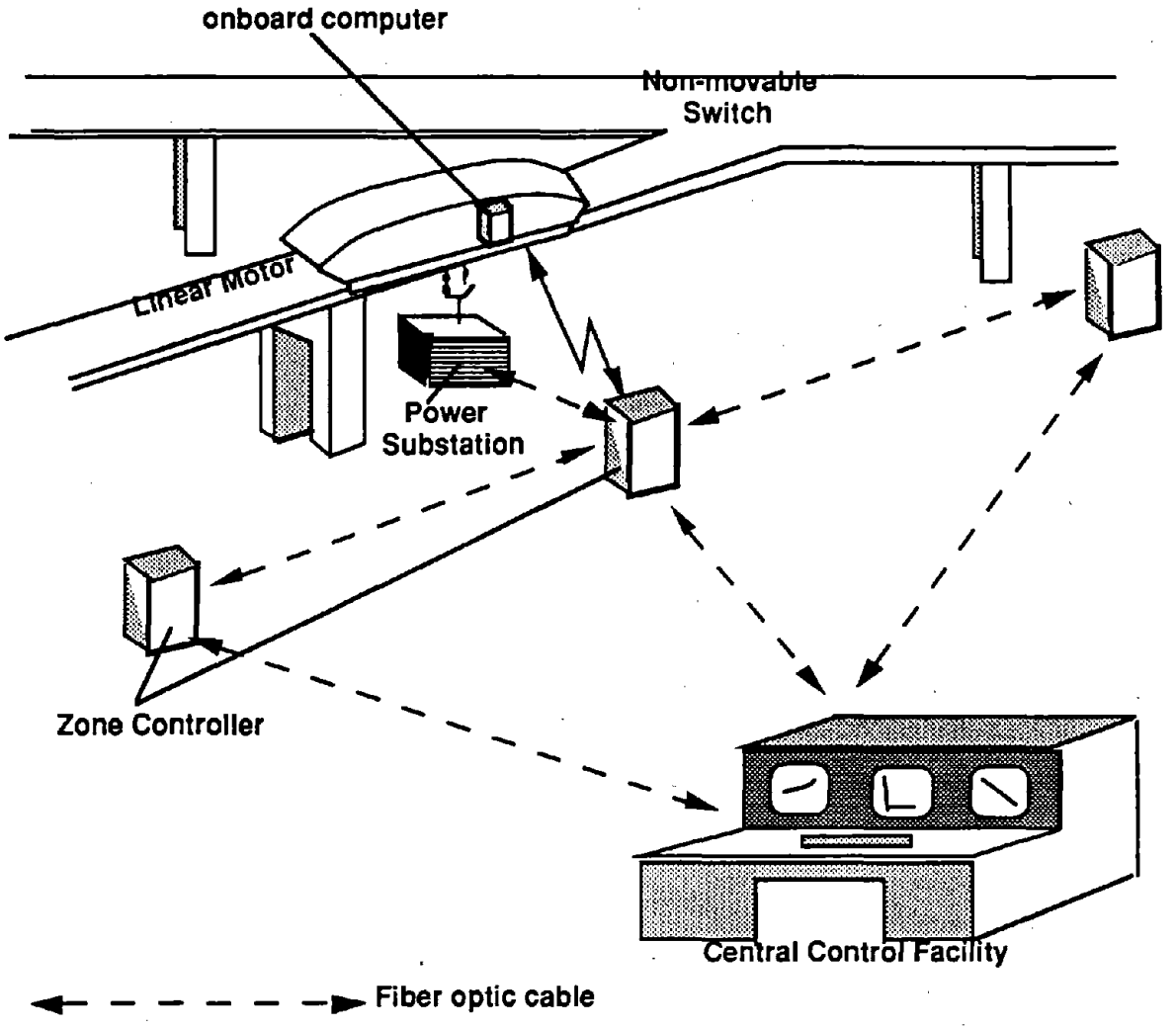


Figure A-7 Communication and control system

The zone controller provides the control function for the inverter which converts dc guideway power to ac for exciting the motor winding. There are two 6-phase, port and starboard, inverters that are functionally distinct, but in normal operation the two act in consort to propel the vehicle.

The zone controller also controls dynamic braking. In case of complete failure of the power system or both inverters, the zone controller can connect passive resistors across the motor windings in order to effect braking. This operation can be performed using only standby battery power and in spite of any malfunction in the inverters.

The zone controller maintains a current data base about the guideway in its zone, including grades, radii of curvature, weather conditions, and any special information needed for speed control. It is preprogrammed to provide a carefully tailored velocity profile for the vehicle. There are many

preprogrammed profiles, and a higher level control specifies which profile to follow, but the zone control operates the electronic power modules in order to follow the selected one. The zone controller also sends position, velocity, and power information back to the higher level controllers on a regular basis, typically about once a second.

Higher level controllers are charged with safe operation of the entire guideway system, but the zone control acts autonomously to provide as much protection as possible, and to mitigate the effect of failures that might occur at higher levels. For example, a zone controller is in continuous communication with neighboring controllers in order to anticipate the entry of a new vehicle into a zone and to notify neighboring zone controllers when a vehicle is about to enter the neighboring zone. In this way there is protection from common mode failures in the communication system and higher level controls.

When a vehicle enters a new zone it generates a vehicle identification signal that verifies to the zone controller the vehicle identification and precise position. In normal operation the appearance of a vehicle in a zone is anticipated well in advance, but the independently generated signal provides a verification that is essential for reliable control. If the sensor signal differs substantively from what was expected, then the zone controller must assume there is a problem and take corrective action.

6.3 ON-BOARD VEHICLE CONTROL

The vehicle contains a substantial number of systems requiring on-board control, including: the cryogenic system for the superconducting magnets, an on-board power generation system, a secondary suspension system which includes active vehicle banking operations, aerodynamic actuators, and a significant number of sensors which continually monitor the vehicle state. Although velocity and position control are managed by the zone control system, the vehicle has sensors that determine its precise position and this is provided to the wayside controllers as a backup source of position and velocity information.

The vehicles use radio links to communicate with the zone and station controllers. There is also a provision for low bandwidth backup communication from the vehicles via signals transmitted on the propulsion windings and via a "leaky" coax cable.

6.4 POWER SUBSTATION CONTROL

Every utility substation has a controller that is charged with monitoring the behavior of the substation and providing protection for the transformers, rectifiers, and dc distribution system. These controls can request power load reduction and may even order a momentary power-off condition while electrical disconnects are operated.

Protection is provided by circuit breakers in the primary of the high voltage transformers. These allow total isolation of the guideway from the power grid, and limit voltages and currents. Electrical disconnects allow isolation of any part of the power distribution system. For example, because there are continual feeds, if there is a failure in an underground dc cable in a section of guideway, that section can be isolated without interrupting power transmission to any inverter. The power controller may have to request a power load reduction in the affected section of the guideway, but guideway capacity should not be affected.

6.5 STATION CONTROL

Each station has a control system that is responsible for monitoring the behavior of neighboring zone controllers, including the acceleration and deceleration lane zone controllers, and for docking and dispatching vehicles when they enter and leave the station. A station is manned at all times, and there are always personnel on hand who are trained to deal with common types of control problems. For example, the station personnel can dispatch a rescue vehicle to evacuate passengers or effect minor repairs.

Global level control of the zones and vehicle movement is normally exercised from The Central Control. However, if the stations detect that The Central Control is not operational, the stations will assume prime responsibility for controlling the zones and managing vehicle movement. Since the multiple station controllers will each exercise control over a limited section of guideway (that between adjacent stations), vehicle movements will be slightly less efficient than when exercised by The Central Control.

In the event of multiple failures involving The Central Control and one or more stations, individual zone controllers, working only with adjacent zone controllers, will still be able to keep vehicles moving from station to station, but with a further reduction in frequency of service.

The station control system has some manual control functions that can be performed by station personnel. These primarily concern low speed operation of vehicles and communication with personnel on stopped vehicles.

6.6 CENTRAL CONTROL

For proposed corridors that are a few hundred kilometers long, a single central control can manage all traffic. The Central Control is the highest level of control and is responsible for all functions that cannot be handled as well at lower levels. This includes monitoring the operation of all station and zone control systems and taking appropriate actions in case of problems. Central Control can shut down any part of or the entire system, when necessary, and is responsible for restarting the system after any shutdown.

The Central Control has global knowledge of the state of the system and therefore allocated responsibility for functions, such as scheduling vehicle movements, which require this global knowledge. Scheduling the movement of any one vehicle, for instance, must take into account the position and expected movement of all other vehicles in the system in order to integrate the movement of all vehicles most expeditiously. Therefore, this level of scheduling responsibility is exercised by The Central Control.

Central Control must approve all requests for a vehicle to enter or leave the guideway, and assumes responsibility in case of major failure. It directly controls the zone controllers and the station controllers. Accounting functions are handled by the Central Control. This includes assessing guideway and energy usage and billing the customers.

The Central Control computer is built with a high level of fault tolerance, and the facility is manned 24 hours a day with personnel who can make repairs as needed. Spare modules allow continuous operation with negligible down time.

6.7 COMMUNICATION

All wayside controllers communicate with each other over a fault tolerant network that is installed along the guideway. This network uses fiber optic cables installed in the guideway. The vehicles can communicate with the wayside controllers over radio links, and also, with limited bandwidth, using the motor windings.

7. MAINTENANCE

7.1 GUIDEWAY MAINTENANCE

Automated test vehicles will make daily inspection trips to ascertain the guideway condition. These vehicles will record acceleration and velocity in all dimensions, and computer processing of this data will allow estimates of guideway irregularity. The test vehicle can be an instrumented passenger vehicle which carries passengers at the same time it records test data. By tracking the guideway condition over time, developing irregularities can be corrected during routine maintenance. The large gap between the levitation magnets and the guideway allows slowly developing irregularities to be tolerated until repair is convenient.

Experience with similar structures suggests that there will almost never be a case when there is a need to reconstruct a section of the guideway because of sudden and severe damage. The only exception is a catastrophic event, such as an earthquake, which can cause disruptions to any transportation system. In all other cases temporary repairs can be made that allow continuing operation until permanent repairs can be completed.

7.2 PROPULSION AND CONTROL SYSTEM MAINTENANCE

Automatic diagnostics will allow most failures in the propulsion and control systems to be detected before they produce serious problems. The fault tolerant design allows nearly full speed operation in the event of single failures and reduced speed operation in the event of many types of multiple failures. When necessary, the system can be shut down long enough to perform minor repairs.

A rigorous program of preventive maintenance, conducted with frequent and thorough monitoring, and the enforcement of conservative criteria for replacement, will preclude the necessity of shutting down for a major repair. Necessary maintenance operations are conducted on the propulsion system, central computer facilities, communications equipment, stations and wayside power stations based on both continuous condition monitoring and routine scheduled maintenance. The maintenance schedule assumes a high degree of modularity in the design and construction of the propulsion and control systems.

In extreme cases requiring extensive maintenance, it is possible to operate vehicles in both directions on a single guideway lane by using the crossovers at stations. The operation resembles the mode used on highways with vehicles allowed to pass in one direction while they are held in the other direction, and then periodically reversing the direction of travel. Maintenance requiring

single-lane operation can usually be scheduled for times of reduced demand, a method commonly used for highway repair.

7.3 VEHICLE MAINTENANCE

Vehicles are serviced at least once a day to replace cooling fluids, recharge the superconducting magnets, and perform other conventional vehicle service functions. Routine maintenance is scheduled for every vehicle in accordance with the manufacturer's specifications. On-condition monitoring ensures that the minimum dispatch complement of all system components is present before a vehicle leaves a station. Exceptional cases requiring unscheduled maintenance of a vehicle will normally result in the substitution of a spare vehicle in place of the vehicle which does not pass certification.

In order to achieve high availability, the vehicle uses state-of-the-art methods to monitor and record performance data in order to anticipate most failures. Although a system can fail catastrophically, usually performance degradation can be detected by careful analysis of measured data. The use of scheduled maintenance plus performance monitoring will be used to minimize unexpected failures.

The Bechtel Team's Maglev Integrated Prognostics and Diagnostics System will provide the capability to meet the required availability of the maglev vehicle. All maintenance will be performed at a maintenance facility on a scheduled basis. The system's design goal will be to provide 100 percent fault prediction for non-electronic components. The design approach for increasing the availability of electronic components is to provide real-time fault detection capability, online reconfigurability, and sufficient component redundancy to meet the reliability and availability requirements of the onboard electronics. This obviates the need for unscheduled maintenance by automatically replacing a failed component with a working spare. Preventive maintenance recommendations as well as unambiguous fault isolation guidance will also be provided to maintenance personnel.

The Maglev Integrated Prognostics and Diagnostics System will monitor and analyze data from all subsystems of the maglev vehicle. The performance and environmental monitoring system will be distributed throughout the vehicle. The monitoring system will be hierarchically structured so that the determination of the maintenance requirement can be efficiently implemented.

Environmental conditions at the time of failure will be recorded by built in non-volatile memory on each line replaceable unit (LRU). The repair/maintenance history of each LRU will also be stored

in the nonvolatile memory. This data will be used to help weed out intermittent LRUs and to replace electronic components which have been exposed to environmental conditions which exceed their specifications.

When the prognostic system determines an impending failure, redundant functionality, if available, can be activated and an alert provided to the maintenance manager. Preventive maintenance or LRU replacement can then take place at a maintenance facility on a scheduled basis.

The Maglev Integrated Prognostics and Diagnostics System will use artificial intelligence, prognostics, and electronic information delivery technology to provide an efficient maintenance management and aiding system. Maintenance personnel will require minimal formal training and their proficiency will be greatly improved through the use of these technologies. Special support equipment requirements will be greatly reduced because Built In Test (BIT)/Diagnostics and maintenance data will be part of the vehicle system. Overall, system availability will be maximized and all repairs will be performed on a scheduled basis.

8. HYPOTHETICAL ROUTE SIMULATION OVERVIEW

The hypothetical route simulation is a computer program for simulating maglev on a benchmark guideway alignment for performance assessment of the maglev transportation system within the context of the current System Concept Definition contract. The total guideway distance of the hypothetical route from terminal #1 where it starts, to terminal #4 where it ends, is 800 kilometers and consists of a number of horizontal curves with radii of curvature as small as 400 meters, and elevation grades as steep as 10 percent. Terminal #2 is located at 400 kilometers and terminal #3 is at 470 kilometers. In addition, there is a 5-kilometer tunnel beginning at 515 kilometers from terminal #1. The route meanders horizontally and vertically until 475 kilometers, at which point it is straight and level until terminal #4.

Our maglev simulation has adapted the hypothetical route alignment for determination of significant characteristic parameters for the Bechtel concept maglev. This simulation consists of programs that have been specifically tailored to allow analysis of the route, and in fact these same programs are being used by the Government in its analysis of the performance characteristics of alternate SCD concepts for the National Maglev Initiative.

Inputs to the simulation include route alignment data, positions of stations, maximum line speed, maximum banking angle, kinematic parameter limits such as accelerations, jerks, and braking. Outputs include total trip time, velocity vs distance or time and acceleration vs distance or time. The distance and time increment resolution is adjustable. Total trip time is the total time for the vehicle to travel beginning to the end of the hypothetical route. The vehicle stops at stations only momentarily in the model. Vehicle velocity and acceleration profiles give the total velocity vs distance or time and acceleration vs distance or time, respectively, traveled by the vehicle at any given distance or time increment.

8.1 PERFORMANCE CHARACTERISTICS

Three sets of performance parameters were simulated: US1 design, minimum requirements, and seat belted. US1 design parameters represent the current Bechtel concept baseline. Minimum requirements and seat belted parameters represent the Department of Transportation's maximum allowable values for ride comfort. Also simulated were judicious departures from the hypothetical alignment route using the US1 design parameter set. The parametric values for each performance set are given in Table A-1.

Table A-1
Performance Parameters

	US1 DESIGN	MINIMUM REQUIREMENTS	SEAT BELTED	MINIMUM REQUIREMENTS with ZERO TILT	
Line speed	134	134	134	134	meters/second
Maximum speed at maximum acceleration	120	120	120	120	meters/second
Total Banking angle	30	30	45	15	degrees
Lateral acceleration limit	0.16	0.16	0.20	0.16	g's
Lateral jerk limit	0.25	0.25	0.25	0.25	g's/s
* Downward acceleration	0.10	0.10	0.10	0.10	g's
* Upward acceleration	0.30	0.30	0.40	0.30	g's
Vertical jerk limit	0.30	0.3	0.30	0.3	g's/s
Fore-aft acceleration	0.16	0.20	0.6	0.20	g's
Fore-aft jerk limit	0.25	0.25	0.25	0.25	g's/s
Braking limit	0.16	0.20	0.6	0.20	g's

* The other three System Concept Definition teams used 0.05 g and 0.2 g acceleration limits; therefore, a direct comparison is not possible.

8.2 TOTAL TRIP TIMES

The total trip times and average speeds for US1 design, minimum requirements, seat belted, and minimum requirements with zero tilt parameter sets to travel from station #1 to station #4 on the hypothetical route is given in Table A-2.

Table A-2
Total Trip Times

	TOTAL TRIP TIME	AVERAGE SPEED	TRIP TIME DIFFERENCE from US1 Design	AVERAGE SPEED DIFFERENCE from US1 Design
US1 DESIGN	1h 59m 02s 7142 seconds	111.8 m/s 250 mph		
MINIMUM REQUIREMENTS	1h 58m 24s 7104 seconds	112.4 m/s 251 mph	0m 38 38 seconds	0.6 m/s 1 mph
SEAT BELTED	1h 45m 15s 6315 seconds	127 m/s 284 mph	13m 47s 827 seconds	15.2 m/sec 34 mph
MINIMUM REQUIREMENTS with Zero deg. TILT	2h 11m 11s 7871 seconds	102 m/s 228 mph	-12m 09s -729 seconds	-9.8 m/sec -21.9 mph

8.3 NUMBER AND SIZE OF VEHICLES

For the hypothetical route, only one vehicle at a time was simulated. Each vehicle has a passenger capacity of 120 people.

8.4 ENERGY DEMAND

The energy consumption for one vehicle to traverse the hypothetical route in the forward direction from terminal #1 to terminal #4 is given in Table A-3. The US1 design parameter set was used to determine the energy values. The top row represents the baseline, and the succeeding rows of the table shows the increase in energy requirements as the acceleration and braking parameters are increased. If 400 vehicles were to be put into operation (200 each way) for the hypothetical route (800 km) to provide 12,000 passengers per hour per direction, the total energy for a 2-hour period would be 26×10^{12} joules (7,350 MWh). This is 3,675 MW average continuous power and is equivalent to the output of 2 or 3 average sized power generating stations, an average station producing between one and two thousand megawatts (per Southern California Edison).

Table A-3
Total Energy per Vehicle per Trip

Forward Acceleration Limit	Braking Limit	Megajoules	Kilowatt-hours
0.16 g	0.16 g	66,153	18,376
0.20 g	0.16 g	66,838	18,566
0.16 g	0.20 g	69,253	19,237
0.20 g	0.20 g	69,984	19,440

8.5 BI-DIRECTIONAL ANALYSIS

A simulation was performed showing the differences between trip times in the forward and reverse directions as shown in Table A-4. The traversing of the hypothetical route in the reverse direction results in only a small difference in total trip time.

Table A-4
Reverse Direction Trip Time

	TOTAL TRIP TIME	AVERAGE SPEED	Time Difference	Speed Difference
US1 DESIGN	1h 59m 02s 7142 seconds	111.8 m/s 250 mph		
REVERSE DIRECTION	1h 59m 56s 7196 seconds	111.4 m/s 249 mph	54 s	0.4 m/s 1 mph

8.6 "JUDICIOUS DEPARTURE" RESULTS

Two simulations were run after making the radii of curvature not less than 1,000 meters and not less than 3,000 meters, respectively. Table A-5 shows the total trip time of the redesigned routes compared to the standard route. Standard and redesigned routes used the minimum requirements parameter set. The 3,000 meters minimum radii of curvature is especially significant, since increasing this value a little to 3,120 meters would allow geometric chords to be used in the guideway construction rather than curved beams. Not having to build any bends into the beams would reduce the cost of the guideway.

Table A-5
Redesigned Route Alignment Trip Time

	TOTAL TRIP TIME	AVERAGE SPEED	Time Difference	Speed Difference
STANDARD ALIGNMENT USING MINIMUM REQUIREMENTS	1h 59m 02s 7142 seconds	111.8 m/s 250 mph		
REDESIGNED ALIGNMENT WITH NO RADII OF CURVATURE LESS THAN 1000 METERS	1h 55m 55s 6955 seconds	114.8 m/s 256.6 mph	0h 3m 07s 187 s	3 m/s 6.6 mph
REDESIGNED ALIGNMENT WITH NO RADII OF CURVATURE LESS THAN 3000 METERS	1h 42m 09s 6129 seconds	130.3 m/s 291.3 mph	0h 16m 53s 1013 s	18.5 m/s 41.3 mph

8.7 REQUIRED VEHICLE HEADWAY

Required headway was calculated for three cases given in Tables A-6, A-7, and A-8: These are respectively, Case I Safety/Brickwall Distance Capacity Analysis, Case II Equal Distance System Capacity Analysis where distance headway is equal to 4,000 meters, and Case III Equal Time System Capacity Analysis where time headway is not allowed to be less than 40 seconds. For a complete description of how each value was arrived at, see the Final Hypothetical Route Report.

Table A-6
Case I Safety/Brickwall Distance Capacity Analysis

Speed m/sec	Braking Rate m/s^2	Time to Stop seconds	Minimum Stop Dist. meters	Minimum Headway meters	Minimum Headway seconds	**System Headway seconds**	Vehicles Per Hr	**System Capacity pphpd**
28	3.00	9.3	236	2000	72.0	**72.0**	50	**6000**
56	3.00	18.5	650	2000	36.0	**36.0**	100	**12000**
83	3.00	27.8	1321	2000	24.0	**24.0**	150	**18000**
111	3.00	37.0	2249	4000	36.0	**36.0**	100	**12000**
139	3.00	46.3	3434	4000	28.8	**28.8**	125	**15000**

Table A-7
Case II Equal Distance-Headway >= 4000 Meters

Speed m/sec	Braking Rate m/s^2	Time to Stop seconds	Minimum Stop Dist. meters	Minimum Headway meters	Minimum Headway seconds	**System Headway seconds**	Vehicles Per Hr	**System Capacity pphpd**
28	3.00	9.3	236	4000	144.0	**144.0**	25	**3000**
56	3.00	18.5	650	4000	72.0	**72.0**	50	**6000**
83	3.00	27.8	1321	4000	48.0	**48.0**	75	**9000**
111	3.00	37.0	2249	4000	36.0	**36.0**	100	**12000**
139	3.00	46.3	3434	4000	28.8	**28.8**	125	**15000**

Table A-8
Case III Equal Time-Headway >= 40 Seconds

Speed m/sec	Braking Rate m/s^2	Time to Stop seconds	Minimum Stop Dist. meters	Minimum Headway meters	Minimum Headway seconds	**System Headway seconds**	Vehicles Per Hr	**System Capacity pphpd**
28	3.00	9.3	236	2000	72.0	**72.0**	50	**6000**
56	3.00	18.5	650	2000	36.0	**40.0**	90	**10800**
83	3.00	27.8	1321	4000	48.0	**48.0**	75	**9000**
111	3.00	37.0	2249	4000	36.0	**40.0**	90	**10800**
139	3.00	46.3	3434	4000	28.8	**40.0**	90	**10800**

9. COST SUMMARY TABLES

Note to Reader

The following estimate summary table, Table A-9, focuses on a first-cost comparison between our System Concept Definition cost estimate data and that of a representative system segment from the Government Cost Model, namely segment 1213RF, double elevated in rural flat. Footnotes are provided to indicate the assumptions we made regarding the data in 1213RF, in order to make as clearly a like comparison as possible. Since our concept uses a unique approach to levitation and guidance which is fundamentally different from that assumed in the Government Cost Model, we felt that by segregating line items for guidance and propulsion and levitation, and by clearly referencing the Government Cost Model cost codes, the reader could clearly understand the basic nature of the comparison. Special note is made to the footnote regarding the line item Guideway Electrification since the current data in the Government Cost Model seems to be unclear.

Also included is a reduced first Cost summary matrix table, Table A-10, which shows our best judgment regarding minimizing first cost exposure for a prospective maglev investor, compared to our baseline concept estimate. Footnotes explain the basis for this modified data, which would be verified in future phases of the project as potential areas for first cost savings.

Table A-9
Estimate Summary

Summary Estimate[10]	Gov't Cost Model, $/Mile[9]	Bechtel Team Concept Estimate, $/Mile[5]
■ Structure Only[5]	10,541,977[1]	9,095,744[3][5]
■ System Guidance Only[1][5]	2,154,240[1]	1,100,000[5]
■ System Propulsion and Levitation[1][5]	Long Stator Core & Hangers[1] 2,323,200 [1526] DG, Long Stator Winding and Assembly 831,400 [1524] Feeder Lines,DG 1,945,000 [1525]Motor Switches,DG 960,000 Total 6,059,800	5,600,000[5]
■ Guideway Electrification[7] [1521] Transmission Line Cost [1523] Power Substation & Switching Station Costs		5,100,000[7]
■ C3 costs/mile, DG	[1532] 1,400,000	1,100,000[2]
■ Vehicles, per unit[6]	$5,000,000 to $7,000,000 per unit	4,000,000 per unit[6]
■ Stations and Parking[8]	Site Specific[8]	960,000[8]
■ Maintenance Facilities[8]	N/A[8]	467,200[8]
■ Construction Facilities[8]	N/A[8]	64,000[8]
■ Sales Tax	Not given	6% of all above (direct) costs, except labor
■ Construction Mgmt	Total Project Management Factor is 25%[4]	4% of [direct costs + sales tax]
■ Systems Integration, Engineering, and Design Management	Total Project Management Factor is 25%[4]	10% of [direct costs + sales tax + construction mgmt costs]
■ Procurement and Project Control	Total Project Management Factor is 25%[4]	4% of [direct costs + sales tax + construction mgmt costs]
■ Contingency Allowance[9]	Recommended Ranges from 15-30% (for items other than land)[9][11]	20% of subtotal of all above items, except where noted
■ Fee	Not given	2.5% of all above items (including contingency allowance)

Footnotes to Table A-9, Estimate Summary
Bechtel Team Concept Compared to
Government Cost Model Segment 1213RF

(1) From Page 6-42 of the Government Cost Model, segment 1213RF, "double elevated in rural flat," cost per mile is shown as $15,009,000. Of this, the sum of plates and hangers is taken as the equivalent of $4,477,440 for the sum of levitation and guidance and propulsion. The item "long stator iron core and hangers" ($2,323,200) is segregated as dedicated principally to propulsion and levitation, with the item "factory installed vertical guiding steel plates" of $2,154,240 primarily dedicated to the guidance function.

(2) See discussion in Part K, Section 6 of this report (command and control costs).

(3) Sum of category values from Part K, Section 4 of this report, for the baseline concept guideway section of 25 meters:

Cat.1.2	7,578
Cat.2.0	61,042
Cat.3.0	73,501
Total	142,121 x 40 = 5,684,840/km x 1.6 = 9,095,744/mile

(4) Taken from page 8-4 of the Government Cost Model.

(5) We understand that the Government Cost Model data represents a structure that will accommodate 12° girder tilt, zero vehicle tilt, and 0.15g longitude acceleration. Our baseline concept accomodates a 15° girder tilt, a 15° vehicle tilt, and 0.20g longitude acceleration and therefore represents a rather conservative comparison (i.e. our numbers are higher than they would have to be for an exact, "apples-to-apples" comparison) with the Government Cost Model.

This point applies to the levitation, propulsion, and guidance elements of the baseline concept as well as to the guideway civil structure, since those elements have had to be defined to accomodate the loads and accelerations of our baseline concept.

(6) See page 6-191, data for category 182 data in the Government Cost Model. See Part K, Section 5 for the data sheet on our team's concept vehicle costs. We have rounded off the vehicle cost data for the purpose of this summary table.

(7) We have a serious concern regarding comparative costing for Cost Element 1523 of the Government Cost Model, Power Substation and Switching Station Costs. The assumptions used in the Government Cost Model seem very unreasonable for a high-capacity revenue system. If there is only one inverter station every 20 miles, then it must be capable of providing peak power for maximum consist or multi-vehicle loadings in both directions. This in turn would imply at least 30 or 40 MW of peak power required per direction, or about 1.5 to 2 MW per mile of dual guideway. In actual fact the peak power would have to be even higher to allow for reasonable acceleration capability. On the other hand, to accommodate dispatching of multiple single vehicles each carrying between 100 and 200 passengers, the spacing of the power stations would have to be more frequent. In either case, the current data in the Government Cost Model for this item seem too low by a factor of at least five. Further, note that if one assumes a multiple-consist dispatching, then the motor winding must be changed to allow for the higher winding voltages that would be required.

On the basis of the above, we are unable to provide a precise measure of the costs of the "Electrification" line item for the Government Cost Model and make a true comparison with our baseline concept estimate.

(8) Bechtel Team data are taken from line items in Part K, Section 4 of this report. The reader is cautioned in particular regarding the station estimate, which is taken from past experience but was not developed beyond the concept definition level. Stations are highly site-specific structures and by definition an exercise of this sort does not yield precise data for estimation. Government Cost Model data cannot be derived sufficiently to yield an accurate comparison.

(9) The Government Cost Model does not include any contingency applied to any individual line items, as orally confirmed by Mr. Todd Greene of DOT/VNTSC on 4-21-92.

(10) Total system cost per unit length is the sum of (i) all capital costs; (ii) pro-rated vehicle, station, and construction/maintenance facility costs; and (iii) the integrated mutilplier factor for all taxes, contingencies, fees, and service charges.

(11) Taken from page 8-6 of the Government Cost Model document.

Table A-10
Reduced First Cost Summary

Summary Reduced First Cost	Reduced 1st Cost, $/Mile(1)	Baseline Concept Estimate, $/Mile(1)
■ Structure Only	7,700,000(2)	9,100,000
■ System Guidance Only	900,000(3)	1,100,000
■ System Propulsion and Levitation	4,500,000(3)	5,600,000
Guideway Electrification	0(4)	5,100,000
■ C3 costs/mile, DG	1,100,000	1,100,000
■ Vehicles, per unit	$4,000,000 per unit	$4,000,000 per unit

(1) These data represent an executive summary level of analysis and are rounded off.

(2) Assumed savings of $1.1 million per mile if fiberglass is shown to be unnecessary for guideway reinforcement; another 5 percent savings is assumed from a continuous structure design and refinements in automated guideway fabrication techniques.

(3) Guidance, propulsion, and levitation elements are shown reduced in cost by 20 percent from the baseline. Based on discussions with various vendors, it is our view that it will be possible to use numerically controlled wire winding machines and wet epoxy-coated wire to produce structurally rigid coils. This production technique can be used to fabricate the guidance coils and will eliminate the need for the fiberglass frames which represent 40 percent of total guidance coil installed costs. Similarly, this production method could possibly be used to fabricate the levitation ladder. If feasible, the cost of the levitation ladder would in our judgment be significantly reduced. Extensive discussions were required to develop this information with selected vendors on a conceptual basis, and it will require an allocation of next phase effort to develop this alternative further.

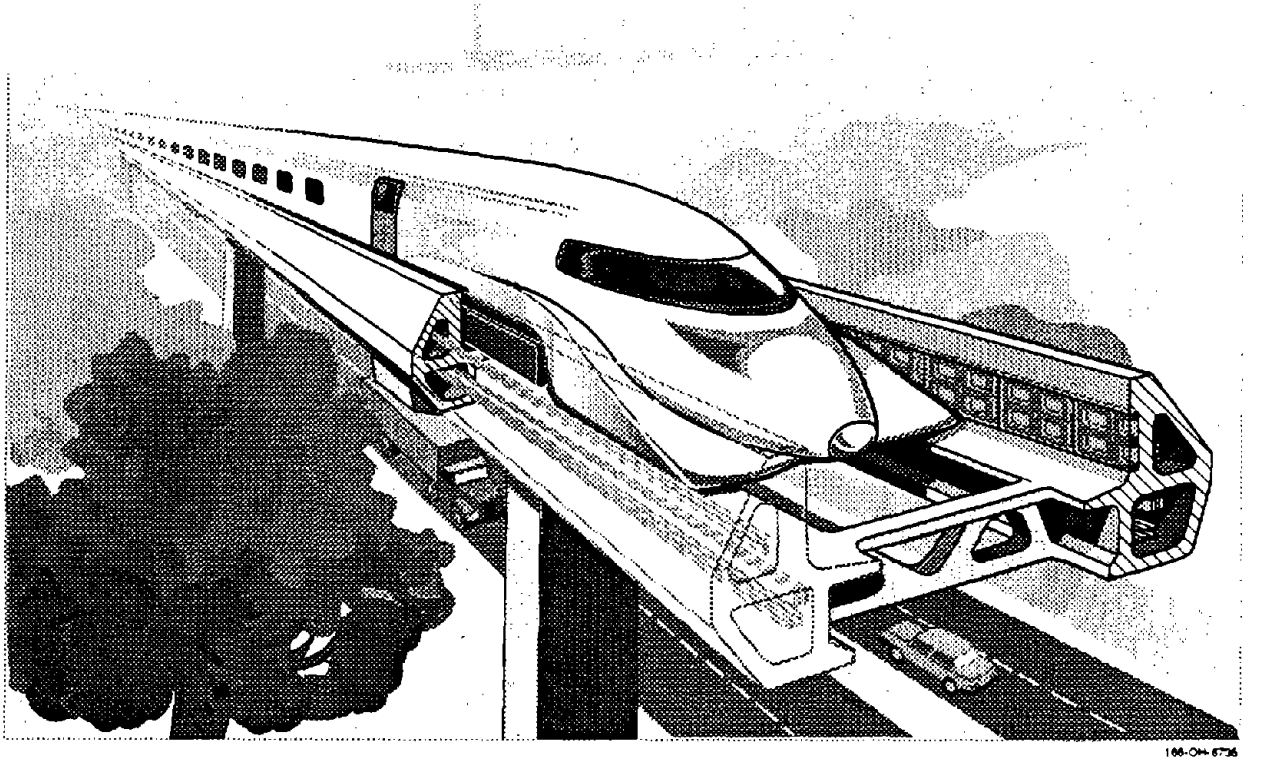
(4) For this reduced first cost scenario we assume the electric utility incurs the direct capital cost of all guideway electrification elements, and passes those costs on to the maglev system owner/operator in terms of changed long-term rate structures. This item is not offered as a life-cycle cost savings issue, since its life-cycle cost value would depend upon actual utility rate structures to recapture their first cost investment. It is offered as a suggested means to reduce first cost exposure only for prospective investors in maglev who are concerned about minimizing first exposure as an investment criterion.

U.S. Department
of Transportation
**Federal Railroad
Administration**

Foster-Miller Maglev System Concept Definition

Office of Research and
Development
Washington, D.C. 20590

EXECUTIVE SUMMARY



CONTENTS

ILLUSTRATIONS

1. CONCEPT DEVELOPMENT BASIS

Foster-Miller along with a team of subcontractors which includes Boeing, Bombardier, General Atomics, General Dynamics, Morrison Knudsen, and Parsons DeLeuw, has developed a Maglev system concept that meets all goals for speed, capacity, safety, reliability and comfort and it has done so by innovatively using state-of-the-art technology. As a result of this work Foster-Miller can, with high confidence, deliver a cost-effective, operational, high performance Maglev system before the year 2000.

This confidence is based on many ideas and innovations which are covered in detail in the concept definition report. Of most significance is Foster-Miller's invention of a high speed, all electric switch made possible by a robust twin-beam guideway and a sidewall coil controlled levitation and propulsion system. This switch along with multicar consist capability permits a low cost, two-way operational, single guideway Maglev system that can serve all but the densest corridors in the U.S. For these heavy traffic corridors the base system can be expanded to well over 12,000 passengers per hour capacity in each direction by adding a second guideway when needed and when revenues warrant.

The Foster-Miller Maglev system definition is based on numerous rational engineering tradeoff studies. There is no perfect solution to a system definition - a design optimized for the best performance in a highly specific application is likely to suffer in applications with different parameters. A design tuned to rely heavily on very specific technologies may not be easily or acceptably modified if those technologies become obsolete in a few years. The most desirable system effectively balances the attributes contributing to overall system performance against flexibility for further growth and improvement.

In the development of the Foster-Miller system, an extensive literature search has been performed which critically evaluated both the German electromagnetic system (EMS) and the Japanese electrodynamic system (EDS). The EDS operates with a large gap between guideway and vehicle, achievable by well developed superconducting magnet technology. The majority of researchers in the U.S. have accepted the EDS as the preferred approach since it can accommodate larger guideway irregularities and leads to an economical guideway structure. Japan is aggressively pursuing an EDS Maglev and has demonstrated fundamental concepts, some of which (such as the null-flux principle) are originally from the U.S. Foster-Miller proposes an advanced EDS Maglev taking maximum advantage of proven systems and technologies and providing major performance and cost advancements.

1.1 System Goals

The first task addressed by Foster-Miller was the formation of a set of goals and requirements for the Maglev system. Some of these requirements were clearly dictated prior to this work, others were the result of collective engineering judgments. Some of the goals and requirements are summarized below:

- Capacity - The system will be configurable to handle a maximum capacity of 12,000 passengers per hour in each direction. The goal is to develop a system which could be configured to also cost-effectively accommodate much lower capacities.

- Speed - The system will operate at design maximum speed of 134 m/sec.

- Costs - The Maglev system must be competitive with aircraft and very high speed rail.

- Passenger safety will be integral with all aspects of the system design.

- Reliability - The system must have reliability on par with high speed trains. This translates to MTBM's (mean time between maintenance) of 1,000 hr for the vehicle, 10,000 hr for the superconducting magnets and 1,250 hr for wayside components.

- The system should make the maximum use of existing rights of way (ROW).

- The system should function in both inter and intramodal capacities with freight transport capability.

- Operational noise and vibration levels will be consistent with ride comfort criteria.

- Aerodynamic efficiency will be maximized and the overall power consumption minimized.

- Magnetic field exposure will be consistent with specified requirements.

1.2 Emerging Technologies

Since much of the existing Maglev examples are rooted in designs from the 1970s, a key issue is the consideration of the best and most current technologies that can be brought to bear today on Maglev. During the last 20 years there have been dramatic advances in a number of technologies which can directly impact Maglev. Probably the most significant advancement has been in computing capability. Cost, size and power requirements for computing hardware have drastically diminished while capability has expanded. Today's embedded microprocessor controllers match the computing capabilities of the main frames of two decades ago. Virtually every area of the Maglev system: safety, performance, operating and capital costs, etc., can benefit from the availability of vastly improved control and computing performance.

Recent developments in high strength to weight materials can improve Maglev design. The higher strength, lighter weight materials make for a lighter Maglev vehicle with no reduction in safety or strength. It is clear that minimizing the Maglev vehicle weight per passenger is beneficial to virtually every aspect of the system. The lower vehicle weight eases guideway loading, making for reduced guideway costs. Lower vehicle weight also translates into reduced propulsion, lift and guidance requirements. This means that the initial costs of these systems are less and the energy costs in operation are less.

Power handling semiconductors is another technology area which has seen tremendous advances in recent years. Like computers, power semiconductors have seen big advances in capabilities and significant reduction in cost. The Insulated-Gate Bipolar Transistor (IGBT) was introduced in 1983. The IGBT offers higher current densities than bipolar transistors, high input impedance, reverse voltage blocking and good high temperature performance. Commercial IGBT capabilities are constantly improving, but current devices can handle 1400V and 800A. In higher powers, Gate-Turn-Off Thyristors (GTO) have seen big advancements in the past 10 years. Commercial GTOs currently can handle 4500V and 4000A (with a single device). On the near horizon U.S. manufacturers are developing special power handling hybrids like the metal-oxide semiconductor controlled thyristor (MCT). These devices will combine the best respective characteristics of IGBTs and GTOs and will be directly interfaceable with microcomputer I/Os.

The impacts on Maglev of these developments in power devices are increases in reliability, safety and system flexibility. The increased power capabilities of single devices means that fewer devices can be used for the same function - translating directly into increased system reliability. The flexibility really comes from the combination of more capable computing and control hardware and the more capable power devices. The computers provide the faster control, the power devices provide the means to implement that control.

There are many more technologies that will impact the direction of Maglev in the 90s and beyond. Fiber optic communication, virtually nonexistent 20 years ago, provides a high bandwidth communications medium which is inherently immune to EM disruptions. Sensor technologies continue to grow in both capability and cost-effectiveness. Manufacturing techniques for concrete structures, composites,

superconducting magnets, and non-ferrous materials have seen and will continue to see steady improvements. These and many more advancing technical areas will positively impact Maglev system design.

During development of a system concept an important question is whether a particular technical concept is too risky or too immature to employ. Tradeoff analyses evaluate these questions. If technical concepts are rated on a scale of risk and maturity, at one end of the scale are mature, hardware proven technologies and methods with negligible technical risk for implementation in a Maglev system. Near the middle of the scale are concepts that are well understood, but demonstrated in scaled-down hardware or laboratory conditions only. These concepts would require some investment in development and would carry some associated risk, to reach a level of maturity sufficient for implementation in a Maglev system. Finally, at the other end of the scale are concepts with no real hardware demonstration history and needing much development to be applied to Maglev. These concepts would require significant investment to bring them up to a level of development suitable for application to real systems. These technology concepts would also carry a significant risk of never reaching a state in which they could be used in a real Maglev system.

Foster-Miller's approach has been to avoid high risk concepts, but to examine moderate risk concepts for potential benefits to the overall system and to tradeoff against the potential development cost and the associated risk of that technology never reaching viability. The baseline system utilizes many new technologies in ways in which these applications have much system benefit and little technical risk associated with them. If moderate risk concepts do offer potentially significant system improvement, system flexibility has been deliberately built in to permit future modifications and enhancements. The envelope of future system needs has also been considered. If the costs (economic and performance) or risk associated with building in system expandability was small compared to the potential future benefits, that flexibility was included in the design.

1.3 Design Tradeoffs

Several major design tradeoffs have been conducted to support the overall system concept definition process prior to detailed design. These tradeoffs first compare options within established/existing technology. Further tradeoffs evaluate the potential risks and benefits, as well as the development status, of the emerging technologies referred to in subsection 1.2. The results of these studies have provided primary thrust for the baseline system definition. Further, potential advancements have been identified for incorporation as the technology becomes available. The key factors considered in each tradeoff are presented in Appendix A. The conclusions which influenced the system definition are summarized below.

- *EDS versus EMS* - A repulsive electrodynamic suspension (EDS) system will facilitate a much larger and more stable air gap between the vehicle and the guideway than an attractive electromagnetic suspension (EMS) system. This results in lower guideway manufacturing and maintenance costs as well as significantly improved safety and ride comfort because the suspension becomes less sensitive to small variations in guideway alignment. Further, the EMS method requires a complex current control system in the magnetic circuits to overcome the inherent instability of attractive levitation, which increases costs. It will also significantly increase the risk of magnet quench due to the resultant eddy current heating, if superconducting magnets are employed in the attractive system. These and other factors listed in Table A-1 led to the conclusion that a repulsive EDS system provides a better and safer Maglev design.

- *Discrete (bogies) versus Continuous Suspension* - Distributed magnets significantly increase the vehicle weight and mechanical complexity, adding to both capital and maintenance costs. Sharp curve negotiation with distributed magnets is also a problem. Discrete location of the magnets in bogies at the vehicle ends also physically separates the passengers from the magnets. This permits simpler shielding of the

passengers from the strong magnetic fields. The tradeoffs presented in Table A-2 show that a discrete end bogie system offers a better design. The bogies can be conveniently shared by adjacent cars, which reduces costs. Such a shared end bogie concept has been successfully used in high speed trains such as the French TGV and the experimental Japanese Maglev prototypes.

- *Coils versus Sheet Guideway* - In comparison to coils, sheet guideways have substantially higher magnetic drag which results in increased operating costs. Further, the design of sheet guideways is difficult and their attachment to the primary guideway structure is highly involved due to their sensitivity to thermal effects. The sheet guideway will experience high cyclic thermal loads which can result in fatigue failures. Discrete coils are favored in the Foster-Miller Maglev concept for several reasons including their lower drag, ease of design and attachment, and relative insensitivity to thermal loads as shown in Table A-3.

- *Sidewall Null-Flux versus Ground Coils* - Several factors including reduced magnetic drag and superior switching (shown in Table A-4) demonstrate advantages of the null-flux system. A null-flux system will have approximately half of the magnetic drag of a ground coil system. As an added advantage, a sidewall levitation system can have an all electric vertical guideway switch. Other levitation systems must resort to cumbersome movement of the entire guideway structure to accomplish switching.

- *Optimum Guideway Configuration* - This tradeoff is driven by safety, long-term durability, ease of operations, and cost. These factors have been applied to conventional guideway configurations to identify their associated deficiencies. The T, inverted T, monorail, round bottom, and conventional U-shape guideways have been compared in Table A-5, which indicate the advantages of the U-shape. The U-shape also results in the guideway "wrapping" around the vehicle, which is superior to the vehicle wrapping around the guideway as shown in the comparisons presented in Table A-6.

Foster-Miller has developed a new twin beam, open floor guideway configuration which overcomes the deficiencies identified in conventional configurations and offers numerous advantages. This new configuration provides the advantages of a conventional U-section (safe vehicle location, maintenance and emergency access, a stiff section for long life, and ease of yard operations) with the additional advantages of low snow/ice/debris problems and the ability to switch in the vertical plane.

- *Single versus Double Beam Guideway* - A single beam guideway has been compared to a twin beam guideway (two beams connected by cross diaphragms at regular intervals). The advantages of double beam construction are in road transportability, ease in handling, assembly, repairability and other factors given in Table A-7. The double beam configuration was therefore adopted.

- *Propulsion Motor Tradeoff* - An advanced locally commutated linear synchronous motor (LCLSM) propulsion system has been invented by Foster-Miller. This propulsion motor uses advanced power electronics technology to control individual coils along the guideway. This provides a very high motor efficiency by only energizing the coils in the immediate vicinity of the vehicle. In addition, Foster-Miller has developed an advanced power transfer scheme which is only possible in conjunction with an LCLSM propulsion system. Tradeoffs with a conventional block switched linear synchronous motor (BSLSM) propulsion system, given in Table A-8, demonstrate the numerous advantages of the LCLSM.

- *Vehicle Material* - Conventional aluminum skin/stringer aircraft construction, aluminum sandwich construction, and composite sandwich construction have been evaluated for this application. Typical commercial aircraft construction (aluminum skin/stringer) has several disadvantages including higher weight, lower fatigue life, and corrosion problems. Aluminum sandwich construction, while providing a significant weight savings, still has corrosion and fatigue problems. Due to weight savings, corrosion

resistance, and compatibility with the Foster-Miller power transfer system, as well as other factors given in Table A-9, a composite sandwich design is favored.

- *Magnet Material* - The material for the superconducting magnets could potentially be niobium titanium (NbTi) or others such as niobium tin (Nb_3Sn). These materials are compared in Table A-10. The Nb_3Sn material manufactured today is extremely brittle and not suited for this application as it can not withstand the large oscillating stresses expected in service. NbTi can be implemented with confidence at this time and its reliability has been established in Japan (Maglev) and the U.S. (Superconducting Supercollider, Magnetic Resonance Imaging). The Foster-Miller magnetic suspension design can easily accommodate any high temperature superconducting material as it becomes available in the future.

These major tradeoffs and further preliminary design work have resulted in the definition of a baseline system concept. Cost tradeoffs have also been performed to arrive at the baseline design.

2. BASELINE SYSTEM DEFINITION

Figure 2-1 illustrates the basic vehicle. The basic system can be configured as a consist of two to eight cars. These configurations permit sizing the system for a range of 1,500 to 12,000 passengers per hour in each direction. A design which mounts the magnets (the lift, guidance and propulsion) in bogies at the ends of the cars has been selected. A single bogie is shared by two adjacent cars. In addition, the bogie arrangement is inherently more supportive of cost-effective future modification and enhancement of the magnetic systems. Bogie designs can change while passenger cars need not be affected or taken out of service.

Vehicle construction is illustrated in Figure 2-2. The cars utilize composite sandwich construction. The specified construction provides high strength and stiffness to weight along with relatively low fabrication costs. Other features of this construction are sound attenuation, corrosion immunity and relatively easy repair procedures.

The guideway structure is the most important consideration in any Maglev system, as it determines the system cost. In addition, it determines the vehicle configuration and mode of levitation. As discussed previously, a number of guideway configurations were examined and Foster-Miller's innovative guideway is of modular construction and has twin hollow beams connected by structural diaphragms as in Figure 2-3. Factory produced and easily transported by road, the beams can be assembled on-site over the pylons and then post-tensioned forming an integral unit with minimal costs. Other advantages of the Foster-Miller guideway are:

- Open bottom eliminating problems of ice, snow, and debris accumulation.
- Wide "track gauge" provides vehicle stability for all speeds and environmental conditions.
- Sidewalls offering significant protection of vehicles under crosswinds and gusts.
- Most convenient for the sidewall levitation scheme.

The fundamental basis of the guideway design was to optimize the cross-sectional area and material selection to give the maximum possible structural stiffness, while minimizing costs. Naturally, other considerations enter as well, such as the need to provide sufficient internal volume for complete protection of enroute power and services, to allow practical, high volume factory manufacture. This required stiffness is principally driven by the considerations of the maximum permissible dynamic load factor to limit operating stresses and deflections, in order to assure a 50 year service life for *all* the structural components of the guideway. The structural integrity and safety is verified through complying with existing construction codes and design practices, such as the American Concrete Institute (ACI) and the American Association of State Highway and Transportation Officials (AASHTO) codes.

The guideway stiffness is not directly governed by the ride quality, as some workers misconceived in the past. While ride quality can be influenced by guideway stiffness, the primary drivers on ride quality in the accepted regime of Maglev vehicle and guideway parameters are the characteristics of the primary and secondary suspensions systems. In particular, the secondary suspension can permit superior levels of ride quality without undue complexity in the vehicle design. For vehicles without secondary suspension, but with an active primary suspension control, the guideway stiffness becomes a

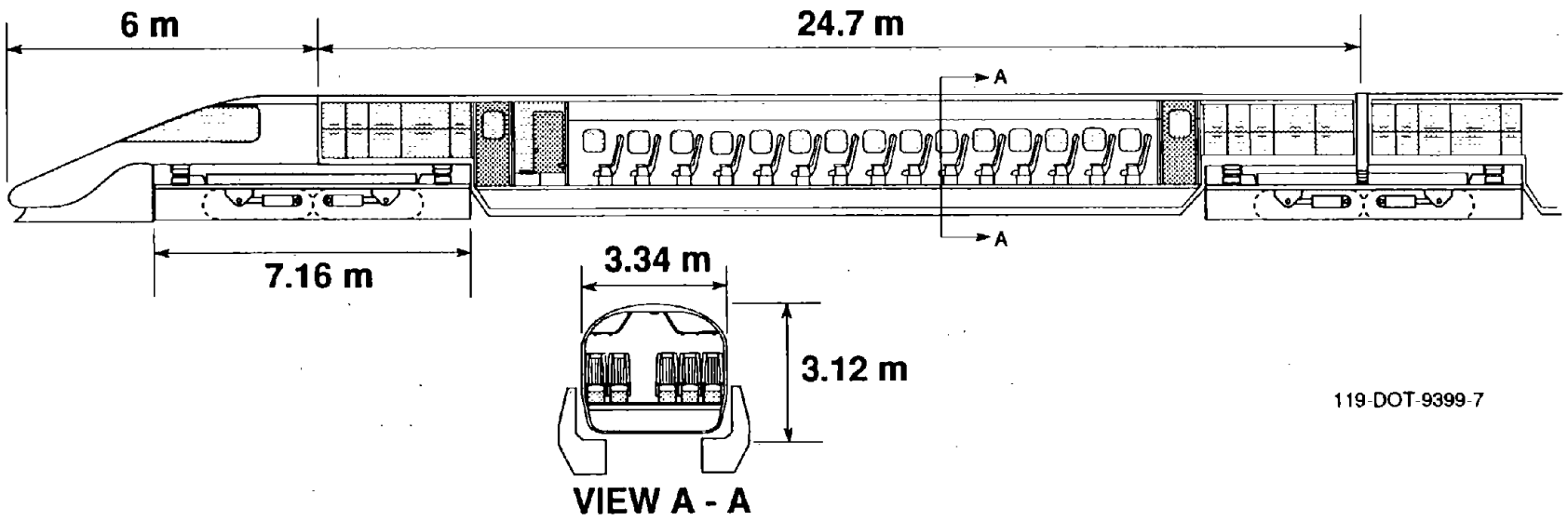


Figure 2-1. Overall Vehicle Configuration

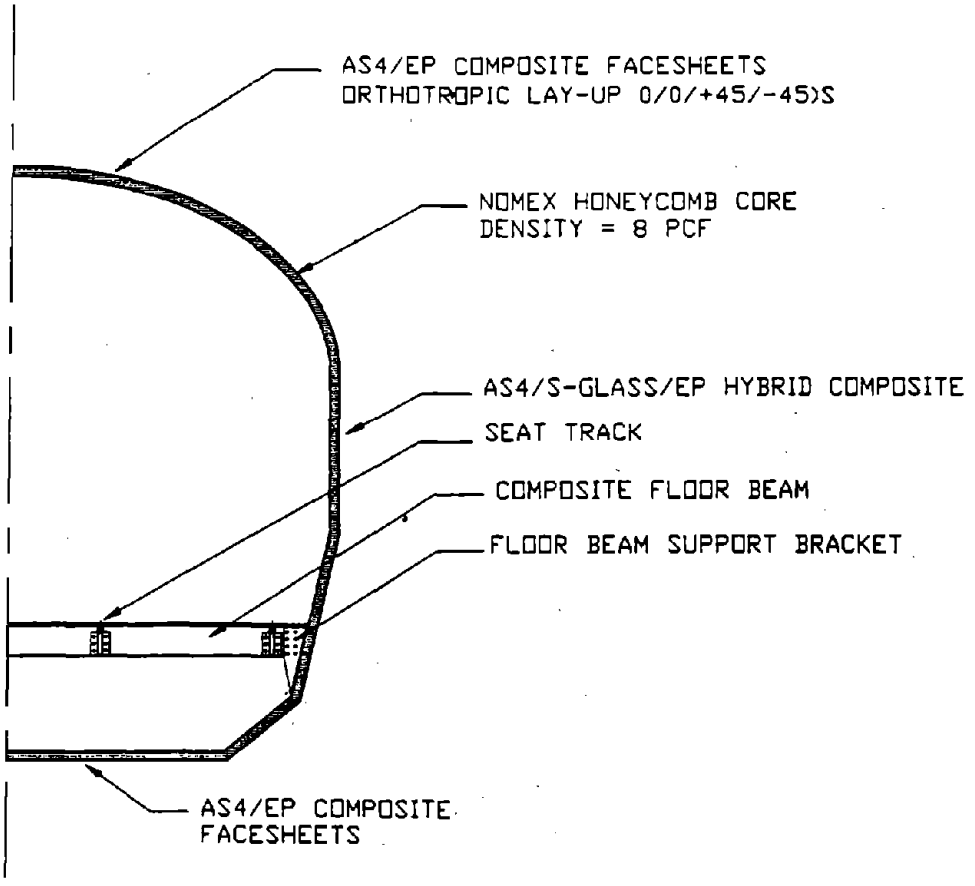


Figure 2-2. Construction Details

sensitive parameter in providing adequate ride quality. Even in this case, the flexibility of the guideway is limited by fatigue life considerations of both primary structure and components such as coil attachments. Adherence to accepted design code requirements also effectively limits guideway flexibility.

The importance of providing adequate flexural stiffness in the guideway cannot be overemphasized, since insufficient stiffness can quickly increase stresses and deflections to undesirable levels. In addition, the dynamic amplification of stresses and deflections can rapidly increase with reduced stiffness, especially when the lowest resonant modes of the guideway beam vibration lie below the pylon passing frequency of the vehicles in the upper speed ranges. Consequently, design prudence dictates that stiffness be maintained high enough so as to provide a safe margin against these sensitivities from coming into play in real-world operation, and this is reflected in past transportation system design practices.

Levitation and guidance of our vehicles will be accomplished through cross-connected null-flux sidewall coils. The advantages of this system include compatibility with high-speed vertical switching. The combination of an open bottom guideway and the sidewall levitation and guidance permits a vertical track switching arrangement which needs only electrical power switching components and allows full-speed operation through the switch. Figure 2-4 illustrates the guideway with the high-speed

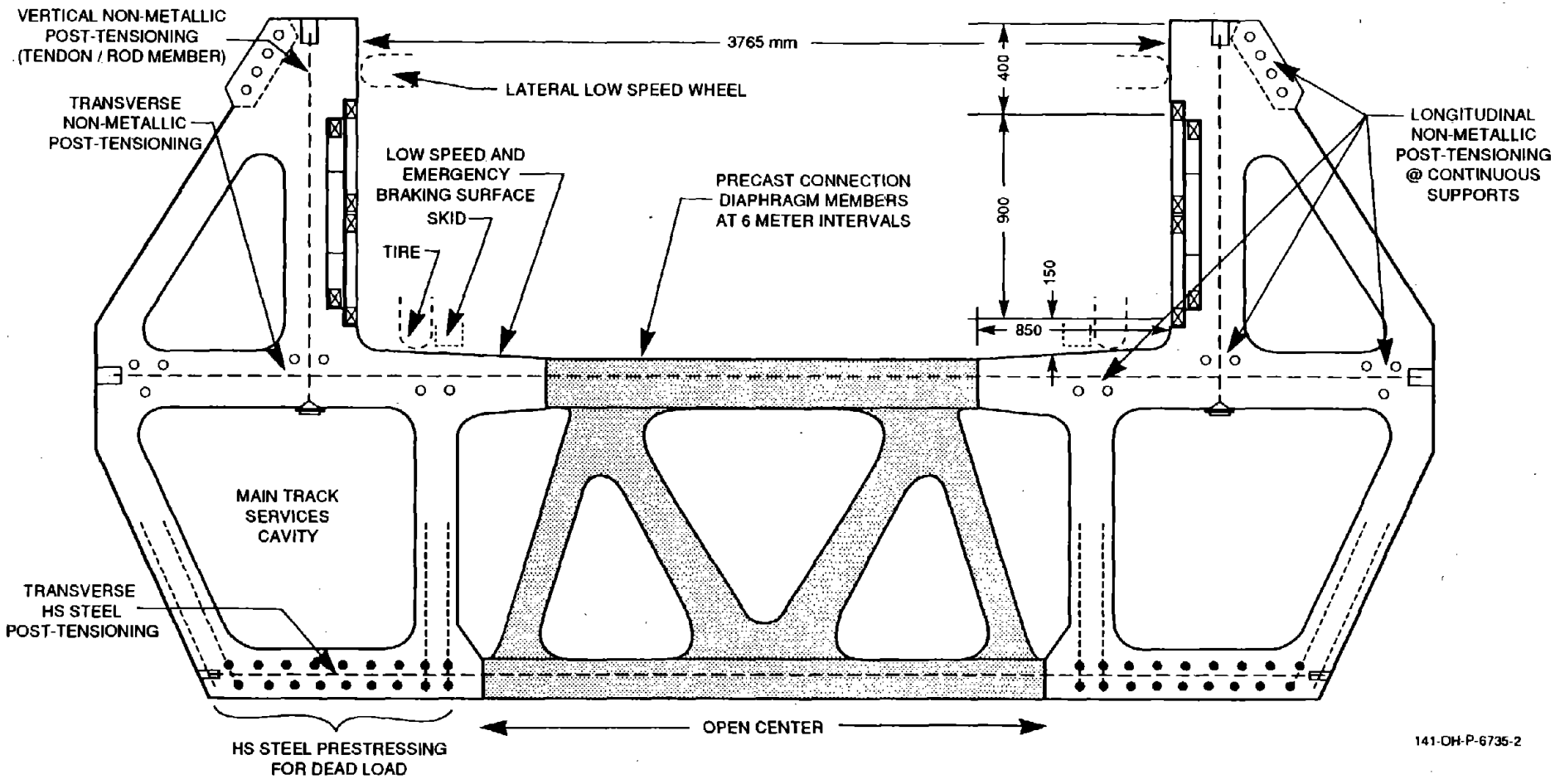


Figure 2-3. Integral Sidewall Guideway

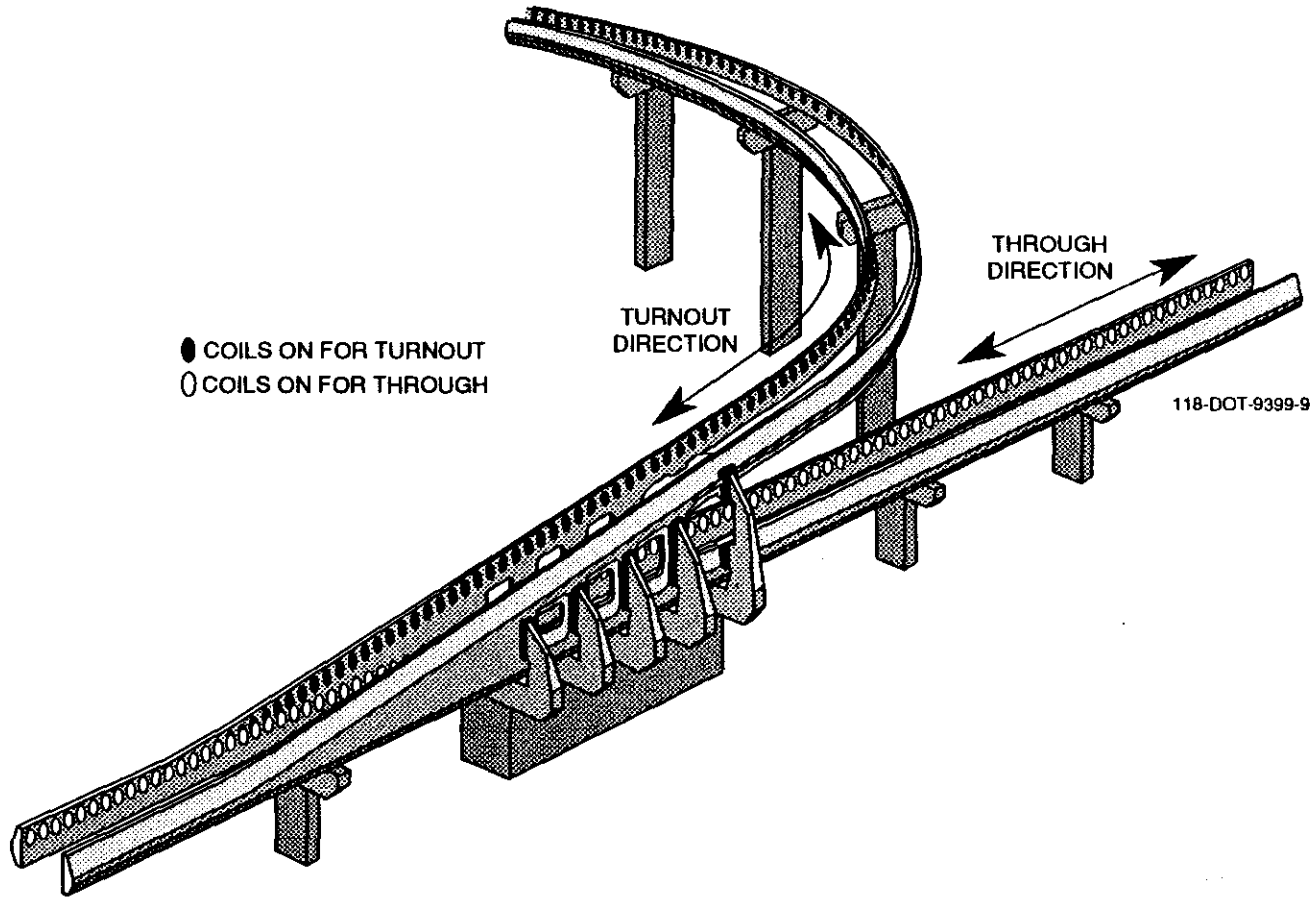


Figure 2-4. Vertical Switch Using Sidewall, "Null-Flux," Levitation and Sidewall Propulsion Coils

vertical switch. *For station design and high capacity operations with reduced headway, it is fundamentally important to system viability to have simple, reliable and relatively inexpensive high-speed guideway switches.*

Vehicle propulsion has a number of goals and requirements associated with it. Low EMI is necessary for Maglev acceptance. High efficiency and full regenerative braking will impact operating costs. System reliability must meet specification and failure modes must lead to graceful system degradation. System requirements include 0.16g nominal acceleration and deceleration rates, 0.25g emergency deceleration capability and full-speed operation on grades up to 3.5 percent. The solution is an advanced linear motor design which places the propulsion coils along the sides of the guideway alongside the null-flux lift and guidance coils. Each propulsion coil will be driven by individual semiconductor switching devices co-located on the guideway. This arrangement is called local commutation since only DC power is brought to the guideway and the variable frequency drive is generated by switching on and off the individual coils. This design is somewhat analogous to conventional brushless DC motors.

The advantages of the locally commutated propulsion motor are significant. Instead of energizing blocks of track as the vehicle passes and feeding variable frequency AC power to all windings in these blocks, the system only energizes the windings immediately alongside the vehicle. Operating headways are not affected by block sizes, there is no resistively wasted power in extensive lengths of linear motor with no vehicle over it and only DC power is supplied to the guideway so there are no distributed power substations needed to generate variable frequency AC power.

This locally-commutated linear synchronous motor (LCLSM) also enables the same propulsion coils to transfer power inductively to the passing vehicles, without the need for contact which is a major problem at high speeds. Figure 2-5 shows how the LCLSM coils propel the vehicles at the bogies with a "moving wave" of low frequency power, but between bogies the same coils use higher frequency energy to transfer power to pickup coils on the vehicle. System reliability is high since isolated coil failures are tolerated.

The vehicle bogies carry four superconducting magnets on each side. A bogie is illustrated in Figure 2-6. These magnets provide the DC field for the null-flux levitation and guidance and for the propulsion motors with air gaps of 10 cm nominally. The magnet design provides a lift to weight ratio of 12 and is realistically based on niobium-titanium superconductors. The specification of four magnets per side limits stray flux paths thus reducing shielding requirements. If one magnet quenches the corresponding magnet on the opposite side of the bogie will be automatically driven into quench to maintain balanced guidance forces. The proposed design will continue to operate with a pair of magnets per bogie inoperative. Levitation will be maintained even if two of the four magnet pairs on each bogie are lost.

The bogies carry deployable landing gear and guidance wheels for low-speed support and emergency skids are present if catastrophic failure forces vehicle and guideway contact. A complete secondary suspension is also built into the bogies to act between each bogie and its associated two cars. The secondary suspension, shown in Figure 2-7, provides secondary vertical and lateral control and has active tilting (roll) of the cars with respect to the bogies. The tilting capability can be used alone or in addition to guideway tilt to maintain proper ride comfort in curved paths and will be essential to maintaining vehicle speed on existing ROW.

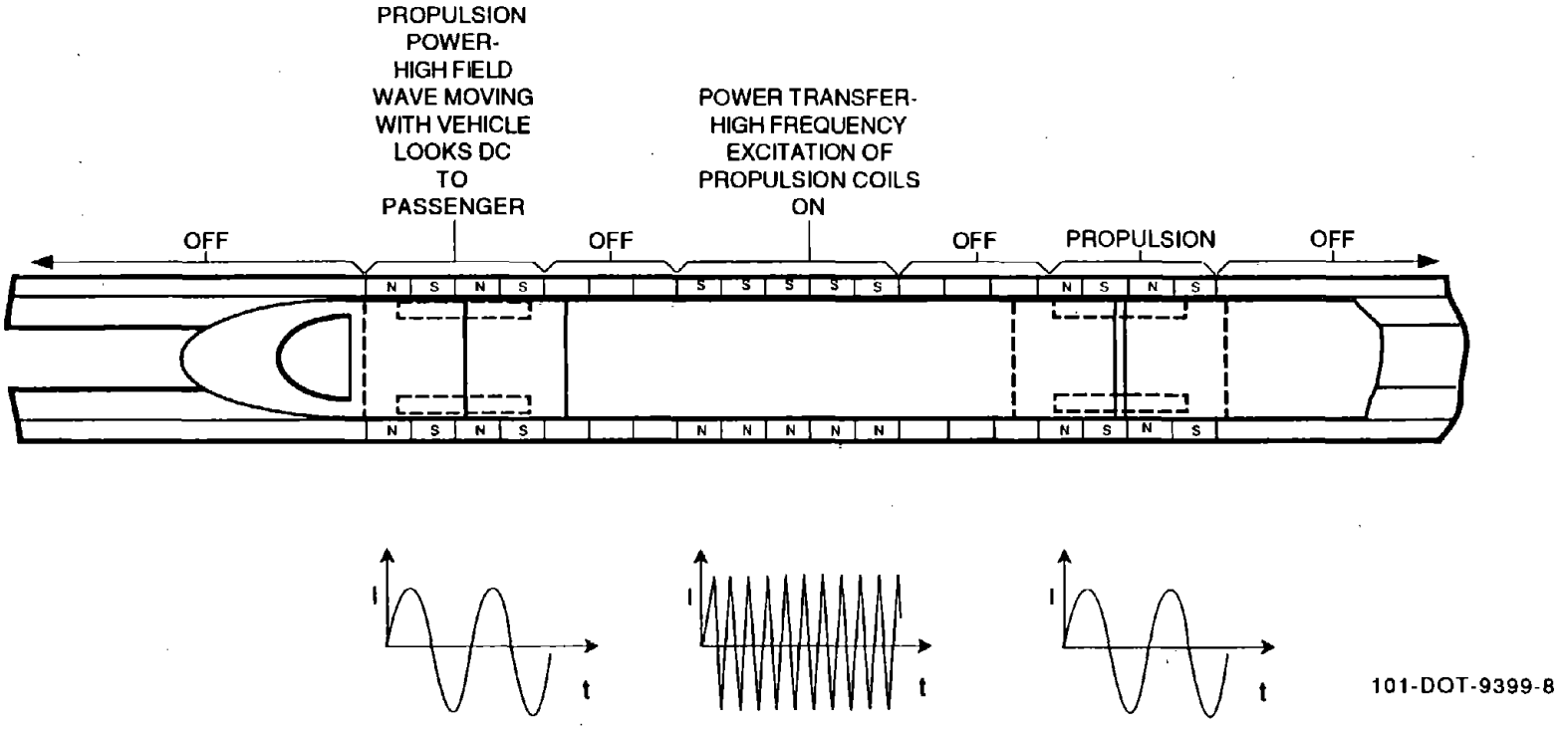


Figure 2-5. Locally Commutated LSM and Power Transfer

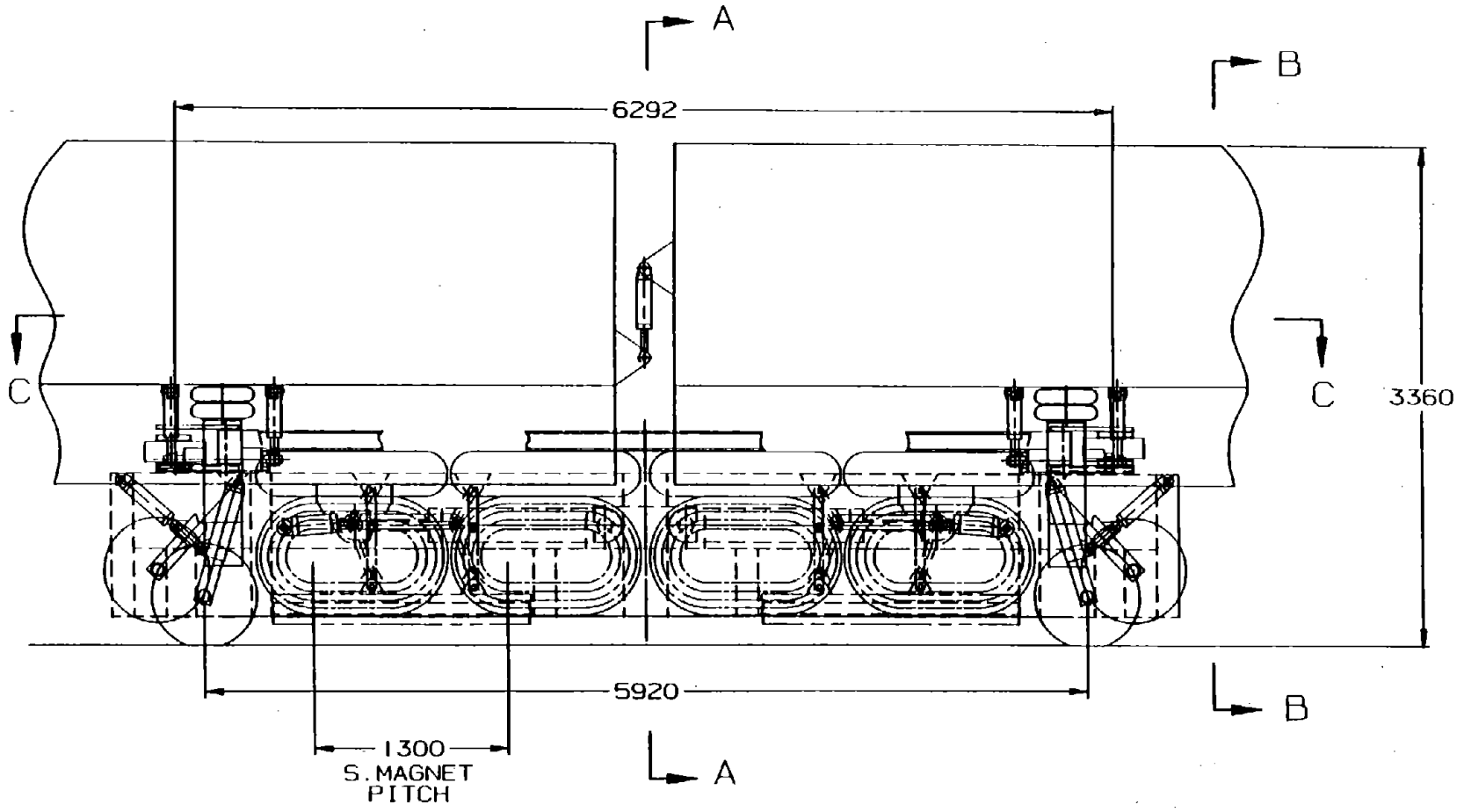


Figure 2-6. Bogie (Elevation)

Dimensions are in mm

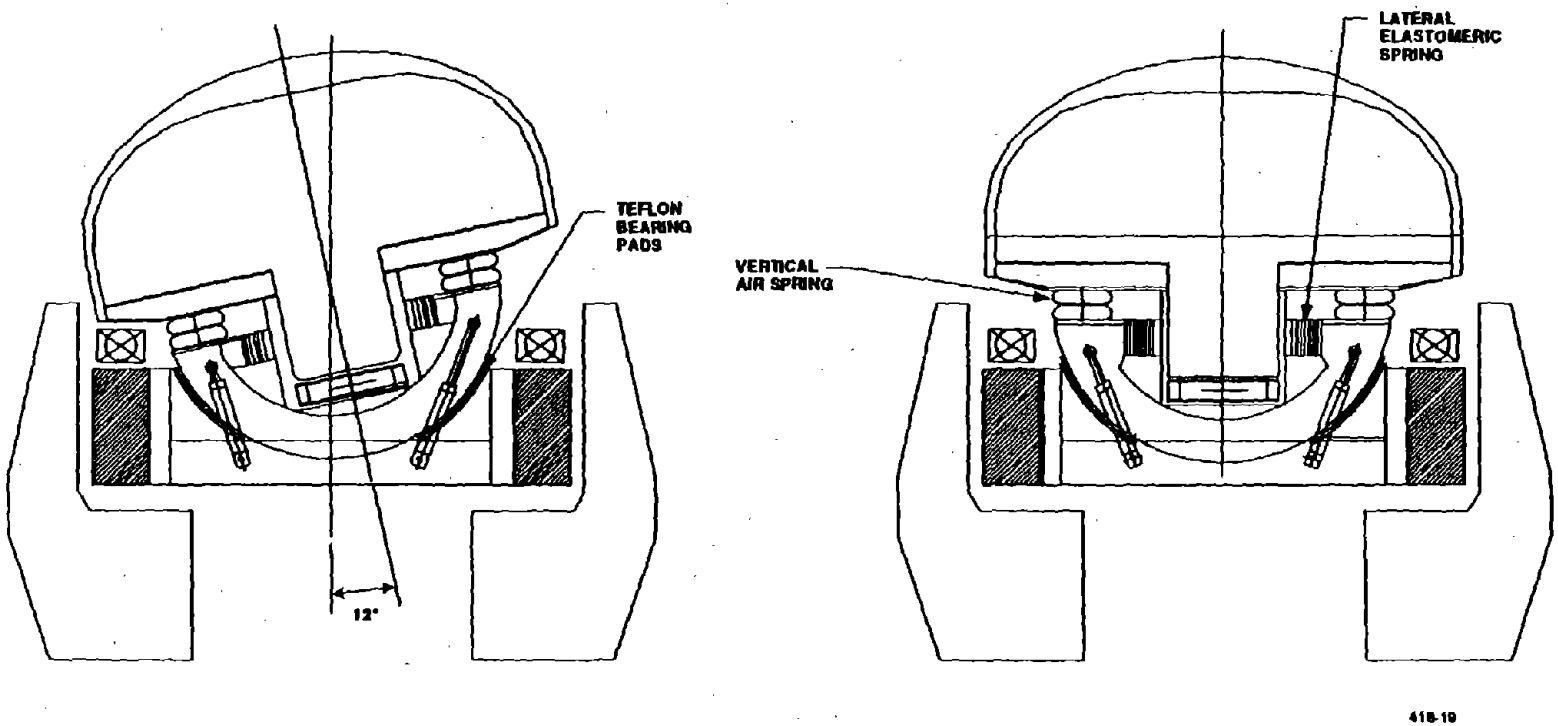


Figure 2-7. Tilting Mechanism

3. SYSTEM COSTS

Major transportation systems are usually evaluated for at least two general categories of costs: the capital, or initial construction costs, and the annual system operating costs. (Often, total annual operating costs are formulated to include the effect of capital costs by adding an equivalent annual depreciation cost to represent the financing needed to acquire both the new and replacement system elements.) Consideration of these costs was an integral part of the Foster-Miller system development.

High-speed Maglev networks, such as those proposed by Foster-Miller, can achieve their considerable advantages of speed, safety, convenience and low environmental impact at costs which meet or beat available competitive transportation modes such as VHSR (Very High Speed Rail) and aircraft. For example, Maglev corridor transportation could unload congested intercity air travel systems, which consume up to 30 percent of the total capacity of major metro-corridor airports. With Maglev, much greater passenger capacity can be provided at a lower total per-passenger operating cost, with competitive downtown-to-downtown travel times achieved at a fraction of the energy consumption.

3.1 Capital Costs

Throughout the design process for the Foster-Miller Maglev system, many detailed cost tradeoffs were made to ensure that the entire range of system performance, safety, reliability and long life goals were achieved at the lowest cost. Sometimes, the rigorous approach to safety increased costs somewhat, but on balance was judged the best approach. A partial list of such features would include: high-stiffness, wide-track twin beam guideway to assure excellent stability and durability over the full range of speeds and loads, including under extreme environmental conditions; incorporation of multiple safe braking modes; low passenger magnetic field levels; and crash-absorbing body structures.

Guideway System

The guideway system will comprise about three-fourths of the total construction cost for a typical intercity network, and the Foster-Miller design has achieved a cost of $6 million/km for a system handling 4,000 passenger seats/hour continuously in both directions, and which can be upgraded to handle up to 12,000 passenger-seats/hour for a total of $9 million/km. The 4,000 passenger seats/hour system uses single guideway with a number of high speed passing sidings, made practical though the use of Foster-Miller's high-speed switch design. Higher capacities are achieved by providing dual guideway for the full length of the route, which also permits slightly higher average speeds, and results in the $9 million/km construction cost. Of these costs, about one-half comprises the guideway structure itself, an additional one-third covers the electrical and electronic guideway components, and the remainder is used for power substations, transmission/communication/signal, and monitoring. These are summarized in Table 3-1. Costs shown are for a completely elevated system, but where terrain and safety conditions permit, the guideway costs can be reduced up to 25 percent by using an at-grade system which takes advantage of continuous ground support.

The low guideway structural costs are achieved through use of modest dimensional tolerances and the high volume factory production of the twin-beam modular guideway elements, which allows for ease of transportation, erection and alignment. These advantages are complemented by the wide-track layout of the sidewall null-

Table 3-1. Overall Foster-Miller Dual Guideway System Cost

	(1992)	
	$/m	$Mil/mi
Guideway structures*	4,650	7.5
Coils (null-flux and propulsion)	1,860	3.0
Guideway LSM switches and connections	1,230	2.0
Substations	315	0.5
Transmission, Communication and Signal	990	1.6
Monitoring	60	0.1
Total	9,105	14.7

Guideway and wayside electrical systems installed, complete: $9.11 Million/km ($14.7 million/mil).

*Spans = 27m; Pylon height = 7.62m.

flux levitation system for the twin-beam configuration, and the relatively large levitation air gap which increases the safe tolerance of irregularities.

Detailed cost analyses for guideway components and construction procedures showed the relative cost constituents. In the case of the primary guideway beams, for example, materials contribute about 40 percent, factory manufacture about 30 percent, and the remainder divided among erection, transportation, alignment and miscellaneous hardware. This cost tracking enabled Foster-Miller to highlight the most productive routes for cost reduction in the design process. Also, detailed costing for a range of major parameters such as beam span and pylon height resulted in the lowest cost configuration for average terrain conditions, as illustrated in Figure 3-1. (Many other design-cost trades were also performed in the development of the guideway, but are not described here.)

Lastly, the cost of pile-type pylon foundations was examined, since intercity routes will typically have some areas of poor soil conditions. For example, if 25 percent of the pylons required pile foundations, guideway structure costs increase about 4.5 percent for the route.

The guideway structure costs presented do not include highly route-specific costs along the ROW for cuts and fills, access roads, fencing, etc. that are not associated with the guideway itself, but which would be estimated for particular route situations.

The electrical components installed on the guideway to provide propulsion, guidance and levitation consist primarily of the coils themselves, plus power electronic modules with each propulsion coil which provides the heart of the innovative Locally-Commutated Linear Synchronous Motor concept (LCLSM). As was seen in Table 3-1, these electrical components comprise about one-third the cost of the guideway, so extensive cost tradeoff studies were used throughout to optimize both the coils themselves (sidewall null-flux and propulsion) and the power switching modules. This was done from several directions. First, the use of the LCLSM minimized the number of different guideway coils by using the propulsion coils for power transfer to the vehicles as well, plus providing guidance in conjunction with the null-flux levitation coils and crossovers. Also, the power devices required for the LCLSM are inherently of lower power rating than those for a conventional block-switched LSM (BSLSM), thereby reducing the cost of each device. Then, coil material was minimized in favor of the individual power electronic modules, since the cost of control and power semiconductors is continuing to fall rapidly as production volume and device capability increase, while conductor prices are relatively stable. Complete fabricated coil costs were held to $1.86 million/dual km.

New innovations in the power electronics industry are also appearing on the average of every 45 days, and this can be illustrated by a comparison of the LCLSM coil power module as designed today (1992) versus only two years from now, as seen in Figure 3-2. With the cost data history for all the components of these modules in production form, an average cost reduction of 10:1 over several years relative to

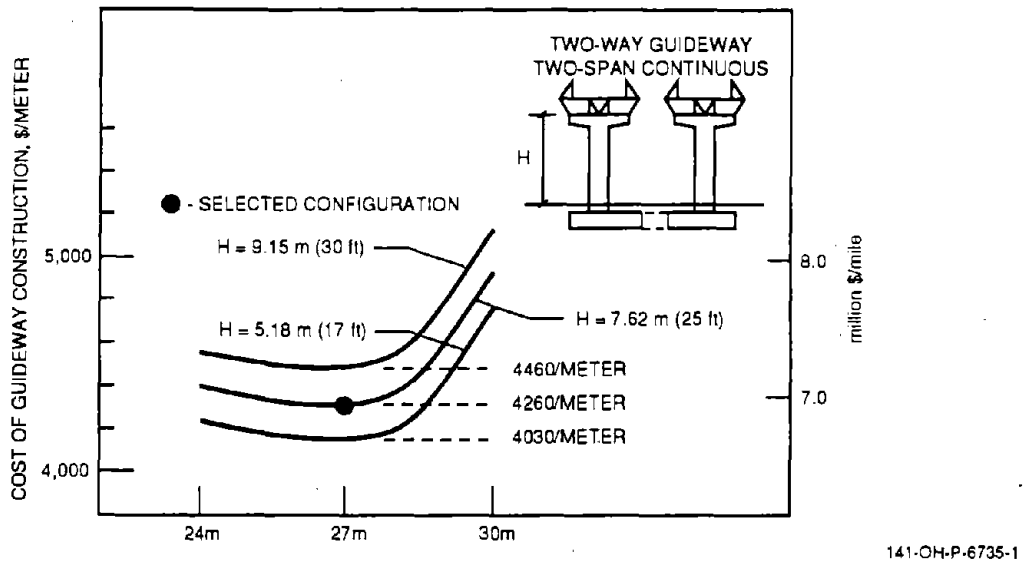


Figure 3-1. Foster-Miller Guideway Structure Construction Cost per Unit Length of Two-Way Guideway versus Span

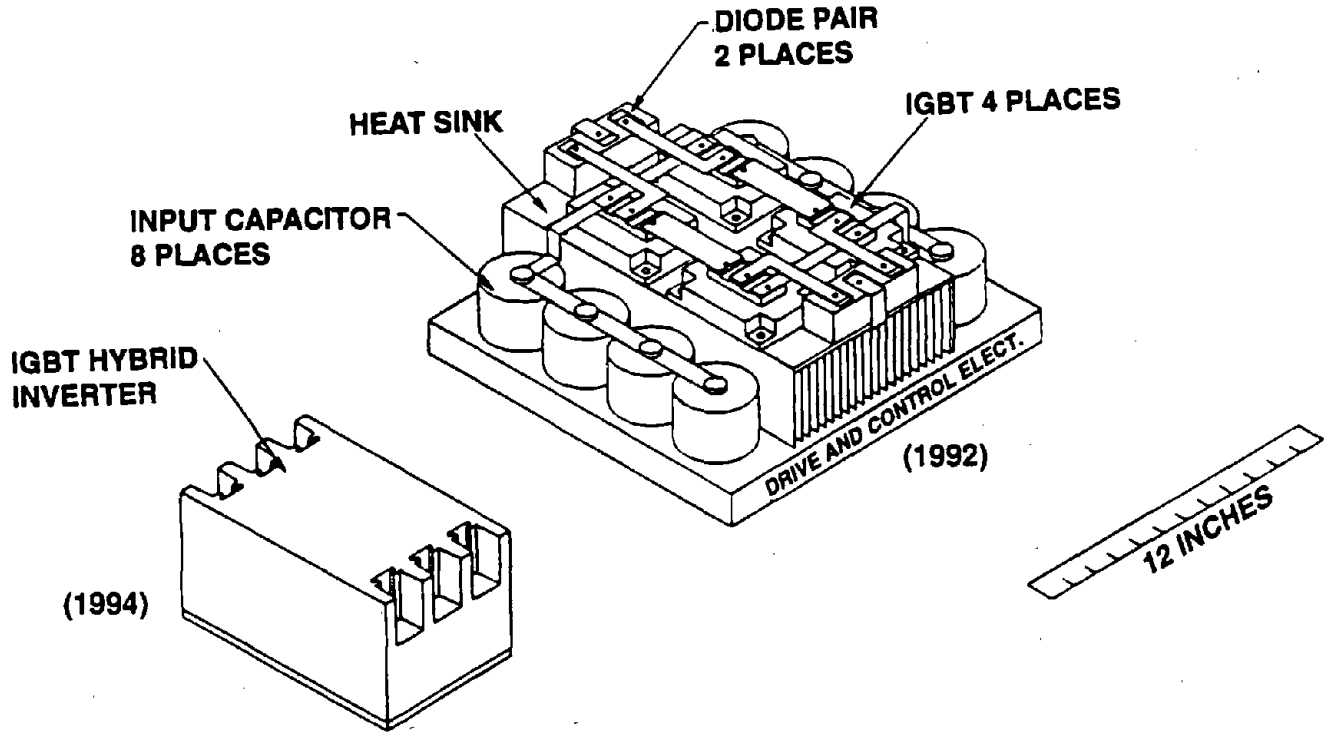


Figure 3-2. IGBT Single Phase Inverter: 1992 and 1994

today's custom-built version can be expected, especially in the volumes needed for a typical Maglev corridor. The resulting $1.23 million/dual km cost of these modules (and connections) is therefore reasonable, and in line with that for a BSLSM. (The Foster-Miller Maglev is also compatible, as an alternative, with a BSLSM.)

Other electrical system costs were likewise examined for cost versus performance. Substation interval and size/cost trades resulted in 8 km spacing of dual substations for high capacity routes. The transmission/communication/signal system uses the newest moving block automated train control system for efficient, safe operation of the network. And the multimode monitoring for guideway integrity, obstruction, and weather conditions provides several levels tailored to differing route conditions and needs.

Vehicles

The Foster-Miller Maglev vehicles reflect the use of cost-effectiveness in the vehicle structure, bogies with superconducting magnets, and provision for operating in multi-car consists. The use of stiff, lightweight composite honeycomb for body structure, with selective use of carbon only where beneficial, enabled structure weight to be held to 20 percent of gross weight, while retaining relatively low fabrication cost, easy repairability and long fatigue life, and high body bending stiffness for ride comfort. The bogie design integrated a tilting, secondary suspension for high speed curve negotiation and excellent ride quality, with multiple redundant SC magnet modules which use repressurization of onboard helium and efficient central liquefaction stations rather than onboard refrigeration. And the ability to operate in consists permitted much lower aerodynamic drag per passenger, high system capacities while retaining safe headways, and flexibility in meeting a wide range of demand levels. Several trade studies including costs, produced the five-abreast, 75-passenger car configuration as an optimum.

These efforts resulted in a complete vehicle cost of approximately $6 million, plus another $400,000 for contingency pending complete engineering design of all components and processes. A breakdown is shown in Table 3-2.

Table 3-2. Foster-Miller Vehicle Cost Breakdown

Components	Cost ($)
Vehicle shell	1,800,000
Interior	250,000
Bogie	
Mechanicals	430,000
Magnets and dewars	800,000
Shielding	100,000
Services	810,000
	4,190,000
System assembly labor	1,600,000
Production facility and overhead	250,000
Contingency	400,000
Total per vehicle	6,440,000

3.2 Operating Costs

Extensive use was made of detailed network operating cost models, which included all factors affecting direct operation, maintenance, financing and equipment replacement. A wide range of system capacities were covered, ranging from 1,000 to 12,000 passenger seats/hr in each direction. Using a government-furnished 800 km intercity route with two intermediate stops, known as the Severe Segment Test (SST), direct operating costs were 2.8 cents/passenger-km, including energy, maintenance, operations and administration. This was for a relatively high demand level of nearly 10,000 passengers/hr in each direction. Costs per passenger-km increase for reduced demand with the same system. Some ways in which direct operation costs were controlled include: reduced energy consumption due to low magnetic drag of the all-coil guideway and low aerodynamic drag for multi-car consists; enroute high-speed switches with no moving load-bearing parts, and tilting suspension requiring less deceleration and reacceleration on curving right of ways (ROW).

Depreciation of new and replacement equipment, both rolling stock and fixed facilities added 3.8 cents/passenger-km, making the total operating cost for the system 6.6 cents/passenger-km. Some factors that controlled depreciation costs include the long-50-year life and low acquisition cost for the modular guideway structure, and long fatigue life of the composite vehicle carbodies.

This particular SST route had severe curves and grades in one-half of the length, to envelop all severe operating conditions, while the remainder could be run at maximum speed. Other studies by Foster-Miller for a more complex five-station intercity route, with varying demand levels enroute, showed slightly higher costs, but the bottom line is that the system operates for costs at or below those of alternative modes as mentioned earlier.

4. ADVANTAGES OF FOSTER-MILLER MAGLEV SYSTEM

- Cost competitive with existing systems (≈$6 million/km for 4,000 passengers/hr for elevated system).
- Safe and reliable.
- Low technical risk.
- Accommodates future growth in traffic (12,000 passenger/hr each way).
- Service life of at least 50 years.
- Null-flux levitation to reduce magnetic drag.
- Sidewall levitation to facilitate high speed switch, with no moving load bearing parts.
- Open floor channel guideway configuration with no ice and snow accumulation problems.
- Hollow beam guideway for high stiffness (high fatigue life) and low cost.
- Advanced composite material for lightweight vehicle body.
- Vehicle body tilting capability to reduce guideway tilting requirements for safety.
- Reliable magnets with redundancy for levitation safety and quench protection for guidance assurance.
- Advanced motor (LCLSM) for high efficiency, facilitating power transfer to vehicle, and assurance of propulsion unlike conventional motors using block switching.
- Low cost high performance GTO-based substations.

Acknowledgments

This work was performed on a contract from the NMI under the direction of Dr. John Harding, Chief Scientist and Mr. Michael Coltman of VNTSC. The Program Manager at Foster-Miller is Dr. Gopal Samavedam. Foster-Miller is solely responsible for the technical content and preserves all the rights on the material in accordance with the U.S. Government Contracting regulations, and no rights are conveyed to other parties by this disclosure.

APPENDIX A

SYSTEM TRADEOFFS AND COMPARISONS

This appendix presents the major tradeoffs considered in arriving at the Foster-Miller System Concept. The following tradeoffs are given with their associated table numbers.

1. EDS versus EMS - Table A-1.
2. Discrete versus Distributed Magnets - Table A-2.
3. Coils versus Sheet Guideways - Table A-3.
4. Sidewall versus Ground Coils - Table A-4.
5. Guideway Configuration Tradeoff - Table A-5.
6. Guideway Wrapped versus Vehicle Wrapped - Table A-6.
7. Single versus Twin Beam - Table A-7.
8. LCLSM versus BSLSM - Table A-8.
9. Carbody Materials - Table A-9.
10. Magnet Materials - Table A-10.

Comparisons to three alternative transportation systems are also presented in tabular form. The following systems are compared to the Foster-Miller Maglev in the tables noted.

1. Very High Speed Rail (VHSR) - Table A-11.
2. German Transrapid TR 07 Maglev - Table A-12.
3. Japanese Superconducting Maglev - Table A-13.

Table A-1. EDS versus EMS

Parameter	EDS	EMS
Magnet	Fewer strong magnets, can be accommodated in end bogies	Requires distributed magnets
Vehicle Weight	10 to 15% smaller	Larger due to multitude of suspension elements
Negotiable Curve Radius	400m	5,000m
Levitation Gap	100 mm	10 mm
Negotiable Misalignments (Pylon Settlement)	25 mm or larger	<10 mm
Sensitivity to Thermal Loads	Low	High due to relatively small gap

Table A-2. Discrete versus Continuous Suspension

Parameter	Discrete	Continuous
Aero Drag	Less	High due to increased frontal and base areas
Magnetic Field Shielding	Easy to implement due to passenger distance from magnet	Shielding is a problem despite reduced magnet strengths
Vehicle Power Loads	Less due to reduced cryo loads	Increased due to eddy currents
Vehicle Weight	Less	Too many suspension elements increase vehicle weight
Tight Curve Negotiation	Good	Requires almost straight track
Load on Guideway	Non uniform	More uniform

Table A-3. Coils versus Sheet Guideways

Parameter	Coil	Sheet Guideway
Manufacturing Costs	High	Low
Magnetic Drag	6 to 20 kW/ton	40 kW/ton
Attachment to Primary Structure	Backup plates bolted to guideway	Difficult technique
Thermal Effects	Not significant	Potentially severe • Buckling • Fracture
Design Methodology	Simple	Extremely involved

Table A-4. Sidewall versus Ground Coils

Parameter	Sidewall Null-Flux	Ground Coil
Magnetic Drag	10 kW/ton	20 kW/ton
Ice and Snow Effects	Not significant	Can be severe
Guideway Switch	No movement of load bearing structure	Only mechanical switch
Coil Alignment	Reduced labor for collocated propulsion and levitation coils	Increased labor due to different locations of propulsion and ground coils
Suspension	Stiffer	Softer

Table A-5. Guideway Configurations

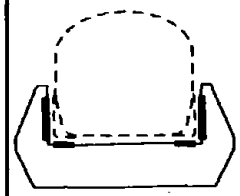
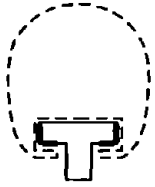
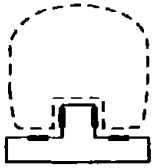
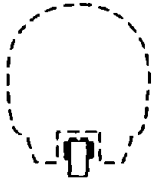
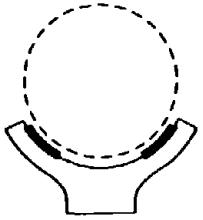
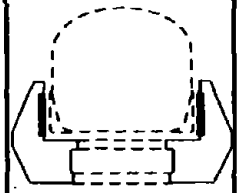
Criteria	Configuration					
	 Solid U-shape with ground coil levitation and sidewall guidance and propulsion	 T-shape with horizontal surface attractive levitation and propulsion and vertical surface guidance	 ⊥-shaped with horizontal levitation, center stem guidance and propulsion	 Monorail-type beam containing levitation, guidance and propulsion	 Round U-shape with propulsion, guidance and levitation for banking vehicle	 U-shape with sidewall levitation guidance and propulsion and open floor
1. Positive Vehicle Location Safety	Good	Good	Fair	Fair	Poor	Good
2. High Speed Switch	No	No	No	No	No	Yes
3. Structural Stiffness	High	Moderate	Moderate	Low	High	High
4. Emergency/ Maintenance Access	Good	Fair	Poor	Poor	Fair	Good
5. Influence on Vehicle Size	None	Moderate	High	High	None	None
6. Wind Stability	Good	Fair	Poor	Poor	Fair	Good
7. Yard Operations	Easier	Highly Involved	Highly Involved	Highly Involved	Involved	Easier
8. Snow/Ice/Debris Risk	Very high	High	High	Moderate	High	Low

Table A-6. Guideway Wrapped versus Vehicle Wrapped

Parameter	Guideway Wrapped Around Vehicle	Vehicle Wrapped Around Guideway
Cross-Sectional Area and Moment of Inertia	Larger	Smaller due to single beam
Stability Under Wind Loads	Good	Can be problematic
Switch	No load bearing moving parts	Cumbersome bending switch
Crossovers	Easy to design	Complex design
Adaptability to Maintenance and other Conventional Vehicles	Good	Poor
Adaptability to Existing ROW (Highway/RR Bridges)	Good	Height problem
Guideway Fatigue Life	Good	Lower due to low stiffness

Table A-7. Single versus Twin Guideway Beams

Parameter	Twin Beam	Single Beam
Handling and Transportability	Relatively easy	Involved
Track Width	Extendible to wider gauge	Significant cost impact
Alignment Adjustment	More flexibility	Difficult
Repairability	Relatively inexpensive	Can be expensive

Table A-8. Propulsion Motor Tradeoffs

Parameter	LCLSM	BSLSM
Efficiency	96%	92%
Power	5 MW	More expensive transmission (7 MVA)
Guidance Stiffness	High (5 MN/m)	Low
Coil Heating at Slow Speeds	Small (0.25°C)	Larger (1°C) More copper needed
Vehicle Onboard Power	Advanced lightweight power transfer scheme	Conventional schemes using heavy battery

Table A-9. Carbody Material Candidates

Parameters	Composite Sandwich	Aluminum Skin/Stringer	Aluminum Sandwich
Weight Savings	15%	-	15%
Fatigue Life	High	Lower	Moderate
Cost	Moderate	Low	Moderate
Vehicle Power Collection	Easy application of induction pickup	Not readily adaptable	Not readily adaptable
Number of Panels and Fasteners	Low	High	Moderate
Corrosion Resistance	High	Moderate	Low
Acoustic Noise Damping	High	Low	Medium

Table A-10. Magnet Materials

Parameter	Niobium-Titanium	Niobium-Tin
Magnet Mfg.	Proven, well understood	Difficult
Quench Protection	Simple protection	More difficult
Ductility	Ductile, easy to handle	Sensitive to strain, brittle
Conductor Mfg.	Repeatable, large database	Small database
Stability	Less but adequate margin	More margin
Field	<8T at 4.5K	<12T at 4.5K
Cost	$40/kg	$100/kg

Table A-11. Maglev versus VHSR

Criterion	FM Maglev	VHSR
Maximum Speed	134 m/sec (300 mph)	90 m/sec (200 mph)
Maximum Gradient	10% (no limit)	<<5% typically
Minimum Headway	Under 1 min can be achieved	Much higher, several minutes typically
Trip time	Significantly reduced due to the above factors	Higher
Noise	Quieter than steel wheel on rail at same speed	
Wear	Very low	High due to rotating parts and Hertzian contact stress. Rail/wheel wear and corrugations, track degration are frequent problems
Ride Quality	Can be designed for minimum required or higher levels of comfort.	Tends to be poor in revenue conditions due to wear
Costs	Higher initial but low O&M	Lower initial but high O&M
Technical Risks	Projected to be low, but needs to be demonstrated	None, mature technology

Table A-12. FM Maglev versus TR 07

Criterion	FM Maglev	TR 07
Safe Negotiable Misalignment	25 mm	<5 mm
Minimum Curve Radius at 134 m/sec	2,800m	5,800m
Motor Efficiency	Higher	Lower
Aero Drag	Lower	Higher
Vertical Clearance	100 mm	8 mm
Weight/Passenger (kg)	430	680
Cost	Lower (LCLSM costs to be resolved)	Higher
Switch	Reliable high speed vertical switch with no moving parts. Full speed	Mechanical bending switch with load bearing moving parts. Reduced speed
Sensitivity to Temperature Variations	Low due to large gap	Can be high due to small gap

Table A-13. FM Maglev versus Japanese S.C. Maglev

Criterion	FM Maglev	Japanese SC Maglev
Guideway	• Multicells • Stiff and cost efficient • Open floor, snow ice problem minimized	Simple U channel
Switching	High speed vertical switch with no load bearing moving parts	Mechanical switch with reduced speed
Body		
Body	Advanced composite design	Aluminum, fiber glass
Tilting	Yes	No
Propulsion		
Coils	Single layer (cost and copper saving)	Double layer
Motor	LCLSM for high efficiency	BSLSM
Power Transfer	"Unlimited" power transfer, reduced battery requirement	Cumbersome schemes, including S.C. magnet, heavy batteries, poor performance at low speeds
Substation	Transformer/GTO rectifier • Allows regen power • High performance • Low cost	Cycloconverter • High harmonic ripple • Interface problems with adjacent substations
Power Distribution	D.C., low EMI	A.C., high EMI
Magnetic Field Shielding	<1 Gauss by passive shielding	10 Gauss anticipated for revenue vehicles

GRUMMAN TEAM SYSTEM CONCEPT DEFINITION OF A SUPERCONDUCTING MAGLEV ELECTROMAGNETIC SYSTEM

EXECUTIVE SUMMARY

Prepared for
National Maglev Initiative

Contracting Administration
U.S. Army Corps of Engineers
Huntsville, AL 35807-4301

in response to

Contract No. DTFR53-92-C-00004

1 - EXECUTIVE SUMMARY

Grumman, under a U.S. Department of Transportation and Army Corps of Engineers contract, has completed a System Concept Definition (SCD) study to design a high-speed 134 m/s (300 mph) magnetic levitation (Maglev) transportation system. The primary development goal was to design a Maglev that is safe, reliable, environmentally acceptable, and low-cost. The cost issue was the predominant one, since previous studies have shown that an economically viable Maglev system (one that would be attractive to investors for future modes of passenger and/or freight transportation) requires a cost that is about $20 million per mile.

The Grumman Corporation assembled a team of seven corporations and one university that were exceptionally qualified to perform this study. The Grumman team members and associated responsibilities includes:

- *Grumman Corporation* - system analysis and vehicle design
- *Parsons Brinckerhoff* - guideway structure design
- *Intermagnetics General Corp.(IGC)* - superconducting magnet design
- *PSM Technologies* - linear synchronous motor (LSM) propulsion system design
- *Honeywell* - communication, command, and control (C^3) design
- *Battelle* - safety and environmental impact analysis
- *Gibbs & Hill* - power distribution and system control design
- *NYSIS* - high temperature super conductor (HTSC) and magnetic shielding analysis.

As a result of the team's efforts, a unique high-speed Maglev system concept (Fig. 1-1), has been identified. If implemented, this design would meet all of the objectives specified above and would satisfy U.S. transportation needs well into the 21st century. The

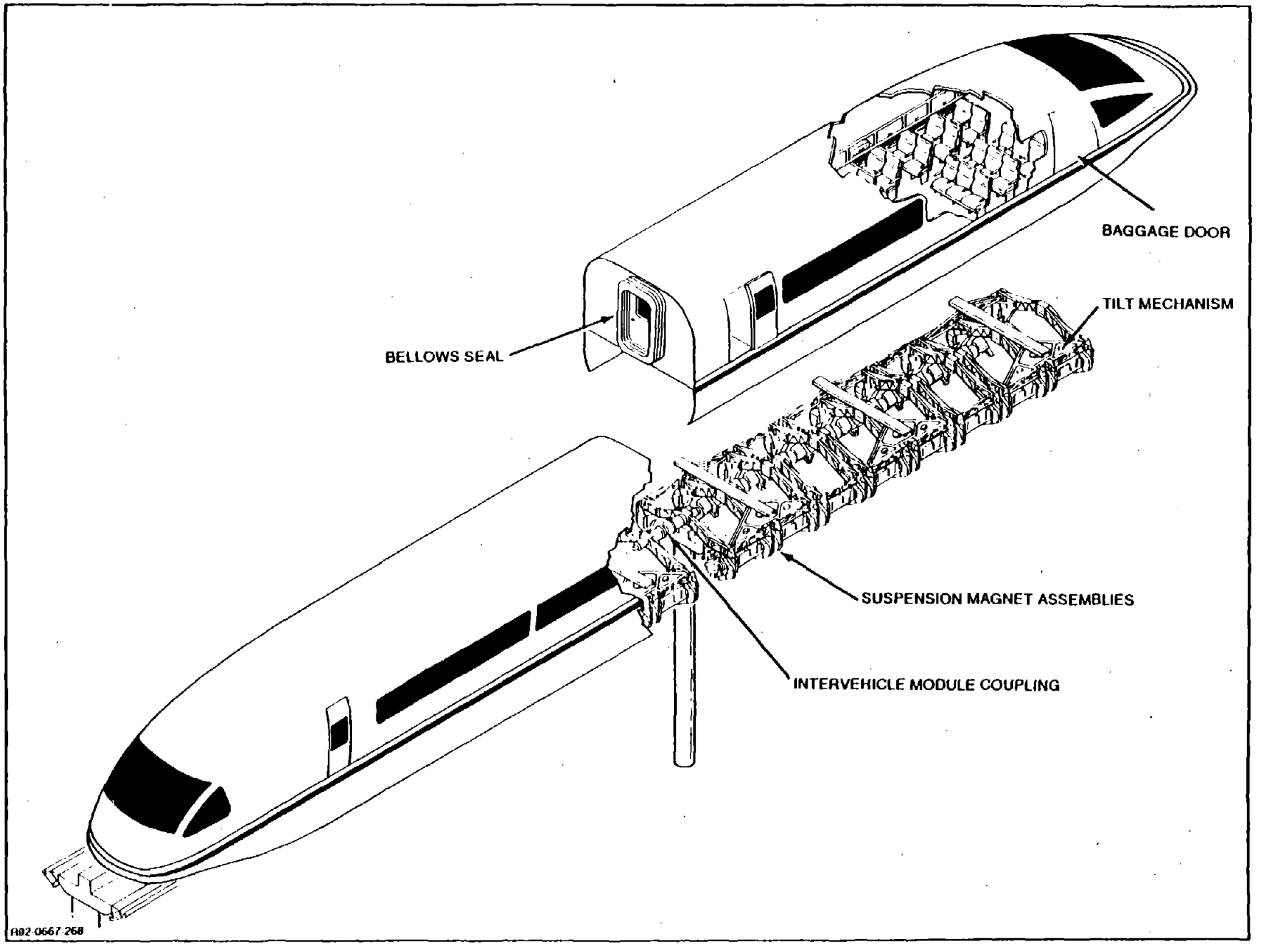


Fig. 1-1 Baseline Grumman Team Vehicle Configuration

design is based on the electromagnetic suspension EMS system concept using superconducting (SC) iron cored magnets mounted along both sides of the vehicle.

The Grumman team selected an EMS design instead of an electrodynamic suspension (EDS) design because of the following significant advantages that the EMS offers over the EDS design.

- Low magnetic fields in cabin and surrounding areas (this eliminates or minimizes the need for magnetic shielding)
- Uniform load distribution along the full length of vehicle (minimizing guideway loads and vibrations in the cabin and contributing to the elimination of a secondary suspension system)
- Small pole pitch (results in smoother propulsion)
- Magnetically levitated at all speeds (needs no supplemental wheel support)
- Wrap-around configuration (safer operation).

Existing EMSs like the German Transrapid and the Japanese High Speed Surface Transportation (HSST) systems use copper coils on the vehicle's iron cored magnets instead of SC coils. This results in a number of basic disadvantages:

- Small gap clearance (1 cm (0.4 in.)), which results in tighter guideway tolerance requirements
- Heavier weight with limited or no tilt capability to perform coordinated turns and maximize average route speed
- Limited off-line switch speed capability (56 m/s maximum)
- Large number of magnets and control servos (~100 total).

The Grumman team design has retained all of the advantages of an EMS system. At the same time it has succeeded in eliminating, or significantly improving, every aspect of the identified EMS disadvantages. A brief description of our system and how it has accomplished this goal follows.

Levitation, Guidance & Propulsion System Design

Figure 1-2 illustrates the Grumman Team's Maglev concept. Figure 1-2a, shows a cross section of the vehicle with the iron core magnets and guideway rail identified in black. The laminated iron cored magnets and iron rail are oriented in an inverted "V" configuration with the attractive forces (F1 and F2) between the magnets and rail acting through the vehicle's center of gravity (cg). Vertical control forces are generated by sensing the gap clearance on the left and right side of the vehicle and adjusting the currents in the control coils, shown in Fig. 1-2b, to maintain a relatively large 4 cm (1.6 in) gap between the iron rail and the magnet face. Lateral control is achieved by differential measurements of the gap clearance between the left and right sides of the vehicle magnets. The corresponding magnet control coil currents are differentially driven for lateral guidance control. There are 48 magnets, 24 on each side of a 100 passenger vehicle. In

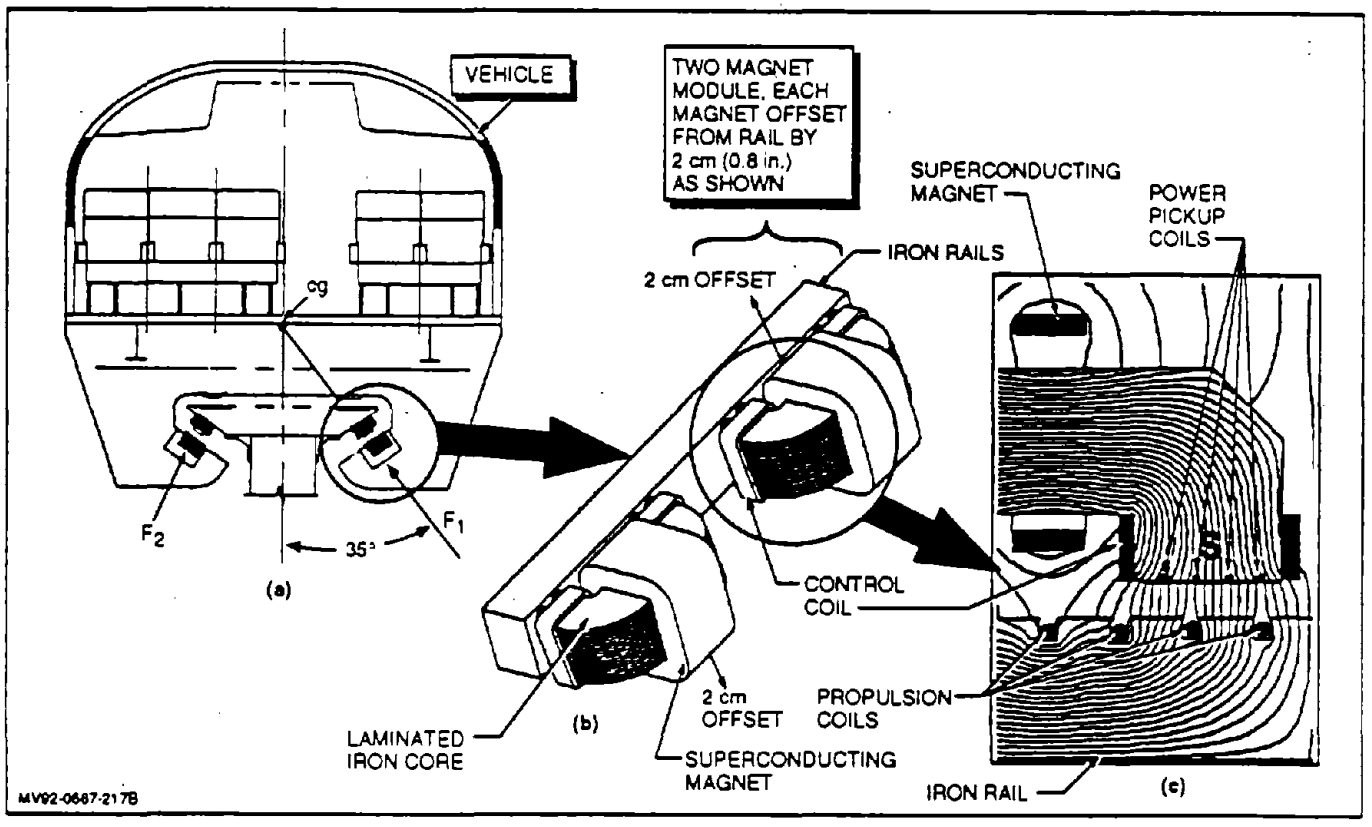


Fig. 1-2 Levitation, Propulsion & Guidance System

this manner control of the vehicle relative to the rail can be achieved in the vertical, lateral, pitch, and yaw directions. The control of vehicle speed and roll attitude is discussed below.

Two magnets combined as shown in Fig. 1-2b make up a magnet module (MM). Each magnet in a MM is a "C" shaped, laminated iron core with a SC coil wrapped around the center body of the magnet, and two copper control coils wrapped around each leg. Vehicle roll control is achieved by offsetting the magnets by 2 cm (0.8 in.) in an MM to the left and right side of a 20 cm (8 in.) wide rail. Control is achieved by sensing the vehicle's roll position relative to the guideway and differentially driving the offset control coils to correct for roll errors. The total number of independent control loops required for a complete 100 passenger vehicle control is 26 (1 for each of 24 MMs and 2 for roll control).

The iron rail shown in Fig. 1-2b also is laminated and contains slots for the installation of a set of 3-phased alternating current (ac) linear synchronous motor (LSM) propulsion coils. The coils are powered with a variable frequency variable amplitude current that is synchronized to the vehicle's speed. Speed variations are achieved by increasing or decreasing the frequency of the ac current.

Comprehensive two- and three-dimensional magnetic analyses have been performed to assure that our magnetic design will simultaneously meet all levitation, guidance and propulsion control requirements identified above, and do it without magnetically saturating the iron core. An example of this analysis is shown in Fig. 1-2c.

Low magnetic fields in the passenger compartment and the surrounding areas represents an important aspect of our design. Figure 1-3 identifies constant flux densities in the cabin and station platform that can be expected for our design. Flux density levels below the seat are less than 1 gauss, which is very close to the earth's 0.5 gauss field level. On the platform, magnetic levels, when the vehicle is in

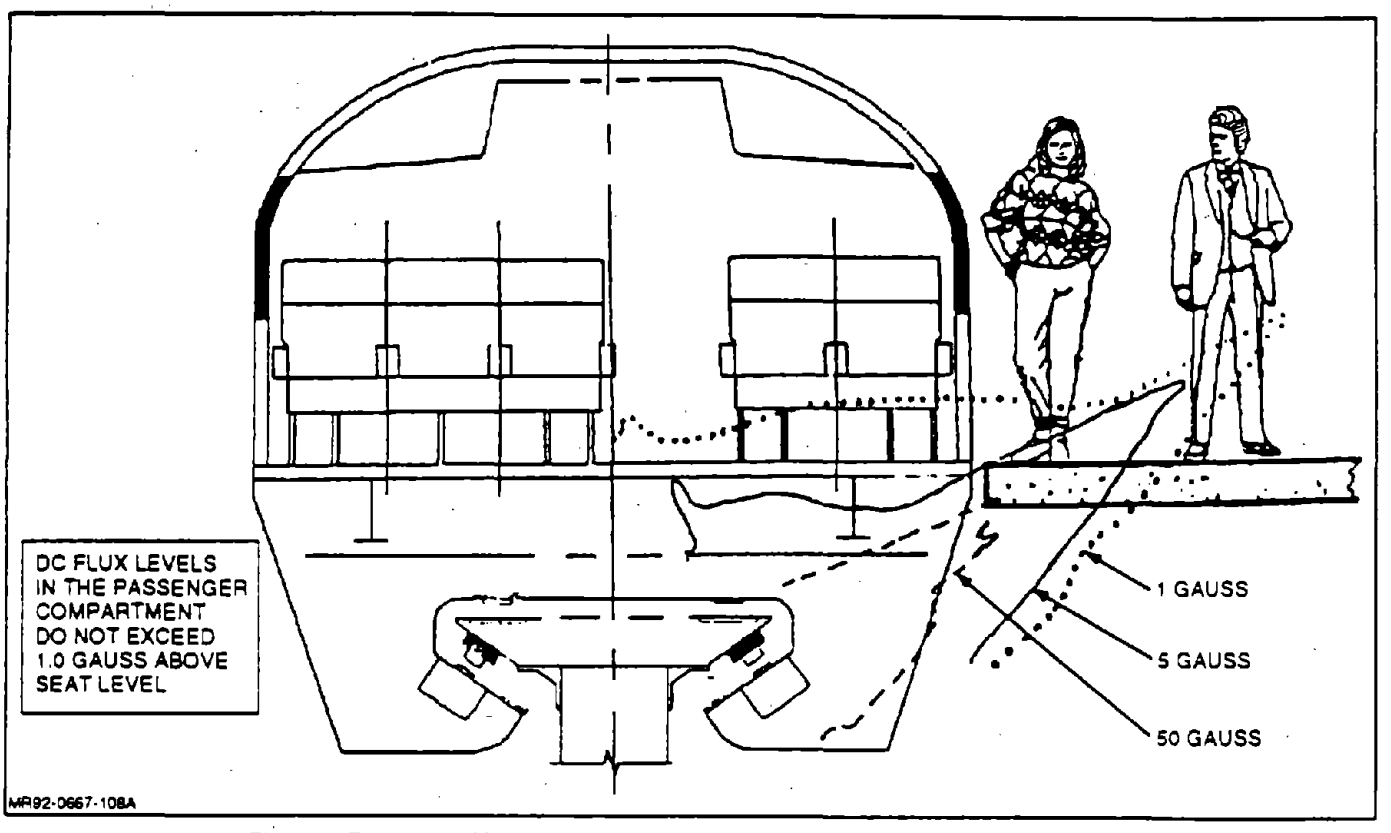


Fig. 1-3 Estimated Magnetic Fields in Passenger Cabin & Surrounding Areas

the station, do not exceed 5 gauss, which is considered acceptable in hospitals using magnetic resonance imaging (MRI) equipment. This data is based on a three-dimensional magnetic analysis program and assumes no shielding. With a modest amount of shielding, these levels could be further reduced should future studies (now under way) indicate a need for lower values. Similarly, ac magnetic fields are anticipated to be within acceptable levels.

Another important aspect of our magnet design is the use of SC magnets in place of copper coils in existing EMS systems. This allows us to operate with a large 4 cm (1.6 in.) gap clearance without paying the heavy weight penalty that would be required if copper coils were used for the same purpose.

The use of an iron core with the SC coil provides an added advantage. The magnetic flux is primarily concentrated in the iron core, not the SC coils as is the case of an EDS system. This reduces the flux density and loads in the SC wire to very low values (<0.35 Tesla and ~17.5 kPa, respectively). In addition we have implemented a patented constant current loop controller on the SC coil that diminishes rapid current variations on the coil, minimizes the potential of SC coil quenching and allows for the use of state-of-the-art SC wire.

The use of iron-cored SC magnets with their associated low flux density and load levels identified above affords an additional advantage of our design over an EDS concept. High temperature SC technology has progressed to a point that the field levels these magnets require are achievable with existing high TC wire. It is now reasonable to consider the application of this new emerging technology to our concept. Although we are not baselining the use of high temperature SC for our application (except for its use as lead-in wire to the low temperature SC coil), we recommend that a one-year development program be undertaken at this time to manufacture samples of high temperature SC coils of sufficient length and with adequate current density carrying capacity to satisfy our requirements.

In summary, the use of SC iron-cored magnets has resulted in a significant number of advantages for our concept:

- Large gap size - 4 cm (1.6 in.)
- Low magnetic fields in superconducting coil - <0.35 T
- Low magnetic fields in passenger cabin - <1.0 gauss dc
- Low load forces in superconducting coil- ~17.5 kPa
- State-of-the-art superconducting wire - 0.65 mm diameter (used in Relativistic Heavy Ion Conductor Program)
- Lower weight than copper coil system - ~80% reduction per magnet
- The potential for near term implementation of high temperature superconducting wire.

Vehicle Design

A number of important system trade studies (e.g., vehicle weight and power) were performed to arrive at the vehicle configuration identified in Fig 1-1. Figure 1-4 shows how the weight and power to propel the vehicle varies as a function of the number of seats across and the total number of passenger seats per vehicle. The best trade between weight and power is identified in the range of four to five seats across. We have chosen five seats across for our baseline configuration to keep the vehicle weight as low as possible with a minimum associated power penalty impact.

The tradeoff shown in Fig. 1-5 identifies how the total system cost, which includes the guideway, vehicles, levitation, propulsion, and operating cost, is affected by the number of passenger seats in the vehicle and the number of passengers per hour utilizing the system. Note that minimum cost results between 50 and 150 seats per vehicle. We have chosen 100 passenger seats per vehicle for our baseline configuration.

The analysis described above has led to the baseline configuration identified in Fig. 1-6. The system lends itself to other single and multivehicle (train) configurations that can be developed based on two basic building block modules shown at the top of Fig. 1-6. The main module consists of a 12.7 m (41.7 ft) long center section, which seats 50 passengers with 2 entrance doors (one on each side of the vehicle), 2 lavoratories (one designed to accommodate handicapped passengers), multiple overhead and closet storage facilities and a galley area. The forward and aft closure sections of the vehicle utilize the second basic module, which consists of a 4.9 m (16.0 ft) long section that is structurally identical, but finished different internally, depending on whether it is used at the forward or rear location on the vehicle. We have adopted one-way vehicle operation to minimize the impact of weight and cost for reverse facing seat mechanisms and duplicating all the electrical controls and displays on both sides of the vehicle.

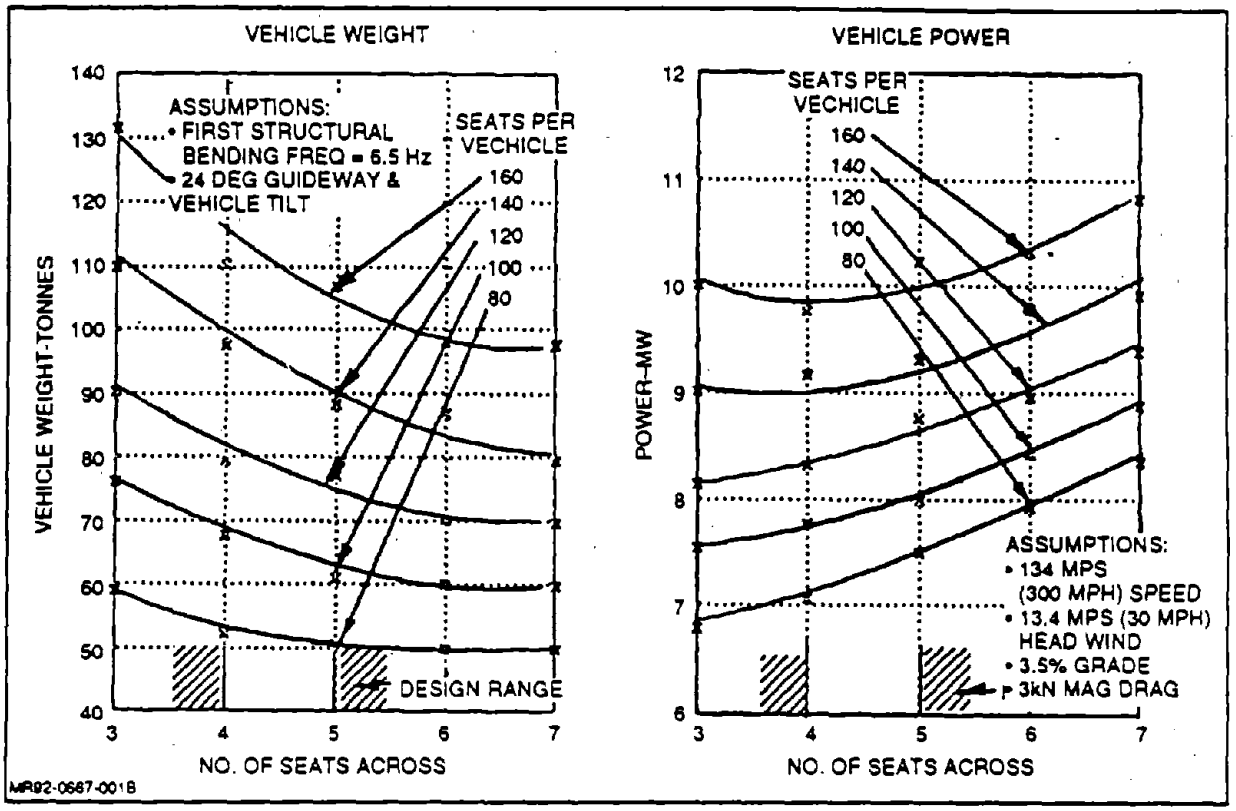


Fig. 1-4 Vehicle Weight & Power Trade Study

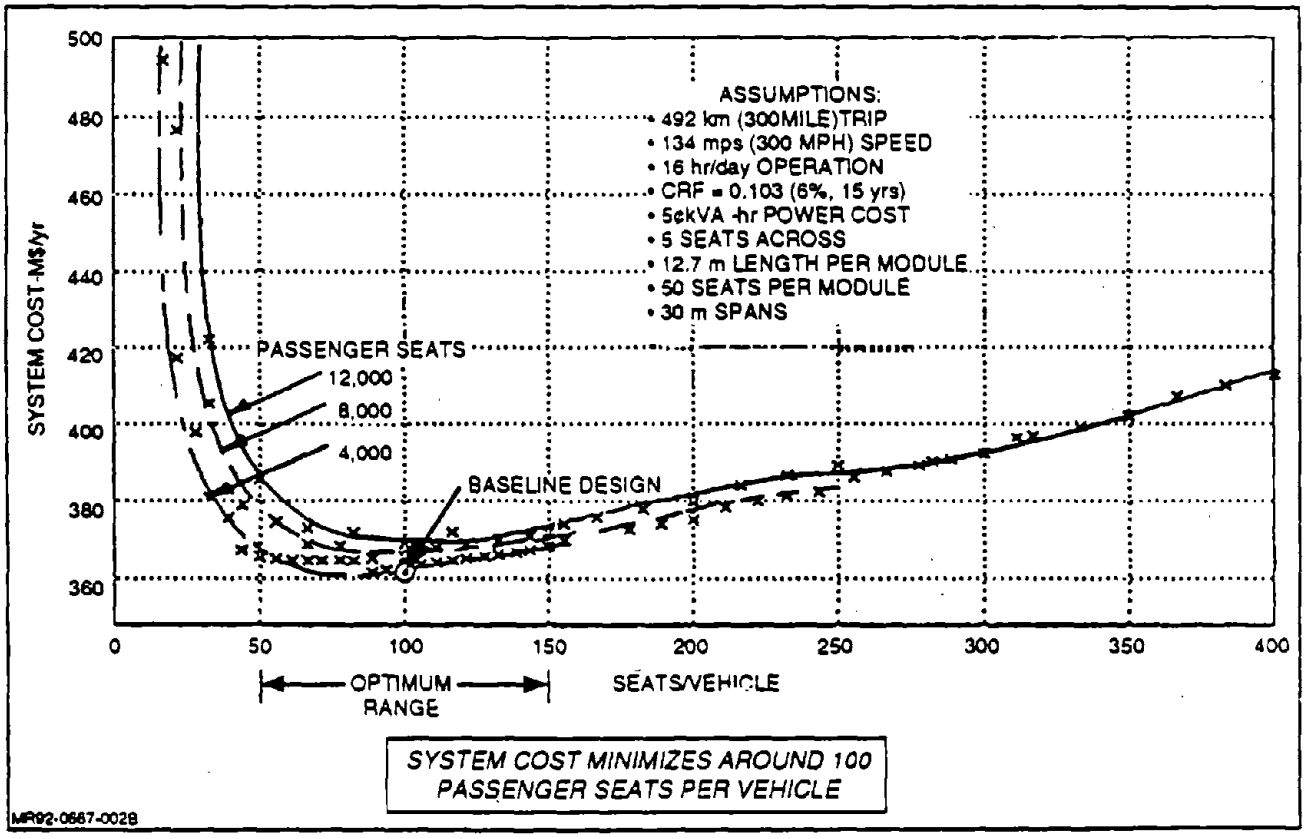


Fig. 1-5 System Cost Trade Study

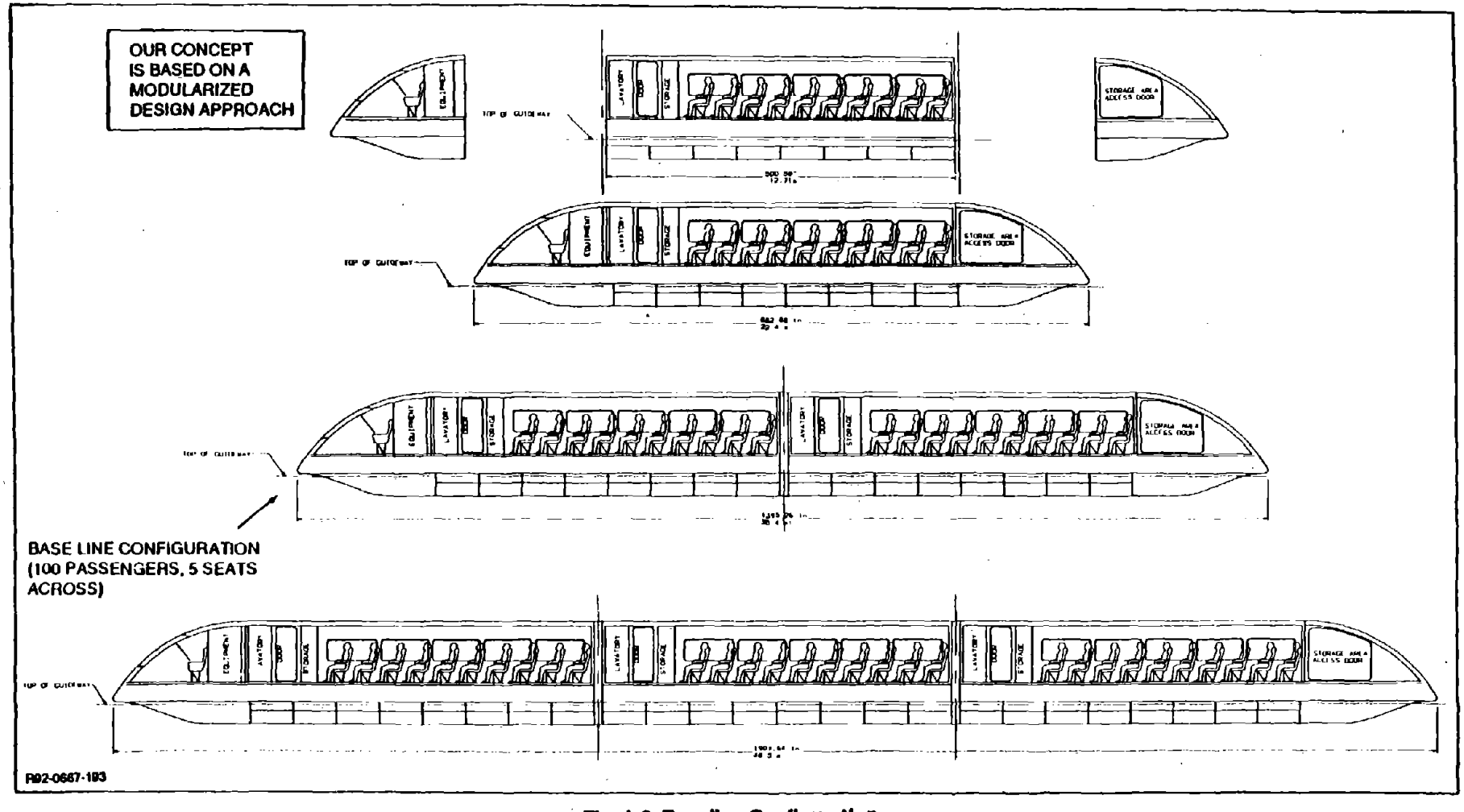


Fig. 1-6 Baseline Configuration

We also have chosen to include business-type aircraft seats with an ample 38 inch (0.96 m) seat pitch to assure a comfortable seating arrangement for all passengers.

Guideway Design

The guideway is an important aspect of our system design because it represents the largest percentage of the total system cost. Figure 1-7 shows how system cost distributes between the four major components, i.e., guideway (64.4%); electrical and communication (14.8%); vehicles (13.3%); and the ancillary facilities such as stations, building and packaging (7.46%).

A number of different guideway designs were investigated. These are shown in Fig. 1-8 and are identified in terms of increasing cost. In each case our design mandated that a center platform exist along the full length of the guideway to provide a safe exit for passengers in the event of an emergency such as a fire or smoke in the cabin. Escape ladders at periodic column locations also were identified.

An analysis of the four guideway configurations identified showed that the guideway design we have chosen is not only lowest in cost, but also is relatively insensitive to span length, Fig, 1-9. This has important implications when the guideway is installed in areas such as the U.S. interstate highway system, which require wide ranges in span length depending on local road conditions. In summary, the "spline girder" configuration shown in Fig. 1-10 has been chosen as our baseline for the following reasons:

- Lowest cost guideway ($7.99M/km ($12.9M/mile), for spread footing); cost is relatively insensitive to span length
- Smaller footprint
- Can be more closely designed to suit span variations
- Visually less intrusive because of single column
- Creates less shadow
- Visually esthetic.

Our total system cost which includes guideway, electrical and communication, vehicles, stations buildings etc is estimated at $12.4M/km ($20M/mile).

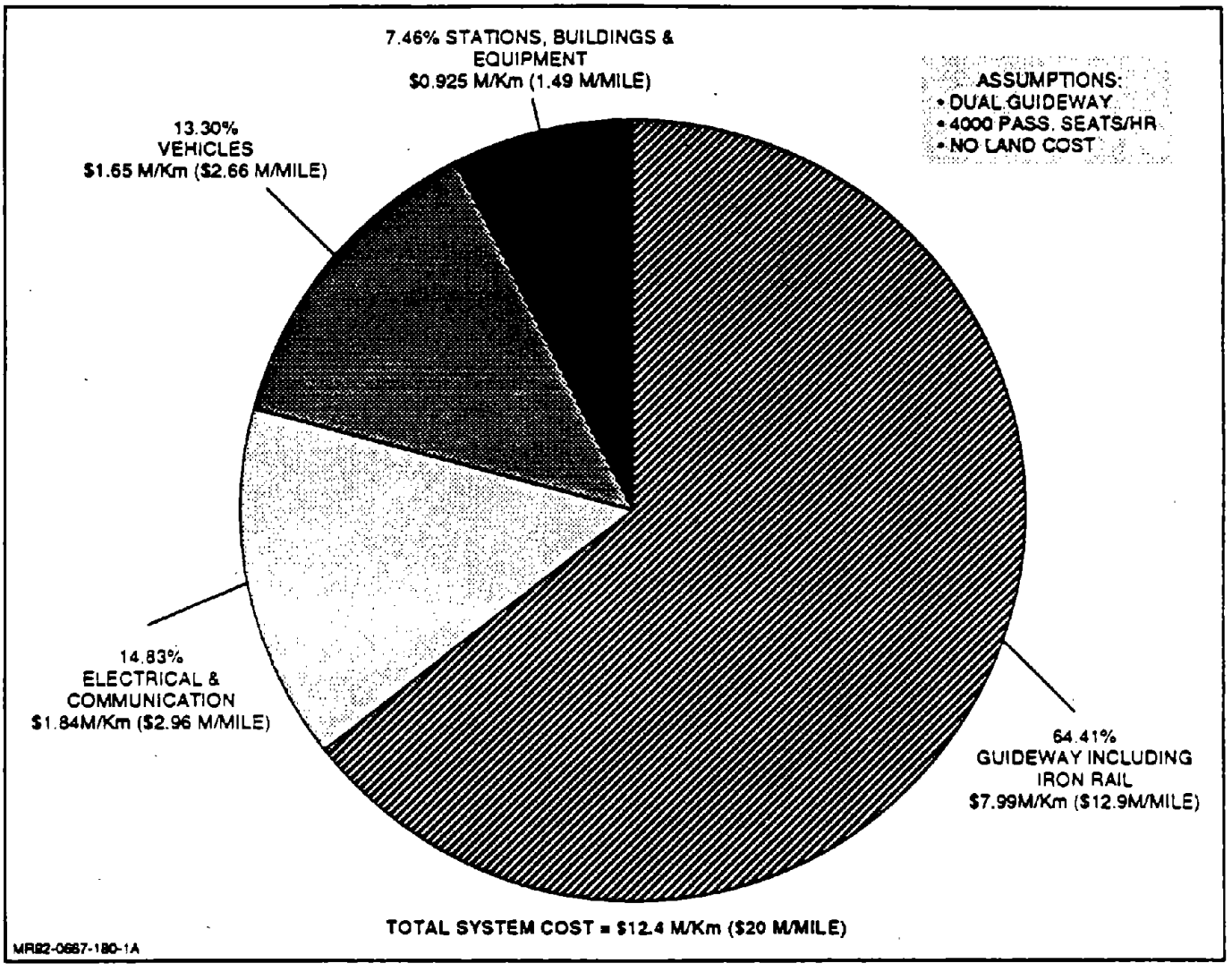


Fig. 1-7 Distribution of System Cost

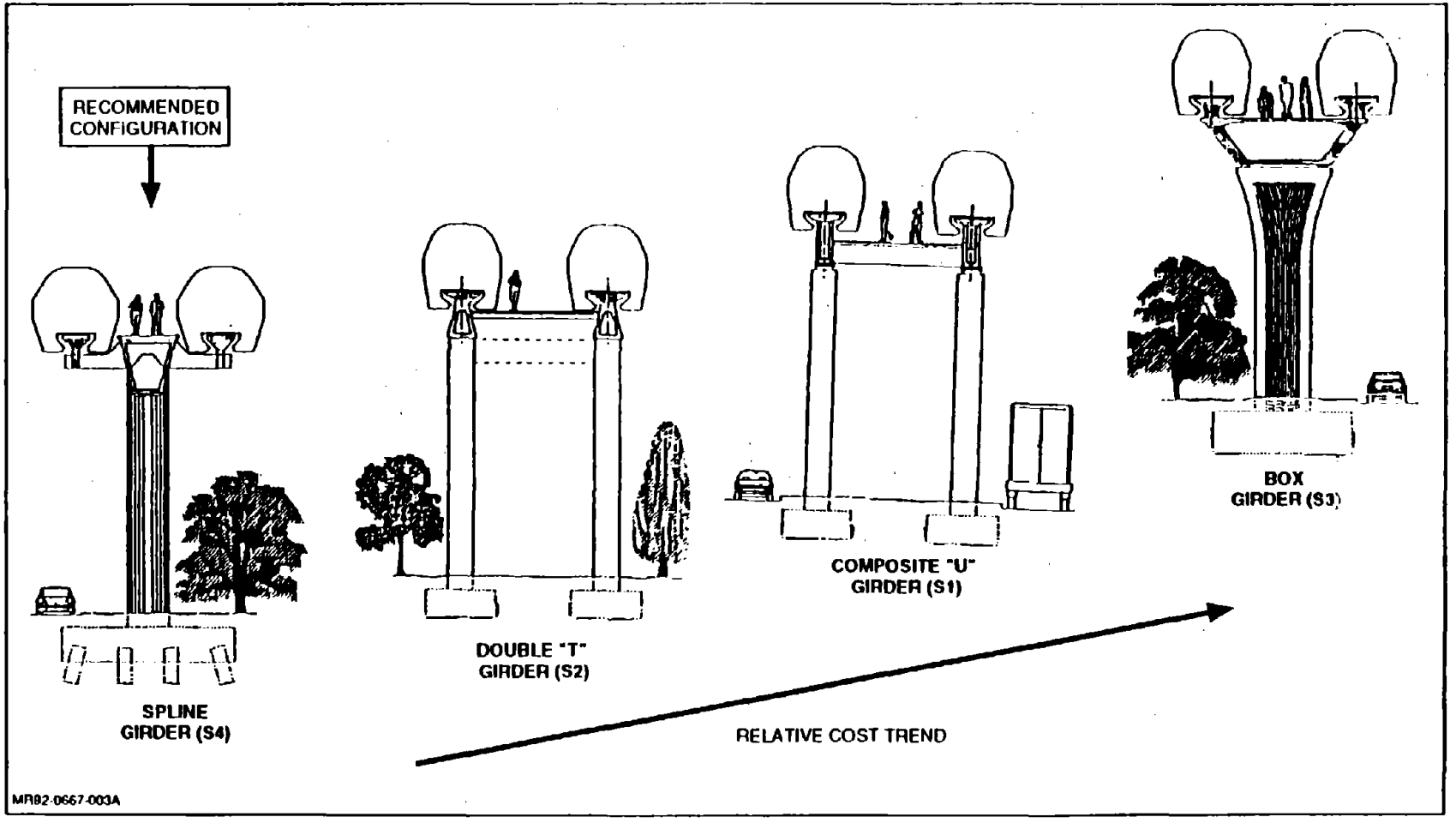


Fig. 1-8 Alternate Guideway Structures Considered

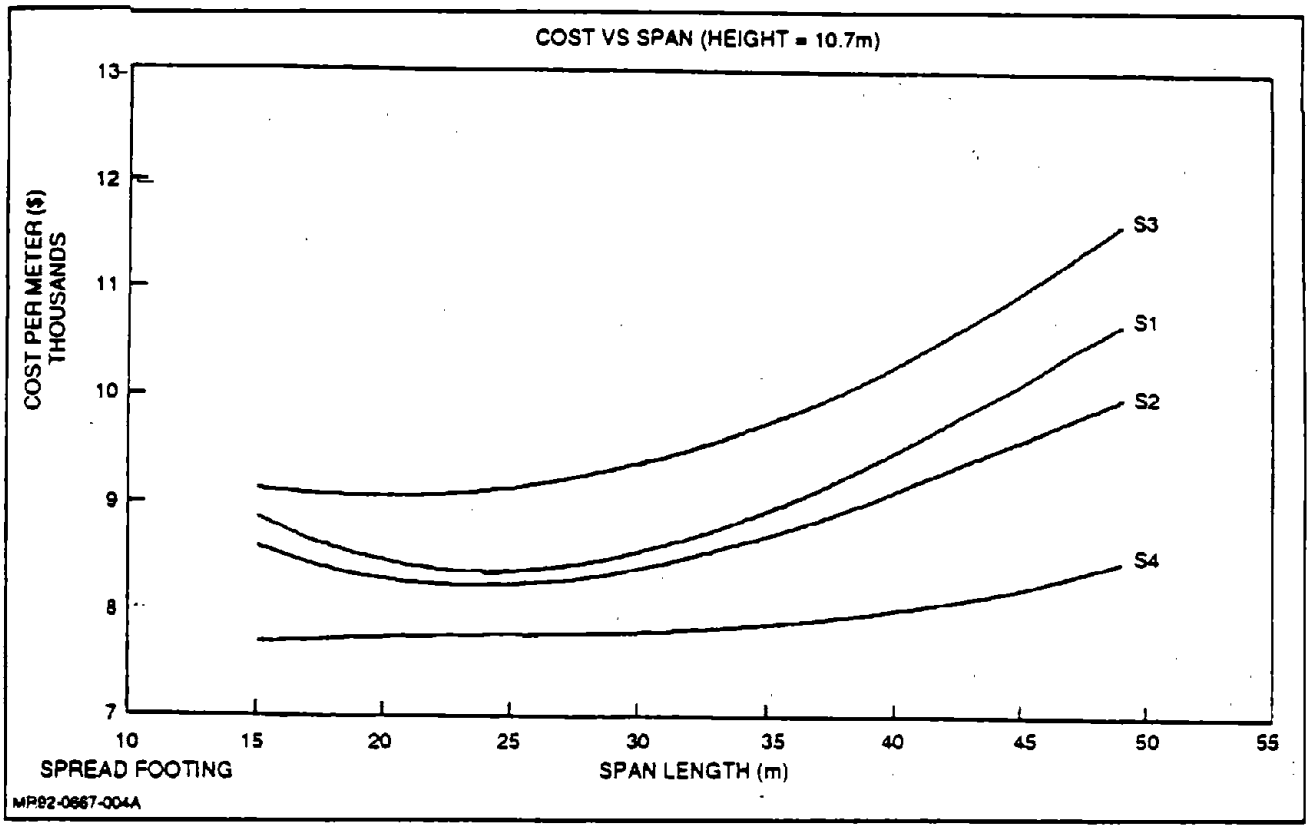


Fig. 1-9 Costs vs Span for S1-S4 Spread Footing Layout

High Speed Off-Line Switching

An important aspect of our design is the capability of providing high-speed off-line switching. Unlike the Transrapid design, which moves one 150 m (492 ft) section of the track laterally 3.61 m (12 ft), we move two sections 3.0 m (10.0 ft) laterally with one actuator motion. Details of our track switching concept are given in Fig. 1-11. It identifies the two sections of the track that are moved to accomplish this function. The upper figure shows the through traffic condition for the track switch. The lower figure identifies how the 60 m long switch, Unit 1, is flexed to a curved section, while the right hand 60 m long switch, Unit 2, is pivoted about the fixed switch points. This combined motion of the two sections (120 m total length) provides a turnout speed of 65 m/s (143 mph). Transrapid turnout is limited to 56 m/s (123 mph) with a longer section length (150 m).

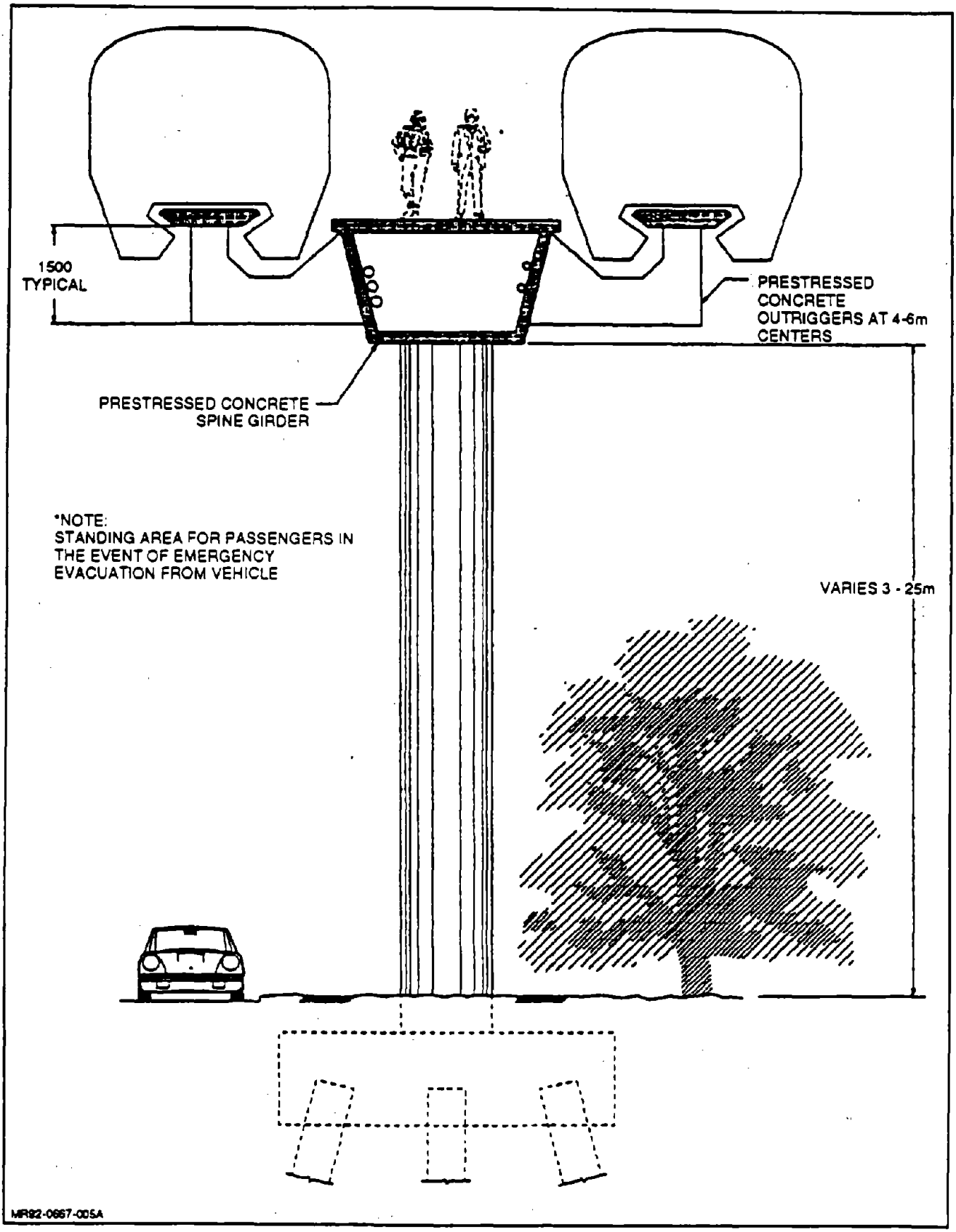


Fig. 1-10 S-4 Tangent Track

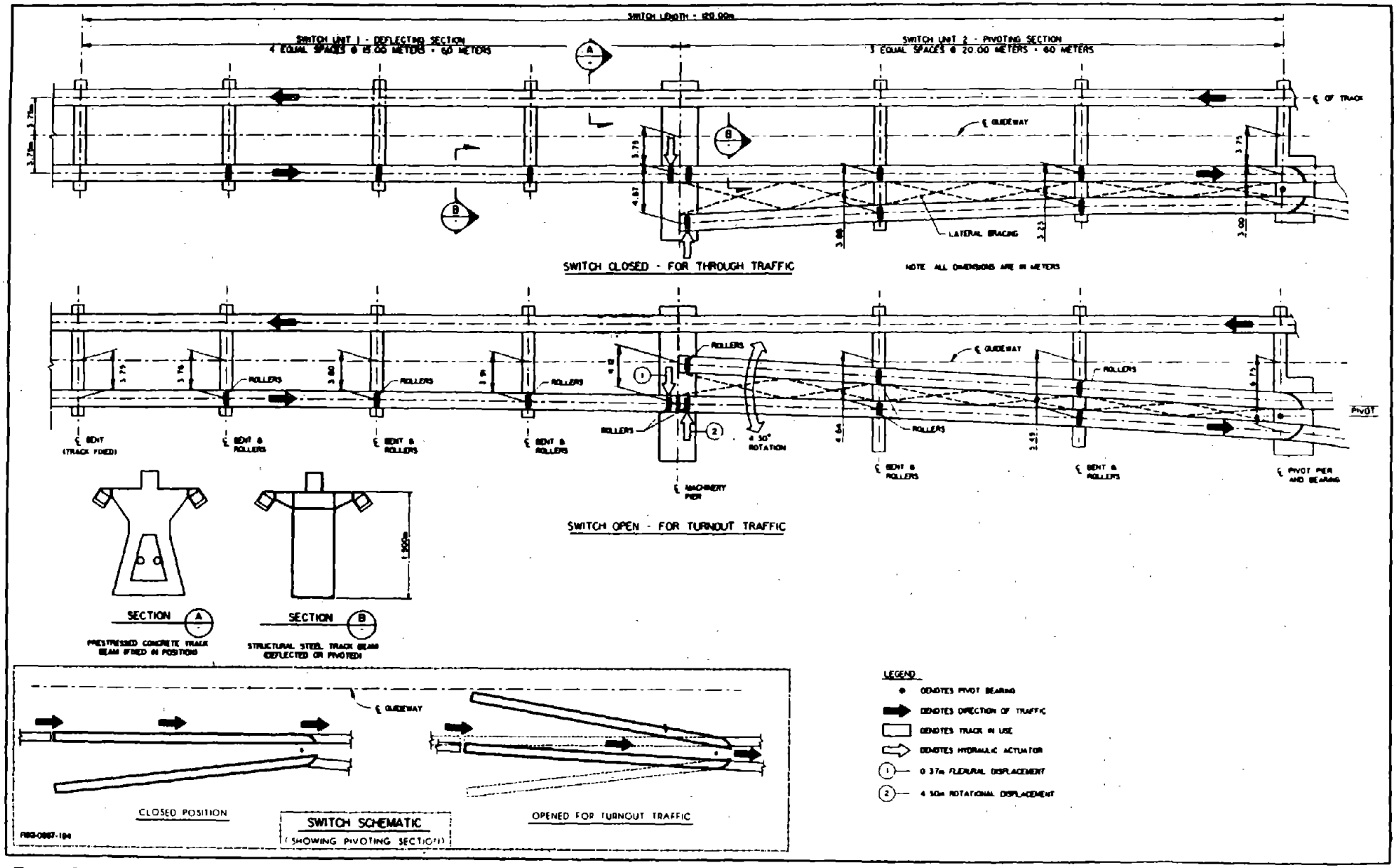


Fig. 1-11 Elevated Switch Layout

Vehicle Cabin Tilt Design

Unlike any of the other existing high-speed Maglev designs, such as, the Transrapid TR07 or the Japanese MLU002, we are providing the capability of tilting the vehicle passenger compartment by ±9 deg relative to the guideway. In this manner, our design, as shown in Fig. 1-12, will allow for coordinated turns up to ±24 deg banking (±15 deg in the guideway and ±9 deg in the vehicle). This capability will assure that all coordinated turns can be performed at the appropriate tilt angle independent of the speed that the vehicle is traversing the turn, as well as allowing for high-speed off-line switching.

Economic Analysis

An economic forecast analysis for a Maglev system was performed as a function of two primary cost drivers: total cost of the major Maglev elements identified in Fig 1-7, and the passengers per hour utilizing

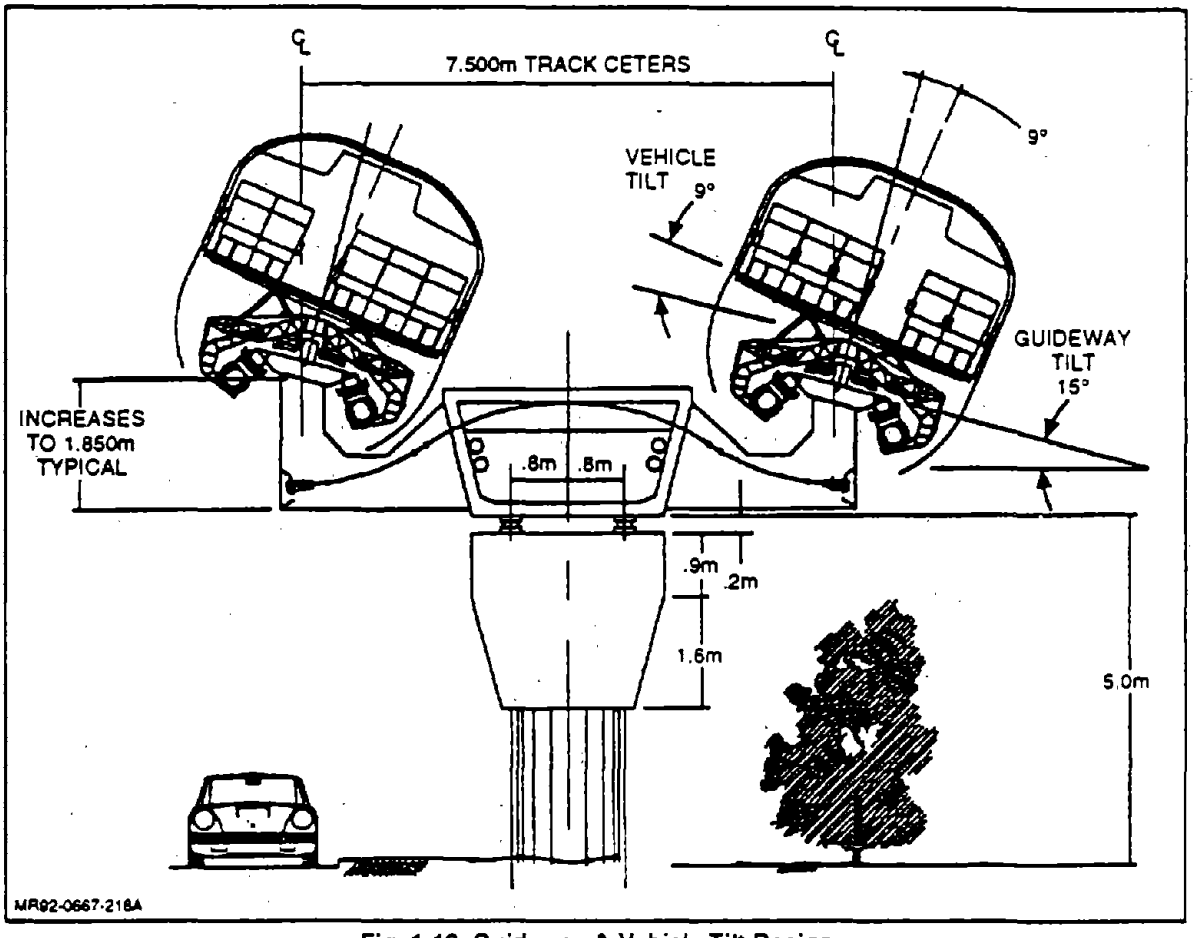


Fig. 1-12 Guideway & Vehicle Tilt Design

the system. The results of this analysis are presented in Fig. 1-13 with the assumptions listed below:

- 483 m (300 mile) corridor
- Development and demonstration cost of the Maglev system is not included
- Federal, state and local governments supply right-of-way at no cost
- Ridership is based on 260 days/year, 16 hours/day, 60% capacity
- 20% pre-tax operating margin on ticket price based upon 5 year build, 15 years of operation
- Future interest (8%) & inflation rate (5.4%) follow "Data Resources, Inc" (DIR) forecasts.

If we assume a 2,000 passenger per hour usage (typical of high volume routes like New York/Washington, DC/Boston or Los Angeles/San Francisco) with the previously identified $12.4M/km ($20M/mile) for our baseline system cost the ticket price that would have to be levied is

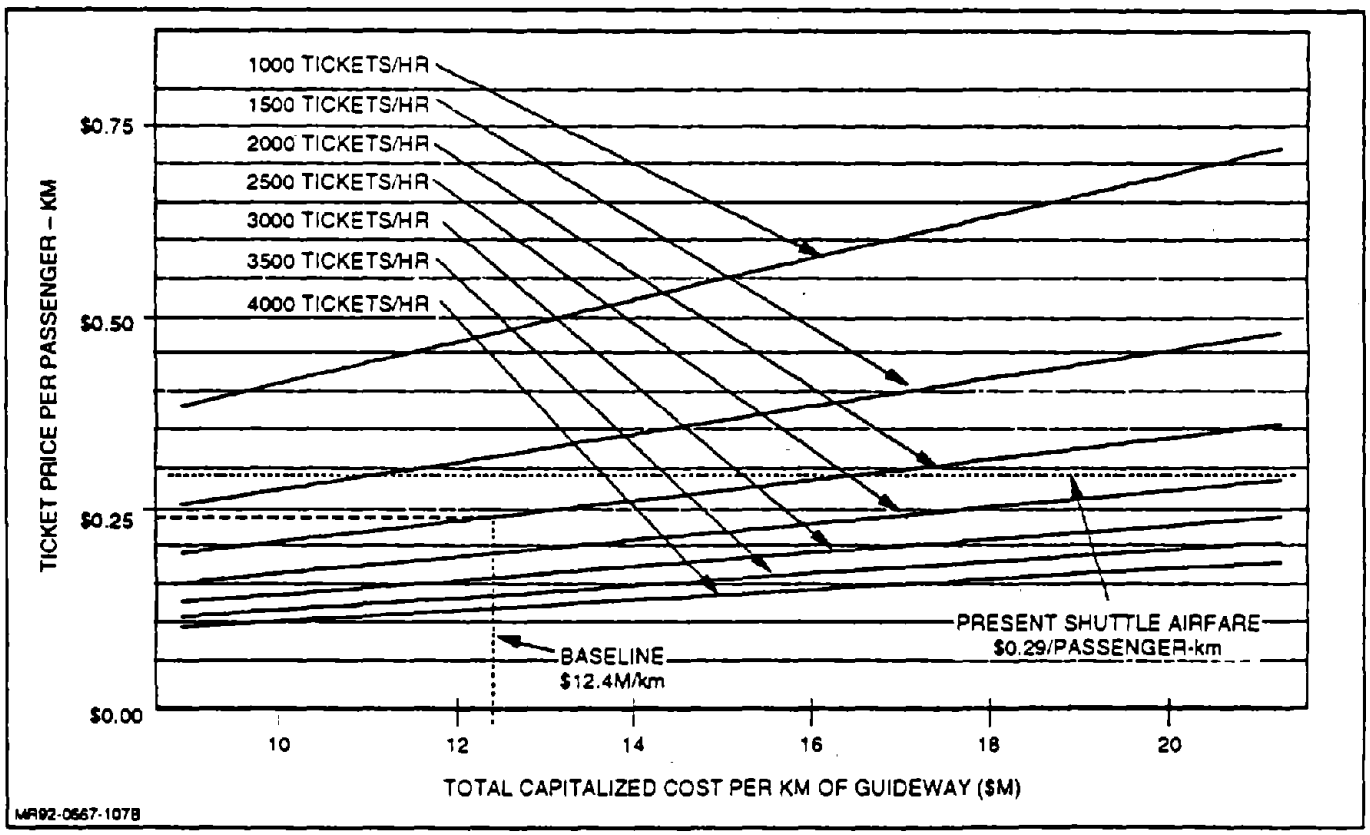


Fig. 1-13 Maglev One-Way Ticket Price as a Function of Demand and Guideway Cost (In constant 1992 dollars and includes 20% margin in ticket price)

$0.23/km ($0.38/mile); this would still provide a 20% margin on the ticket cost for the system operator. Also shown on the figure is the $0.29/km ($0.47/mile) present charge for the New York/Washington,DC/Boston corridor. The results indicate that a Maglev system of the type being recommended in this report can pay for itself during its first 15 years of operation. The implication here is that after 15 years, when the capital investments have been fully paid, the proceeds from the high volume traveled routes could be used to support the building and operation of Maglev routes that are located in less densely populated areas.

Recommendations for Future Study & Development

Based on the work performed in this study, a number of critical areas have been identified for future evaluation and development:

- Conduct a design, development, and test program to demonstrate the performance of a full scale SC "C" core shaped magnet module
- Perform wind tunnel testing to verify aerodynamic analyses
- Perform additional studies to further reduce the vehicle weight and total system cost through:
  - Improved magnet design
  - Lower cost of guideway and laminated iron rail
- Develop and test a guideway integrity and hazard detection system.

Summary

It is our opinion that the Grumman Team EMS Maglev concept as described in this report will provide an effective low cost U. S. Maglev transportation system that can meet all of the expectations identified in the opening paragraph of this Executive Summary and at the same time minimize the negative issues previously discussed. We believe that the Grumman team has performed sufficient analyses in the areas of guideway design, levitation, propulsion and guidance, vehicle structural design, aerodynamics, controllability, dynamic interaction, environmental, safety, and reliability to warrant this optimism.

MAGNEPLANE SYSTEM CONCEPT DEFINITION REPORT FOR THE NATIONAL MAGLEV INITIATIVE

EXECUTIVE SUMMARY

ARMY CORPS OF ENGINEERS

Contract No. DTFR53-92-C-00006

The Magneplane System

CONCEPT RATIONALE

The Magneplane system achieves continuous traffic flow similar to highways, rather than the batch flow process of railroads. Magneplane utilizes magnetic levitation to gain two crucial advantages:

> *individually targeted vehicles can operate safely at 20 second headways, and stop at off-line stations without slowing traffic;*
>
> *vehicles are supported resiliently at 6 inch clearance, and are free to self-bank in turns, with airplane comfort.*

Because guideways carry only individual vehicles, they can be significantly lighter and less expensive to build and maintain then railroad type guideways. They need to carry only 1/20th the live load, and can be compatible with the curves, grades and overpass requirements of highways. Because of the large clearances possible with the Magneplane concept, guideways do not require high stiffness and accuracy of alignment or banking (superelevation), and are aesthetically more graceful.

Less energy is needed because individually targeted vehicles travel non-stop. This eliminates the need to accelerate passengers who did not want to stop at every station, and reduces the cruising speed required to match airline trips.

Individual Magneplanes can transport a continuous stream of 25,000 passengers/hour, five times more that railroads, and can provide non-stop service at high frequency along multi-station corridors.

Magneplane was developed in the seventies to the level of a fully operational superconducting, scale model with initial support by MIT, Raytheon, Avco, Alcoa, and 3M, and with subsequent support from the National Science Foundation under the RANN program. The program was terminated in 1975 for political reasons. Many Magneplane innovations have since been adopted by the Japanese and Germans, who both failed to capitalize on the full potential advantages of the original concept, which remains the most advanced concept, and the one best suited to American needs in the 21st century.

A Next Generation team has been formed by Magneplane International, Inc. in collaboration with the MIT Plasma Fusion Center, MIT Lincoln Laboratory, Raytheon Equipment Division, United Engineers and Constructors, Inc., Beech Aircraft Corp., Failure Analysis Associates, Inc., Process Systems International, Inc., and Bromwell & Carrier, Inc. The first system is planned to be ready for construction beginning in 1997.

1.0 DESIGN OVERVIEW

1.1. MAJOR MAGNEPLANE DESIGN GOALS

Existing transportation technology is nearing saturation and cannot meet projected demands. Airlines have saturated the airspace at major hubs. Automobiles will require 40-lane interstate highways in a decade. Railroads, whether wheelborne or maglevitated, can handle about half as many passengers as one single highway lane; the faster they go, the less their capacity, and the less often they can stop. Radically new technology is needed.

The next revolution in transportation technology has begun, and will become the largest technology venture for several decades. Our economic security requires that we play a leading role in this venture, world-wide.

Magneplane International is designing the only transportation system proposed thus far that can meet projected demands, and help solve the problems of existing technology: *congestion, pollution, environmental destruction, dependence on foreign oil, and unnecessary loss of lives.* Magneplane therefore offers the only technology which can restore US leadership in transportation.

Magneplane's objective is not only to replace short-haul airlines, but primarily to reduce highway traffic, which carries more than 90 percent of passengers and freight along most corridors. This means providing a cost-effective, attractive alternative that people will actually use instead of their cars. If the automobile is partially displaced by a faster, safer, cheaper means for traveling and commuting, driving will be fun again, and we can better protect our health and environment. Magneplane systems will permit measures like the establishment of green-belt zones to revitalize urban centers by reduced congestion, frustration and lost productivity.

Magneplane technology will also enable the United States to develop world leadership in high-speed ground transportation, thereby restoring our balance of trade, our industry, and our jobs.

Our principal design goals are the following:

1. *cruising speed of 300 mph, high average speed, low waiting time, non-stop service when possible .*
2. *capacity of up to 25,000 passengers per hour on a single magway (equal to three highway lanes) .*
3. *transportation alternative to both cars and planes for trips as long as 400 miles.*
4. *ride quality as good or better than airplanes.*
5. *safe, reliable, and operational under all weather conditions.*
6. *no new corridors - should be built along existing highways.*
7. *flexibility in upgrading capacity and service.*
8. *points of access where people live and work, lower use of intermodal connections than required by airplanes.*

1.2. HOW OUR DESIGN MEETS THESE GOALS

We propose a computer-controlled continuous flow system:

- We will build small magports at shopping malls, industrial parks, city centers, and any other place where people go in great numbers. There is no reason to limit maglev use to a few huge hubs. Small off-line magports will be served without interrupting the flow of magplanes along the principal corridor.

- We will connect the stations with a network of magways built along existing highways. New land for straight routes is simply not available in places where maglev is needed most. The Magneplane system allows magplanes to bank in curves like airplanes to provide a comfortable ride at high speeds.

- We will run single magplanes, not trains. Magplanes will be dynamically scheduled: A central computer will plan the routes of each vehicle in response to ticket purchases, so that passengers will get fast service directly to their destination with as few stops between as possible. With long trains, small magports are not possible, nor is dynamic scheduling. Trains cannot stop often enough to be useful.

The magplane is propelled by a powered magway; vehicles ride a traveling wave, like surfboards; they can follow at close headways without colliding. Superconducting magnets on board the vehicle interact with the magway to produce both lift and thrust.

1.3. LEVITATION 3.2.1.a.

Superconducting levitation magnets at the bow and stern produce strong magnetic fields underneath the vehicle. When the magnets move, their fields induce image currents in a 2 cm thick aluminum sheet in the magway. These image currents behave exactly like mirror images moving with the vehicle magnets, and therefore repel them, producing a lift force.

Sheet levitation (as the effect has been called) can produce a smooth ride at a height of several inches above the magway, even when the magway is rough. This magnetic spring is very soft, but becomes very stiff as the vehicle is pushed toward the magway and thus prevents contact. Oscillations are prevented by an active damping system (smart shock absorber) described below.

1.4. PROPULSION AND BRAKING 3.2.1.b.

The Magneplane vehicle is propelled by a linear synchronous motor (LSM), which resembles a "brushless DC motor", stretched out along the magway. In a rotary motor, a rotor with coils follows a rotating magnetic field generated by stator coils which surround the rotor.

In the case of Magneplane, the rotor coils are aboard the vehicle, and the stator coils are in the magway. When they are powered with AC current, the magway coils produce a traveling wave of magnetic field. The speed of the wave depends on the frequency of the AC current. This frequency, and thus the vehicle speed, is controlled by wayside power units which resemble the wayside transformers in a

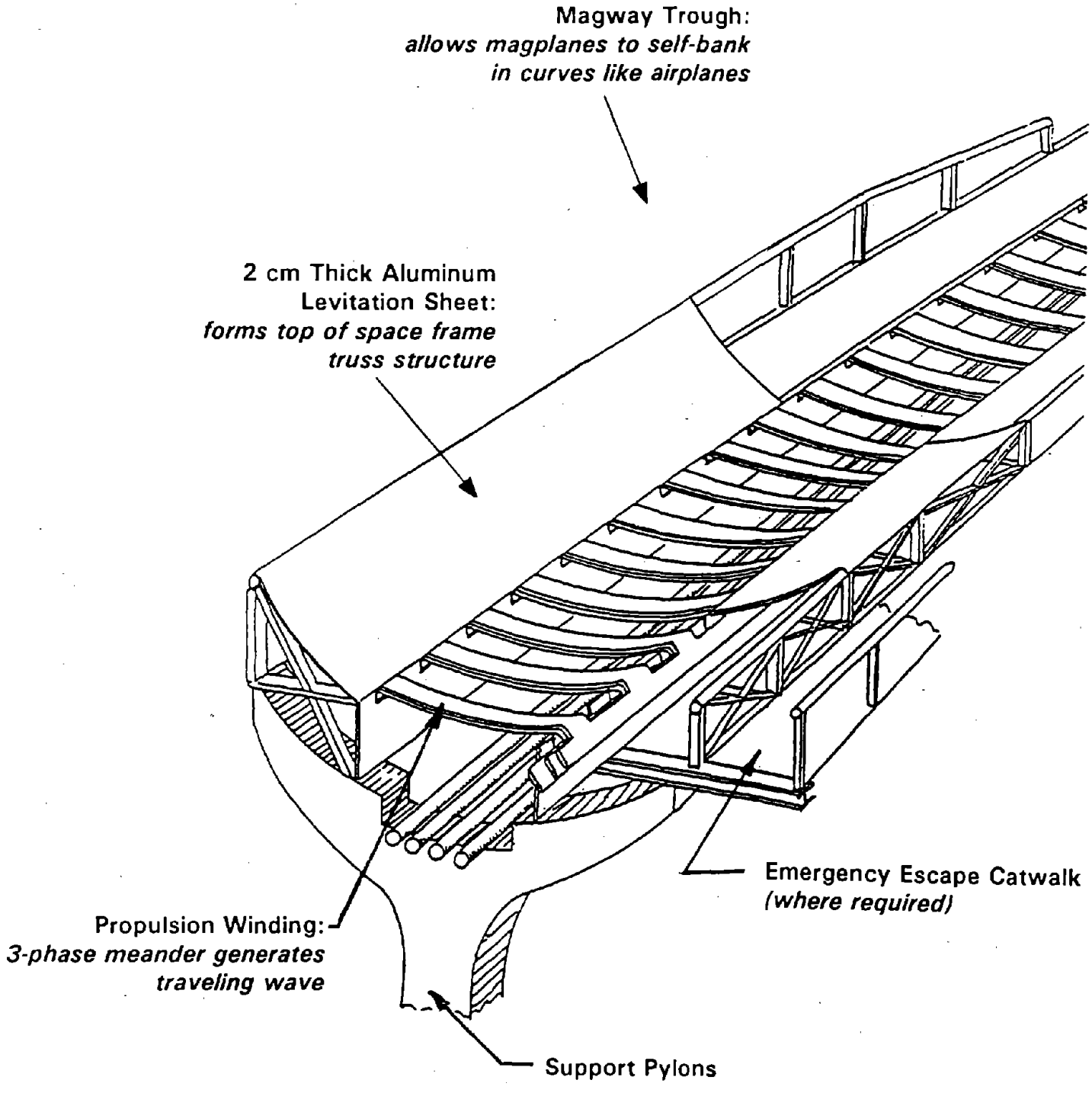


Figure 1 Isometric view of magway showing structure, LSM windings, and levitation sheet

conventional railroad. These units can accelerate, maintain speed, or decelerate the vehicle.

Each unit powers the LSM over a block of up to 2 km. Only one vehicle occupies a block at any given time, so there are never two vehicles riding the same traveling wave.

The wayside power units communicate with the magplane traveling in their particular block, controlling its speed. They also communicate with the central controller which manages all traffic in the entire system.

1.5. MAGWAY 3.2.2.a.

The Magneplane magway can be built on grade. It can also be elevated inexpensively because it carries only one twentieth the live load of a railroad trestle. This is an important advantage, because grade crossings cannot be used at the speed and frequency of magplanes.

The upper surface forms a circular trough designed for passive self-banking in curves (see below). The trough consists of three parts: The center contains the linear synchronous motor winding, which is a meander coil potted in reinforced composite; it is flanked on each side by a curved aluminum levitation plate forming a trough of circular cross section. This trough is supported by an integral aluminum space frame, or where long spans are necessary by a separate girder of concrete or steel.

1.6. COORDINATED CURVES 3.2.1.e.

Magneplane vehicles can perform *coordinated curves*, just like airplanes. A perfectly coordinated curve is a banked curve in which there is no sideways force on the passengers - they are not aware of any banking unless they look out the window. Coordinated curves happen automatically in the vehicles because they are free to roll in the circular magway trough, and the vehicle's own mass provides the rolling moment.

Curved magways are built for a particular optimal speed (the design speed) at each point. At the design speed, the vehicle rolls such that its propulsion magnets are directly over the linear synchronous motor windings. Significant deviation from the design speed is acceptable, without a loss of propulsion power or ride quality.

1.7. VEHICLE SWITCHING 3.2.2.d.

Magplanes must enter and exit the main magway trunk at high speed, without slowing down the flow of traffic. A mechanical switch which requires bending a long section of magway was found to be too slow at minimum headways of twenty seconds to permit detecting a malfunction and taking corrective action. It was also found to be too sensitive to icing and too maintenance-intensive.

We have therefore invented and verified a magswitch without moving parts which can be actuated and confirmed in a fraction of a second, requires only switching power to operate, and is fail-safe in the event of power failure.

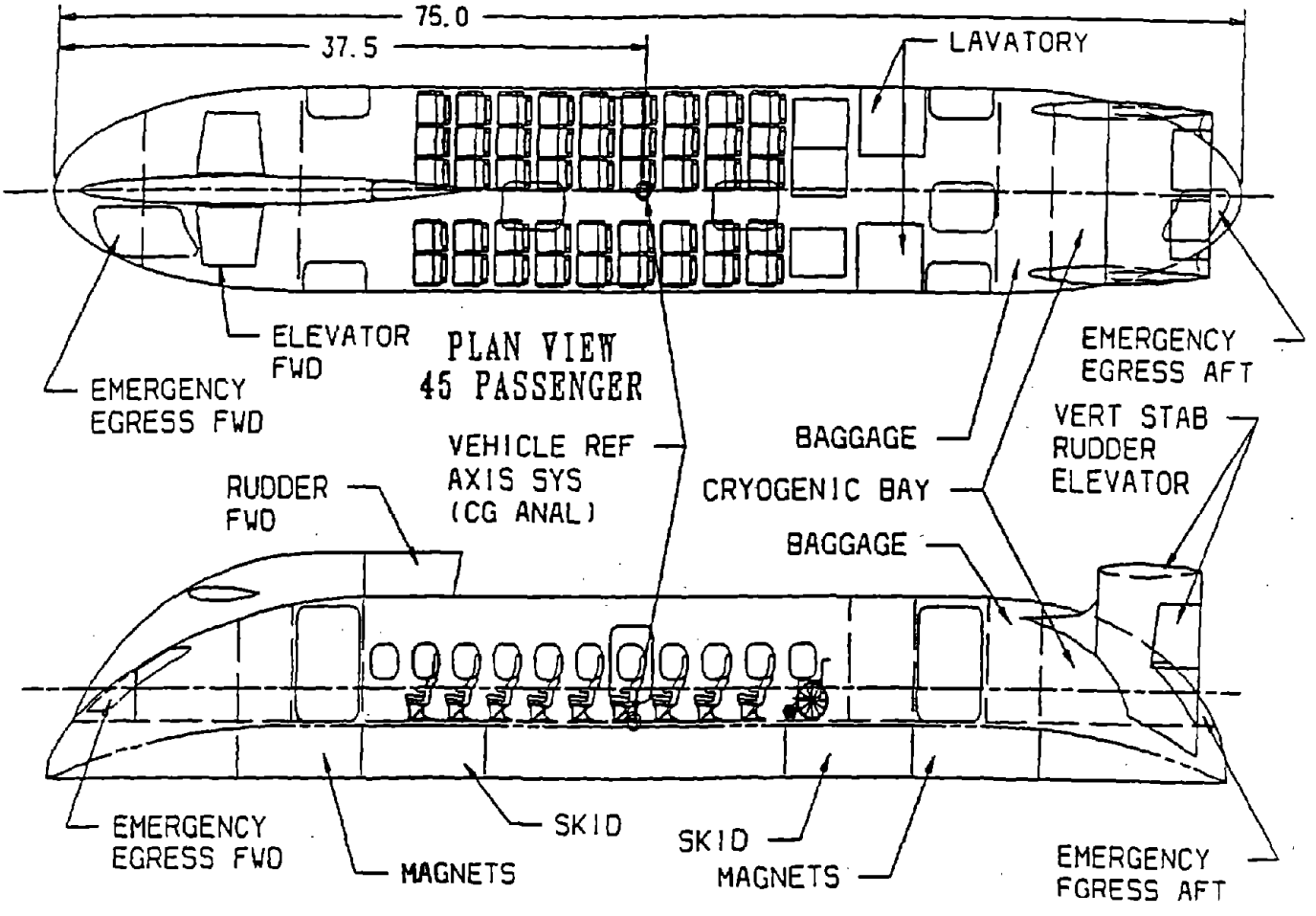


Figure 2 Plan and side views of 45-passenger magplane (measurements in feet)

The magway trough widens to form a side-branch, and the vehicle is guided between the main trunk and the branch by selectively opening or short-circuiting two sets of passive coils by means of relays. These coils are the magnetic equivalent of the mechanical "frog" used in conventional railroad switches. They can be default-wired for the vehicle to continue, or exit the magway in the event of power failure.

1.8. CAPACITY AND UPGRADE 3.2.3.j.

Two sizes of Magneplane vehicles: a 45-passenger and a 140-passenger vehicle have been designed. Small vehicles may be used initially. As part of an integrated upgrade plan, large vehicles (requiring more power) will be built later to provide higher capacity, and wayside power modules will be added to decrease headway. Capacity can thus be upgraded from 4000/hour to 25,000/hour each way.

1.9. COOLING 3.2.1.a.2.

The Magneplane superconducting magnets require cooling to 8 degrees Kelvin. The Magneplane cryogenic refrigerator circulates coolant (supercritical helium, helium above its critical pressure where it cannot form bubbles) through the conduit which surrounds the superconducting wire. "Cable-in-conduit" magnets of this type were developed by our team and are used in most of the largest superconducting magnets world-wide. The technique eliminates the need for immersion in liquid helium. Magnets are surrounded only by a vacuum container and a nitrogen-cooled heat shield.

1.10. ON-BOARD POWER 3.2.1.j.

A high-frequency, backward-traveling wave superposed on the propulsion wave will induce about 200 kW of AC power in on-board pickup coils. It will be converted to standard line frequency and used to power onboard actuators, lighting, heating and air conditioning equipment.

1.11. LANDING GEAR 3.2.1.d.

Magneplane's landing gear uses air-lubricated pads instead of wheels. These pads are lined with an anti-friction material and extended by actuators capable of lifting the vehicle to levitation height. A compressor forces air through holes in the bottom of these pads to generate an air cushion. This type of gear is desirable at landing speeds because it is more durable and dependable than wheels and requires less maintenance. It also facilitates station handling by permitting lateral motion and rotation on a flat surface.

1.12 EMERGENCY BRAKES 3.2.1.d.

Vehicle braking is normally done by the LSM, which can achieve more than 0.4 gee of acceleration or deceleration, converting about 80 percent of braking energy into useful power (regenerative braking). In case of LSM power failure, emergency brakes are used. High friction skids are extended by actuators resembling the

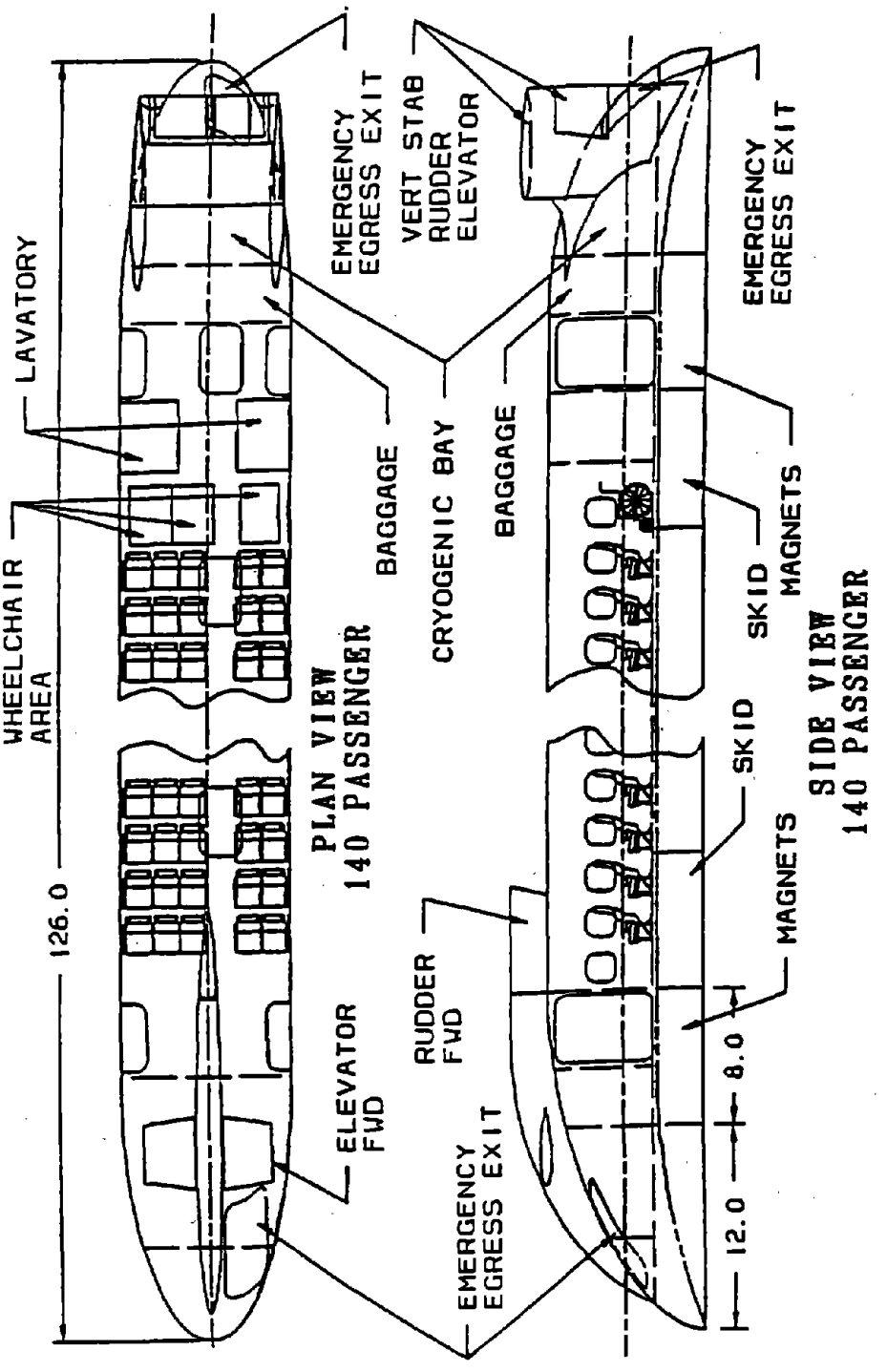
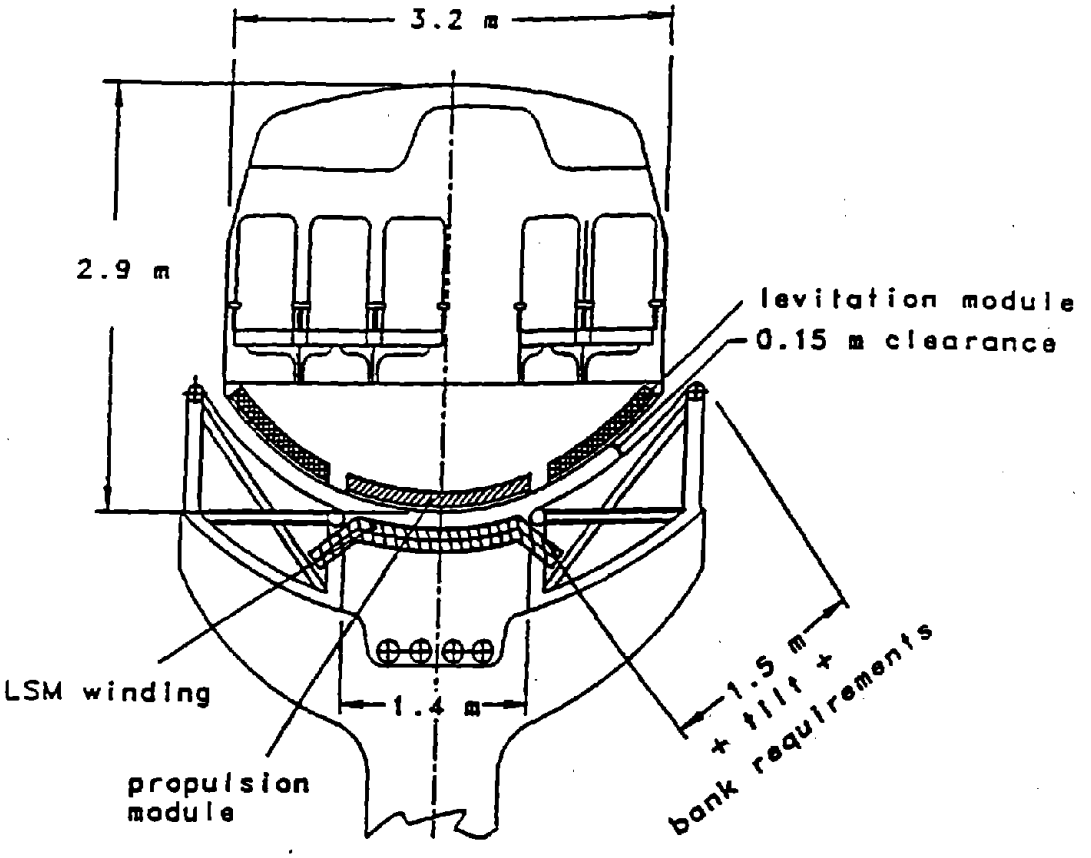


Figure 3 Plan and Side Views of 140-Passenger Magplane (Measurement in Feet)



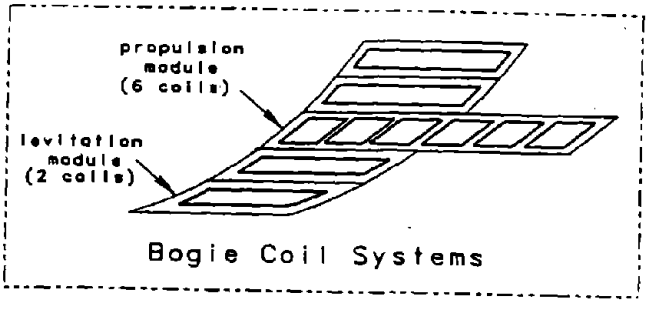


Figure 4 Vehicle Cross-section and Arrangement of Bogie Coil System (Dimensions Approximate)

landing pads and produce up to 0.65 gee of emergency deceleration. Braking energy is dissipated in a length of magway which can absorb much more energy than a disc brake. Even the most advanced multi-disk, multi-caliper aircraft brakes of acceptable size would not suffice for a single emergency stop from 300 mph.

1.13. ACTIVE DAMPING 3.2.2.g.

Magnetically levitated vehicles of any type have no inherent damping mechanisms and will oscillate at their resonant frequencies. Magneplane vehicles exhibit slow oscillations (0.5 - 2 Hz) in all principal modes of motion (heave, pitch, yaw, sway, roll, and thrust). Vibrations at these frequencies are eliminated by an *active damping system.* Two mechanisms for damping are employed: the phase of the LSM is shifted to generate vertical forces which counteract vertical oscillations (heave), and aerodynamic surfaces oppose pitch, yaw and roll oscillations. This active system prevents oscillations before they start, unlike a passive shock-absorber which can only damp oscillations after they have developed.

1.14. CONTROLS 3.2.3.a.

Magneplane uses a multi-tiered self-inspecting fail-safe control system. There are three tiers of control hierarchy: *on-board, wayside,* and *global.*

The **on-board control system** manages the landing gear, airfoils, emergency braking, door operating, and other vehicle-related functions. It monitors vehicle attitude, acceleration in all modes, and magway proximity. It calls the wayside power unit for appropriate correcting forces and moments to maintain ride quality by adjusting the phase and frequency of the LSM current and by actuating aerodynamic surfaces. Its input is a multi-sensor platform, and its output controls the wayside power conditioning units and the on-board control actuators for landing gear, brakes, doors, etc. . The history of vehicle performance may be used to instruct subsequent vehicles about optimal ways to respond to magway conditions and to monitor the structural integrity of the magway.

A **wayside control system** in each magway block manages the LSM in that block. Its inputs come from the on-board control system, and from the Global control system. The wayside system also controls vehicle switching in any block that contains a magnetic vehicle switch.

The **global control system** manages the overall traffic on a continuous basis. It always maintains headways and speeds for all vehicles, plans routes so as to avoid bottlenecks, ensures optimum vehicle availability, and solves emerging traffic problems. It also responds to ticket purchases by scheduling vehicle destinations, and assigning passengers to vehicles. It receives input from the accounting/ticketing system at each station and each of the wayside control systems.

A **back-up system** relies on global positioning to ensure that vehicle position information is preserved in the event of power or communications failure.

1.15 TAKE-OFF AND LANDING MODES 3.2.3.i.

Induced repulsion will not suffice to lift the vehicle at speeds belowabout 18 m/s (40 mph), and available thrust will not suffice to reach take-off speed at zero height. Drag is too high, and the magplane will not "get on the step". The landing gear must therefore lift the vehicle to levitation height and hold it there until take-off speed is reached.

Lifted by air-lubricated landing pads, take-off will require only several hundred meters, or about half the length of a typical runway.

MAGNEPLANE SYSTEM SPECIFICATIONS

This outline includes major specifications that affect subsystem interfaces and all operations, but does not include detailed subsystem specifications.

I. vehicle structure and properties
- A. small vehicle size
  1. length: 22.9 m
  2. bogie separation (levitation coil center to center): 13.0 m
  3. capacity: 45
  4. mass: 25,000 kg
- B. large vehicle size
  1. length: 38.4 m
  2. bogie separation (levitation coil center to center): 28.6 m
  3. capacity: 140
  4. mass: 47,700 kg
- C. cross sectional dimensions
  1. width: 3.5 m
  2. height: 2.9 m
  3. radius of underside: 1.95 m
  4. underside to CG (center of gravity) distance: 1.1 m
  5. underside to CL (center of lift) distance: 1.95 m
  6. walkway height: 1.9 m
  7. floor to underside distance: 0.91 m
  8. seats abreast: 5
- D. other specifications
  1. doors
     a. normal use: four, two on each side
     b. emergency: two: one on each end
     c. total: six
- E. aerodynamics
  1. aerodynamic drag (coefficient of v^2)
     a. small vehicle: 0.85 Ns^2/m^2
     b. large vehicle: 1.07 Ns^2/m^2
- F. landing gear
  1. coefficient of friction: 0.05
  2. deployment time: 6.5 s
  3. area: 7 m^2
  4. placement: 4 pads, 1 at each corner
- G. emergency brakes
  1. coefficient of friction: 0.65 (max.)
  2. deceleration capability: 0-4.9 m/s^2
  3. deployment time (0-75% lift): 3.5 s
  4. area: 3.5 m^2
  5. placement: 4 pads, 1 at each corner

H. on-board superconducting magnets
  1. temperature: 8 K
  2. material: Nb_3Sn (niobium-tin)
  3. form: 5 mm square cable in conduit (CIC)
  4. levitation coils configuration
    a. suspension: 2 points (bogies)
    b. number of modules per bogie: 2
    c. number of coils per module: 2
    d. total lift modules: 4 (one on each corner)
    e. total number of coils: 8, all independent cryostats
  5. propulsion coils configuration
    a. number of modules per bogie: 1
    b. number of coils per module: 6
    c. total number of coils: 12 in 2 independent cryostats

I. on-board power
  1. total demand
    a. normal operation: 185 kW
    b. reduced performance 1: 79 kW
    c. reduced performance 2: 59 kW
    d. reduced performance 3: 12 kW
  2. battery capacity: 119 MJ
  3. battery life without charging
    a. reduced performance 1: 1500s (25 min.)
    b. reduced performance 2: 2040s (34 min.)
    c. reduced performance 3: 9900s (165 min.)

II. magway structure and properties

A. spans, nominal
  1. type: aluminum box beam
  2. length: 9.1 m between supports
  3. deflection tolerance (full scale): 0.0046 m
  4. materials options
    a. reinforced concrete
    b. steel truss

B. trough
  1. radius of cross-section: 2.1 m
  2. radius of horizontal curvature
    a. normal operation: 600+ m
    b. operation on landing gear: no limits
  3. average angle of levitation plates: 36 deg. from horizontal
  4. bank angle: 0-35 degrees
  5. levitation plate
    a. thickness: 0.02 m
    b. width: 1.6 m

C. magway-based linear synchronous motor (LSM)
  1. blocks
    a. each block is a separate motor winding
    b. block length: variable, up to 2 km
    c. restrictions: only one vehicle on a block for normal operation
  2. windings
    a. 3 phases
    b. current: 0-3225 A
    c. wavelength: 1.5 m

d. winding width: 1.2 m (varies in some regions)
e. pole pitch 0.75 m
f. resistance
(1) normal windings: 0.1 ohm/km/phase
(2) low-resistance winding: 0.05 ohm/km/phase
g. configuration: bi-planar, lap-wound aluminum litz cable

3. converter
a. ratings: 6, 12, 18, 24 MW
b. one converter per block

4. efficiency
a. LSM
(1) 2 km with 8.2 MW input power: 91.5%
(2) other configurations: efficiency varies
b. converter: 95.0%
c. substation and other losses: 2.0%
d. approximate total without acceleration: 85% .

III. power distribution
A. substations
1. spacing: 8 block lengths
2. supplies 34 kV bus

B. bus
1. dual
2. length: entire corridor
3. voltage: 34 kV

C. converter station
1. fed by 34 kV bus
2. converters per station: 4
3. converter station spacing: 2 or 4 block lengths

D. upgrades:
1. number and spacing of equip. depends on specific plan

IV. magway-vehicle interactions
A. separations at cruising speed
1. between vehicle skin and magway surface: 0.15 m
2. between levitation coil center and magway surface: 0.20 m
3. between propulsion coil center and LSM winding center: 0.25m

B. separations at zero speed on flat magway (on landing gear)
1. between vehicle skin at landing gear centerline and magway surface: 0.40 m (vertical)
2. between propulsion coil center and LSM winding center: 0.25m

C. total load on levitation plates (no curves)
1. large vehicle: 605055 N
2. small vehicle: 302528 N

D. velocity
1. design range: 0-150 m/s
2. curved magway operating range: 0-134 m/s
3. flat magway operating range: 0-30 m/s
4. range of transition to full magnetic lift and curved magway: 30-50 m/s

E. accelerations
1. normally limited by ride quality and power, up to 0.4g
2. max. emergency deceleration: 4.9 m/s^2

F. roll: +/-3 degrees from magway bank angle

G. headway
1. depends on
a. max. emergency deceleration: 4.9 m/s^2
b. total reaction/brake deployment time: 4 s
c. min. clear headway after complete stop: 300 m
2. headway required for safety at 134 m/s: 20 s

V. communications and controls
A. control levels
1. vehicle
a. controls: vehicle
b. communicates with wayside and global
c. responsible for: fine position/velocity control, magway monitoring, active stabilization
2. wayside
a. controls: vehicles in block
b. communicates with vehicle and global
c. spacing: 1 per block
d. responsible for: LSM control, active stabilization, magswitch control
3. global
a. controls: corridor
b. communicates witb vehicle and wayside
c. spacing: I per 160 km
d. responsible for: scheduling, routing, emergency responses
B. scheduling method: dynamic, responsive to current demand
C. routing method: dynamic, responsive to current conditions
D. active stabilization method: LSM modulation and aerodynamic control surfaces
E. emergency operations
1. methods: responsive to failure and current conditions
2. level of control: all levels

VI. human factors
A. ride quality: as per government specs
B. magnetic field exposure: as per government specs

VII. performance summary
A. minimum radius for coordinated curves (zero lateral acceleration)
1. 134 m/s, 24° roll: 4115 m
2. 134 m/s, 30° roll: 3173m
3. 134 m/s, 45° roll: 1832 m
4. 100 m/s, 24° roll: 2292 m
5. 100 m/s, 30° roll: 1767 m
6. 100 m/s, 45° roll: 1020m
7. 60 m/s, 24° roll: 824 m
8. 60 m/s, 30° roll: 640 m
B. total drag
1. small vehicle at 150 m/s: 26,640 N
2. large vehicle at 150 m/s: 39,150 N
3. small vehicle on landing gear at low speed: 15,130 N
4. large vehicle on landing gear at low speed: 30,250 N
C. operating headway
1. all large vehicles at 4,000 pas/hr: 126 s
2. all large vehicles at 12,000 pas/hr: 42 s
3. all large vehicles at 25,000 pas/hr: 20 s

GLOSSARY

of abbreviations and some terms used in this report

A-PADS. Anti-friction pads used in the landing gear
ATTENDANT. Person who travels on a vehicle to aid passengers; specifically *not* a driver
BAC. Beech Aircraft Corporation, subcontractor
BANK. The angle at which the LSM winding centerline is offset from the bottom of the magway trough
BCI. Bromwell & Carrier, Inc., subcontractor
BLOCK. A portion of magway containing one electrically isolated LSM winding
BOGIE. Set of lift and propulsion magnets; the point of lift in the vehicle
CAPACITY. The maximum throughput, e.g.. passengers per hour.
CHANDELLE. A maneuver that offsets the unwanted upward force from going over the crest of a hill with downward force generated from a horizontal curve
CLEARANCE. Distance between outside surface of vehicle and top surface of magway (see figure)
COORDINATED CURVES. (or coordinated banking) Curves that are negotiated in such a way that passengers feel no lateral (sideways) forces, other than roll acceleration.
CRS. Cryogenic refrigeration system
CRYO-. (cryogenics, cryostat) Prefix denoting refrigeration
DYNAMIC SCHEDULING. The method of planning vehicle routes based on instantaneous need (ticket purchases)
EFFECTOR. An element of control, including the sensors, control logic, actuators, and the whole response pathway
FAA. Failure Analysis Associates, subcontractor (also Federal Aviation Administration)
FORK. The operation of a vehicle going through a switch approaching from the one-troughed end
GAP. (or LSM gap) Distance between LSM winding center and propulsion magnet center (see figure)
H-PADS. High-friction pads used in the emergency brakes
HEADWAY. The amount of clear time or distance in front of a vehicle
HEIGHT. Distance from levitation magnet center to surface of magway
KEEL EFFECT. The tendency of the LSM operation to exert a righting moment to stabilize the vehicle (A boat's keel stabilizes the boat although it does not exert a righting moment)
LANDING GEAR. Apparatus to levitate magplanes in the absence of magnetic levitation
LEVITATION SHEETS. Sheets of aluminum on both sides of the magway trough
LL. Lincoln Labs (MIT), subcontractor
LNG. Liquid natural gas
LSM. Linear synchronous motor
LSM GAP. Distance between LSM winding center and propulsion magnet center (see figure)
MAGLEV. The field of study concerned with magnetic levitation; also the maglev mode of transportation
MAGNEPLANE. The short name for Magneplane International, Inc.
MAGPLANE. Maglev vehicle

MAGPORT. Passenger access point to a maglev system
MAGWAY. Track, or guideway for a magplane
MAGWAY TROUGH. The part of the entire guideway support structure on which the vehicle runs, and which contains the LSM and levitation sheets
MEANDER WINDING. The type of conducting coil used in the LSM
MERGE. The operation of a vehicle going through a switch approaching from the two-troughed end
MI. Magneplane International
MIT. Massachusetts Institute of Technology, subcontractor
MTBF. Mean time between failures
MTTR. Mean time to repair
PFC. MIT Plasma Fusion Center, subcontractor
PFD. Process flow diagram
PSI. Process Systems International, subcontractor
RED. Raytheon Equipment Division, subcontractor
ROLL ANGLE. The angle of roll of a vehicle in a curve, where zero is vertical
SKIDS. The external surfaces of both the landing gear (A-pads) and the emergency brakes (H-pads)
SLOT. A position in the traffic stream that can be occupied by a vehicle, or left open for a vehicle entering the stream; Not to be confused with "block"
SPAN. Distance from magway pier to pier; also the section of magway within that span
SWITCH. The portion of magway on which one trough connects to two
TBD. To be determined
THROUGHPUT. A measure of the activity of a maglev system, typically in passengers per hour
UEC. United Engineers and Constructors, subcontractor