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CONCEPTUAL DESIGN AND ANALYSIS OF THE TRACKED MAGNETICALLY LEVITATED VEHICLE TECHNOLOGY PROGRAM (TMLV) - REPULSION SCHEME

EXECUTIVE SUMMARY

February 1975

DOT-FR-40024 (Task I)

Based on Report FRA-OR &D-75-21

Prepared for:

Department of Transportation

Federal Railroad Administration
Office of Research, Development and Demonstrations
Washington, D.C. 20590

NOTICES

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16. Abstract

This report is an Executive Summary of FRA report OR&D-75-21 which summarizes studies to establish the technology of repulsion magnetic suspension for ultimate use in a passenger carrying high speed ground transportation (HSGT) system - at speeds on the order of 134m/s (300 mph). A baseline revenue system is described in terms of vehicle/guideway configuration, system performance and cost. Levitation and guidance is provided by eight superconducting magnets. The magnetic fields interact with a pair of L-shaped aluminum guideway elements. Propulsion alternatives are discussed but this is the area where much work remains to be done to provide adequate performance and cost data for a final selection.

This technology, designed to free ground transportation from the speed and noise limitations imposed by steel wheel on steel rail, will make possible the short trip times of planes with the huge capacity of trains. Both speed and capacity are essential to meet the demonstrated demand for rapid travel in the nation's congested corridors.

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High Speed Ground Transportation, Magnetic Levitation, Vehicle Dynamics, Ride Quality, High Speed Vehicle Design, Superconducting Magnets, Guideway and Systems Analysis

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PREFACE

The study summarized in this document was conducted by the Ford Motor Company under contract to the U.S. Department of Transportation (DOT), Federal Railroad Administration, Office of Research, Development and Demonstrations. The DOT Program Manager was Dr. John T. Harding.

Overall program management and levitation magnet design were the responsibility of the Ford Scientific Research Staff. Dr. John R. Reitz was the Program Manager. Vehicle and guideway conceptual designs, vehicle dynamics and control, and overall systems analysis were the responsibility of the Aeronutronic Division of Philco-Ford Corporation. The Philco-Ford Program Manager was Mr. R. L. Pons.

Other companies who participated in this study were the Magnetic Corporation of America, Waltham, Mass.; The Cardan Company, Beverly Hills, Calif.; the Raytheon Co. Equipment Division, Wayland, Mass.; and the Hamilton Standard Division of the United Aircraft Corp., Windsor Locks, Conn.

This Executive Summary condenses the most important results for the Tracked Magnetically Levitated Vehicle (TMLV) program, commonly called MAGLEV. The detailed discussion of the designs and analyses is contained in three volumes available from National Technical Information Service:

Volume I - Technical Studies, FRA-OR &D-75-21

Volume II - Appendices A-F (Vehicle Ride Control Mathematics, Ducted Fan Propulsion System Acoustics, and Linear Synchronous Motor Analysis), FRA-OR &D-75-21A

Volume III - Five Degree-of-Freedom Computer Program (for Vehicle Ride Control Analysis), FRA-OR &D-75-21B

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EXECUTIVE SUMMARY

TMLV TECHNOLOGY PROGRAM — REPULSION SCHEME

TASK I — Revenue System Conceptual Design

This document presents a summary of the studies conducted by the Ford Motor Co. and its subcontractors under Task I of the Tracked Magnetically Levitated Vehicle (TMLV) Technology Program - Repulsion scheme. The purpose of this program was to establish the technology of magnetic suspension for ultimate use in a passenger-carrying high-speed ground transportation (HSGT) system - at speeds on the order of 134 m/s (300 mph). These speeds are well above the maximum limit of conventional wheeled vehicles. The reason for going fast, of course, is to reduce travel time for passengers and to increase the productivity of the vehicles (seat-miles per hour) and thus lower the operating costs.*

1.0 BACKGROUND

Magnetic Levitation (MAGLEV) is one of several advanced vehicle suspension concepts which has been studied under U.S. Department of Transportation (DOT) sponsorship as alternatives to conventional transportation modes in the short-haul regime. The search for transportation alternatives is motivated by predictions of heavy traffic congestion - in the 1985-1990 time frame - in highly populated regions of the United States with attendant environmental damage, and substantial hazard to public safety. Also, the national energy shortage has intensified the search for more energy-efficient as well as cost-effective transportation modes.

In 1971-72, DOT sponsored initial MAGLEV research studies at Ford Motor Co. and at Stanford Research Institute (SRI). The results of these studies indicated that magnetic levitation is feasible, and that it offers several unique advantages and should be considered competitive for the ultimate HSGT role with, for example, tracked air cushion vehicles.

2.0 PROGRAM SCOPE

The TMLV Technology Program contract was awarded to Ford Motor Co. on 31 May 1974 (Contract DOT-FR-40024) for the purpose of developing MAGLEV technology relating to the Repulsion, or superconducting, concept. The program consisted of two tasks:

- Task I - A conceptual design of the total suspension and associated guideway for an 80-passenger repulsion MAGLEV vehicle meeting the specified ride quality requirements at all speeds below 134 m/s.
- Task II - The detailed design, construction and test of a high-speed test platform incorporating a scaled version of the suspension system designed in Task I. Also included was the associated guideway (to be constructed at the U.S. Naval Weapons Center (NWC), China Lake, California).

This summary contains only the results of Task I; Task II was terminated shortly after initiation in January 1975, due to cuts in the Federal budget.

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*See, for example, Ward, J. D., "The Future Roles for Tracked Levitated Vehicle Systems," ASME Trans. Journal of Dynamic Systems, Measurement and Control, Vol 96, No. 2, p. 117 (June 1974)

The original scope of Task I was expanded to include larger capacity vehicles, preliminary propulsion studies, conceptual vehicle design (other than suspension-related elements), system engineering studies of the overall system (vehicle, guideway, etc.), and cost studies of the major elements of the system. A simplified cost model was derived to establish cost/effectiveness trends and help make preliminary judgements as to such factors as optimum cruise speed, magnet and guideway configuration, system energy efficiency, etc.

3.0 SUMMARY OF RESULTS

3.1 BASELINE SYSTEM DESCRIPTION

A baseline revenue system has been identified as a reference point for comparative performance and cost analysis. This system consists of both the vehicle and associated guideway, and was selected after consideration of minimum costs, good performance, and the near-term availability and development status of the hardware.

The baseline system consists of an 80-seat vehicle (with a 2 + 2 seating arrangement, i.e., 2 seats on each side of an aisle), powered by two noise-suppressed ducted fans driven by regenerative gas turbines. The vehicle is designed to operate at 134 m/s (300 mph) over a hat-shaped (wide inverted Tee) guideway. The route profile is nominally 750 km (466 miles) long with five intermediate stops.

A sketch of the vehicle is shown in Figure 1; it has a cabin cross section 3.45 m (11.3 ft) high x 2.94 m (9.6 ft) wide and is 33.7 m (111 ft) long, with a gross weight (including fuel at 15% reserve) of 366.5 kN (82,400 lb).

Levitation and guidance is provided by eight cryogenically cooled superconducting magnets encased in insulated dewars and arranged in four modules at the corners of the vehicle. The magnetic fields interact with L-shaped aluminum guideway elements to provide both levitation and guidance forces at a nominal 30 cm (12 in.) levitation height (measured from coil centerline to guideway surface). For operation at speeds below 30 m/s (67 mph), an auxiliary suspension system is provided consisting of retractable, pneumatic-tired bogies at the front and rear of the vehicle.

Ride control of the vehicle is accomplished with conventional electromagnets mounted below the levitation/guidance magnets and external to the dewars. The active control magnets interact with the levitation/guidance magnets and the aluminum guideway elements to damp the vehicle oscillatory motion. This is accomplished by varying the current and polarity of the control magnets in response to onboard motion and position sensor data, processed according to a specified control strategy.

3.2 OVERALL BASELINE SYSTEM PERFORMANCE AND COST

Each of the four superconducting magnet modules has an effective coil size of 0.5 x 3 m, and has a magnetic lift/drag ratio at 134 m/s of 45.5 for 2.54 cm thick, high-conductivity (1100-type) aluminum guideway elements. The total drag power for the baseline 80-seat 366.5 kN vehicle in level, no-wind operation at 134 m/s is 3,739 kW (5,014 hp); the total drag power is 5,279 kW (7,079 hp) for operation on a 2% grade with a 13.4 m/s (30 mph) headwind.

At the 134 m/s (300 mph) cruise speed and a maximum deceleration/acceleration rate of 0.15 g, the vehicle will traverse the nominal 750 km (466 mile) route in

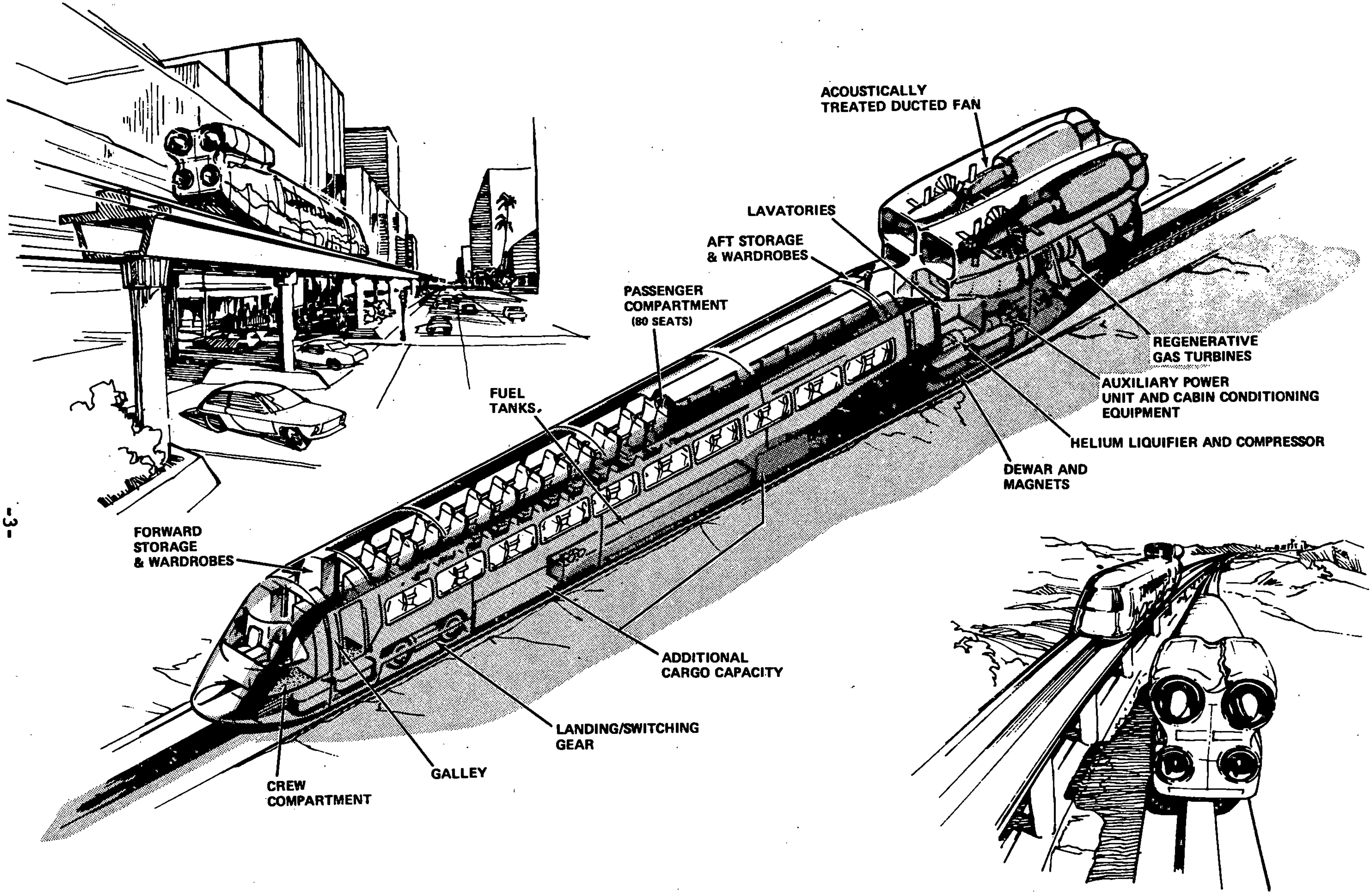

FIGURE 1. MAGLEV REVENUE VEHICLE SYSTEM/BASELINE CONFIGURATION

120 minutes with five intermediate stops, and in 98 minutes without intermediate stops (the express case). This allows two minutes for passenger loading and unloading.

The system with 80-seat vehicles and two minute headway between vehicles can handle ~ 17 x 10^6 passengers per year, assuming 60% load factor and operation 16 hr/day; ~ 1.3 x 10^{10} passenger-km/yr are accommodated for the 750 km route. A system with 140-seat vehicles can handle ~ 5,000 passengers/hr, 30 x 10^6 passengers per year or ~ 2.2 x 10^{10} passenger-km/yr, which is close to the predictions for the Northeast Corridor (NEC) in the year 1990. The larger capacity vehicle has the added advantage of reducing the energy intensity at 134 m/s from 2.18 MJ/seat-km (3,324 BTU/seat-mile) to 1.65 MJ/seat-km (2,516 BTU/seat-mile).

Two or more 140-seat vehicles should be coupled together for headways greater than two minutes or a peak capacity greater than 5,000 passengers/hr. A train set of three 140-seat vehicles shows an energy intensity of 1.33 MJ/seat-km (2028 BTU/seat-mile) at 134 m/s. At a cruise speed of 110 m/s (246 mph), the energy intensity of the three 140-seat coach arrangement is only 1 MJ/seat-km (1525 BTU/seat-mile). Figure 2 shows the energy intensity, ψ, for the baseline Ducted Fan/Gas Turbine-driven MAGLEV vehicle compared to different aircraft as a function of intercity distance. Single coach, 80-seat MAGLEV vehicles are shown as well as one, two, and three 140-seat coupled vehicles. The MAGLEV system with multiple coaches offers better than a 2 to 1 energy advantage (on a per seat basis) over conventional aircraft (CTOL) for distances less than 1000 km (620 mi), as well as a significant improvement over the personal automobile.

The estimated production cost of the baseline 80-seat vehicle is ~ \$2.3 x 10^6 (\$2.3 million). Basic at-grade, double-track guideway cost is approximately \$2 x 10^6/km including land acquisition at \$30,000/acre; the comparable elevated guideway cost is \$3.7 to 4.0 x 10^6/km depending on the type of footings used. The total guideway cost, assuming the NEC mix of 79% of the route at-grade, 16% elevated, 4% tunnels, and 1% bridges and certain ancillary equipment is ~ \$3.3 x 10^6/km. The total system investment cost for a 750 km route with five intermediate stops is \$3.05 billion. This includes the double track guideway, facilities (yards, shops, terminals, communications), and 138 80-seat vehicles (which includes spares).

The estimated guideway and vehicle costs have been converted to an annualized basis (with debt service) and combined with other investment costs (facilities), direct operating costs (fuel, crew, maintenance, and terminal operations), and estimated indirect operating costs to ascertain total system cost. Total system cost using 80-seat vehicles at two minute headway is 4.4 to 5¢/passenger-km for gas turbine (JP) fuel at 5.3 to 10.6¢/liter (20 to 40¢/gal). This is based on 134 m/s cruise speed over the 750 km route and 16 hr/day operation with a load factor of 60%. Operation with 140-seat vehicles drops the cost to 2.9 to 3.3¢/passenger-km. For train sets composed of three 140-seat coaches (also at two minute headway) the cost drops further, to about 1.7 to 2.1¢/passenger-km.

With JP fuel costs between 5 and 30¢/liter (20 to 113¢/gallon), the optimum thickness of the aluminum guideway elements is between 2 and 3 cm. The cruise speed for minimum energy cost is between 80 m/s (179 mph) and 95 m/s (212 mph); cruise speed for minimum total system cost is between 90 m/s (201 mph), and 110 m/s (246 mph) although total cost is not very sensitive to cruise speed for fuel cost up to 15¢/liter (57¢/gal).

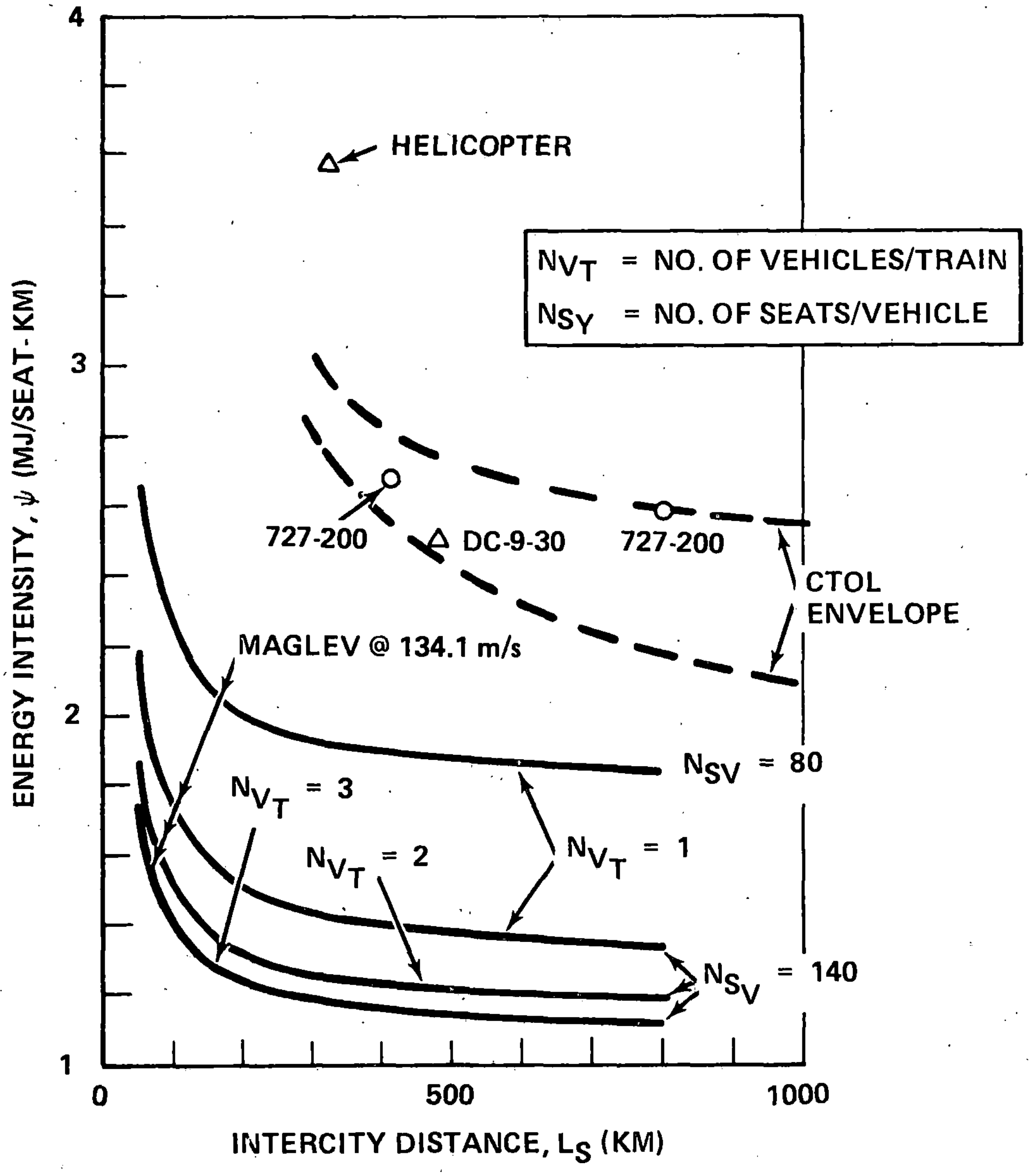

FIGURE 2. ENERGY VERSUS INTERCITY DISTANCE

3.3 SALIENT DESIGN FEATURES

3.3.1 VEHICLE DESIGN

A. Magnets. The liquid helium-cooled, superconducting levitation/guidance magnets are fabricated of niobium-titanium multi-filament twisted wire, wrapped on a stainless-steel racetrack-shaped coil form approximately 0.5 m (19.7 in.) wide by 1.5 m (59.1 in.) long. Eight suspension magnets are used, combined in pairs (for redundancy) in each of the four suspension modules. The baseline design is shown in Figure 3. Levitation and guidance forces are transmitted from the coil to the top of the evacuated dewar structure via epoxy-fiberglass struts specially designed for low heat conduction. Each magnet supports 1/8 of the weight of the vehicle at the design clearance and speed and operates at approximately 350,000 ampere-turns in the persistent mode; the coil winding is intrinsically stabilized, with a current density of 300 A/mm^2. Active shielding of the magnetic field is accomplished with a 0.5 x 1.5 m bucking coil mounted within each dewar and 30 cm above the levitation/guidance magnet. The magnetic field at the seat level in the vehicle passenger compartment is held to acceptable levels (5 to 10 gauss average, $\sim$ 70 gauss maximum) without severe weight penalty. Overall magnet lift/weight ratio is 16.8 including the shielding coil; heat leak per vehicle is 20.8 watts.

A closed-cycle refrigeration system is provided, consisting of two electrically-driven Claude cycle expansion engines served by a single compressor, with an additional back-up compressor for added reliability. The associated cryogenic system includes 16-liter liquid helium storage containers inside each magnet dewar (for the purpose of maintaining magnet cryogenic temperature in the event of refrigeration system failure), transfer lines, etc.

The production cost of the magnet modules and cryogenic system is estimated to be $138,000/vehicle.

B. Ride Control. The ride control system consists of: (1) a set of control electronics to process data from onboard sensors and compute ride control signals, (2) a power control unit to provide power switching, (3) a set of power amplifiers to drive the control magnets, and (4) an emergency back-up power supply. The baseline control system damps the vehicle motion based on feedback of vehicle absolute (inertial) velocity and vehicle position relative to the guideway. Accelerometers and gap sensors provide the necessary signals to the control electronics.

The DOT ride quality requirements are achieved in all dynamic modes (heave, pitch, roll, sway, and yaw) for straight and level operation as well as for turns and transitions to grades as large as 2%. This is based on a guideway surface roughness approximately equal to that for airport runways, and studies show that this level of roughness can be achieved for the MAGLEV guideway using conventional low-cost construction techniques. The displacement or movement of the vehicle in a transition section relative to its steady-state position is small (maximum stroke $\sim$ 5 cm), and the power consumption is relatively low (60 to 150 kW for a short-time 1 km transition to a 2% grade; the comparable value for a straight and level guideway is 17 to 25 kW).

Some alternate control strategies were studied which do not require a gap sensor; these may offer a significant advantage in an all-weather environment where gap sensors may be unreliable. These alternate strategies achieve acceptable ride quality/stroke performance but require increased grade transition lengths.

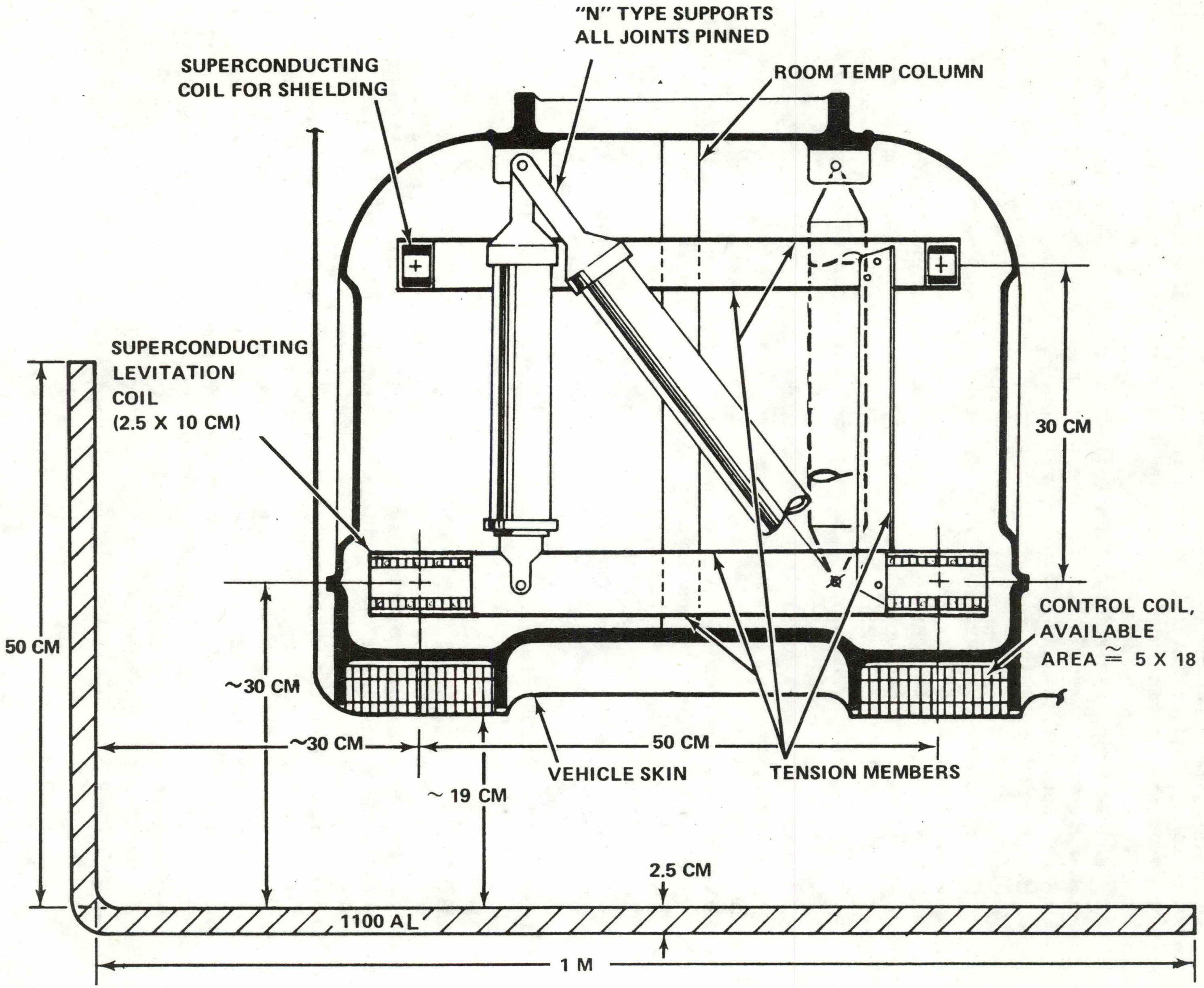

FIGURE 3. CROSS SECTION OF BASELINE MAGNET ASSEMBLY WITH SHIELDING COIL

The total production cost of the baseline position feedback control system is estimated at $272,000 per vehicle, including sensors, control electronics, back-up power supply, installation, checkout and acceptance testing. Also included is redundancy in all components to provide a failsafe system.

C. Propulsion. The baseline propulsion system is comprised of twin rear-mounted ducted Q-fans, remotely driven by twin regenerative gas turbine engines. The regenerative engines provide high operating efficiency; cruise specific fuel consumption is estimated at 5.63×10^{-4} kN/MJ (0.34 lb/hp-hr). The Q-fan is a product of Hamilton Standard Division of the United Aircraft Corp. and is specifically designed for low-noise operation. Noise suppression materials and techniques are also applied to the engines as well as inlet/exit ducting for both the fans and the engines. Estimated total propulsion system noise for level, no-wind cruise at 134 m/s is 86 dBA* (at 15 m sideline distance); the noise level is 92 dBA (at 15 m) for maximum power operation during acceleration or at 134 m/s on a 2% grade with 13.4 m/s (30 mph) headwind. A further reduction in propulsion system noise (~ 5 to 6 dB) is achievable by slightly increasing the separation distance between the fan inlet and the top surface of the vehicle or moving the propulsion system to the front of the vehicle. The Ducted Fan/GT system is a reliable lightweight concept (80.6 kN (18,000 lb) including fuel with 15% reserve) with good acceleration (0-134 m/s in ~ 180 sec), relatively low energy consumption, and has the lowest total cost (including guideway) of all the propulsion systems studied. It is entirely self-contained, thereby permitting complete freedom in selecting a particular guideway shape. Also, it supplies all propulsion necessary for off-line (including switching) as well as on-line operations. Thrust control is provided by varying fan blade pitch; emergency braking can also be provided with full pitch reversal. If necessary, the gas turbines can be operated on a variety of chemical fuels (fossil or synthetic). With current design techniques, exhaust emissions are controllable to very low levels, particularly on a passenger-km basis.

The costs of the fan components (Q-fans, ducts, gearboxes, etc.) are $500,000; the gas turbines cost $700,000 for an onboard propulsion cost of $1,200,000 per vehicle, exclusive of development cost.

D. Structure and Configuration. The basic vehicle structure employs aluminum aircraft-type sheet-stringer construction, modified in fore and aft sections to support the levitation and guidance magnets, landing wheels, and the propulsion system. The vehicle structure is essentially a lightly loaded, very stiff hollow beam configuration. It is designed for a fundamental bending frequency of 4 to 5 Hz, which is substantially larger than the suspension heave-motion frequency and avoids the necessity for considering structural elastic effects on ride control system design. The baseline structural design approach has been extended to encompass larger vehicles (up to 140 seats) and different seating arrangements. A small decrease in bending frequency is allowed, however, since excessive structure weight would result for the longer configurations if the bending frequency were held constant. Preliminary vehicle synthesis analyses show that the 140-seat configuration exhibits 24% less energy consumption per passenger than the baseline 80-seat vehicle; the optimum seating arrangement for the larger vehicle is 2 + 3, rather than the baseline 2 + 2 seating.

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*At 134 m/s, the vehicle self-generated (aerodynamic) noise is estimated at 92 dBA, also at 15 m (50 ft).

The particular vehicle cross section required to straddle the hat-shaped guideway is a favorable shape. It results in a high section modulus and a relatively short vehicle since the part of the structure below floor level provides for convenient packaging of the suspension elements, wheels, fuel and additional cargo. Both factors contribute to a lightweight, low power vehicle design.

The cost of the structure including fairings, attachments, etc. is estimated to be $150,000 per vehicle for the baseline 80-seat design, and $168,000 for the 140-seat design.

3.3.2 GUIDEWAY

The hat-shaped guideway configuration shown in Figure 1 is preferred for its favorable stability characteristics, its compatibility with the proposed passive failsafe switch concept, its low cost, and the fact that it can be fabricated quite easily with standard slip-form highway paving machines.

A. At-Grade Construction. The at-grade guideway is essentially a continuously-reinforced concrete slab 20.3 cm (8 in.) thick and 3.05 m (120 in.) wide, laid on a treated, compacted combination of fill materials; the roadbed preparation is quite similar to that for airports and interstate highways. The central "spine" or curb is a reinforced concrete beam, 79 cm (31 in.) wide and 53 cm (20.7 in.) high, anchored to the primary slab.

The guideway levitation elements are 2.54 cm (1 in.) thick, high conductivity aluminum plates (1100-H14 series) fabricated in L-shaped sections approximately 30 m (100 ft) in length. The aluminum sections are laid end-to-end with transverse gaps on the order of 2 to 3 cm wide, and attached to the concrete surfaces in a manner which permits longitudinal expansion, thus avoiding buckling due to thermal expansion. The use of nearly pure aluminum is essential for achieving a high vehicle magnetic lift/drag ratio.

The aluminum plates are non-structural elements, thus the roughness of the guideway is essentially that of the supporting concrete surfaces. The roughness for the long wavelengths of interest is dictated by the foundation under the concrete, i.e., the roadbed characteristics. On the basis of airport runway evaluation - which generally shows minimal time-dependent roughness degradation - no design allowance for post-installation adjustment is deemed necessary for good soil conditions. Analysis of the conventional roadbed grading and concrete-laying techniques indicates that the achievable guideway vertical roughness level (at the appropriate wavelengths) is actually less than the roughness level used for the vehicle ride quality analysis. The lateral roughness level of the central guideway spine is expected to be even lower, so there is potential for further improvement in ride quality without resort to non-standard (i.e., expensive) construction techniques. The construction cost of the at-grade double track guideway, including the aluminum, is estimated at $\$1.4 \times 10^6$/km, exclusive of land acquisition, route preparation or electrical power (if any).

B. Elevated Construction. The baseline elevated guideway design approach is predicated on cost and the guideway influence on vehicle dynamic response. The conceptual TMLV Revenue vehicle has a low natural frequency (0.6 Hz) with minimal relative damping; this results in a girder design which is relatively light and flexible compared with those designed for a more highly damped tracked air cushion vehicle. The baseline design (Figure 1) employs simply-supported pre-stressed concrete box-beam girders with a depth of 1.07 m (3.5 ft) and a span on the order of 23 m (75 ft). The beam has an integral top cap 15.2 cm (6 in.) thick by 3.05 m (10 ft) wide. The aluminum sections are attached to this cap and the central spine to form the riding surfaces of the guideway. The box-beam girders are supported on columns with sliding joints at one end to accommodate differential thermal expansion, and pinned joints at the other end to transmit longitudinal loads. A uniform prestress is employed to eliminate post-fabrication camber effects.

The construction cost of double track elevated guideway is approximately $\$3.6 \times 10^6$/km. Again, the cost includes the aluminum, but not the land acquisition, route preparation, or electrical power (if any).

C. Switching. To avoid long radii of curvature and excessive switch size, all switching operations are designed to take place at low speed; i.e., at or below the lift-off speed of 30 m/s (67 mph). Upon slowdown to this speed, the wheeled suspension bogies are extended down and out from the vehicle envelope to engage non-movable L-shaped reinforced concrete ramps located outboard of the main guideway. These ramps subsequently rise above the guideway and lead to an apron where the vehicle can "taxi" to the appropriate loading platform. The maneuver is similar to current aircraft procedure; the forward bogies are fully steerable to facilitate the taxi operation.

The passive method of switch operation permits the "express" vehicles to pass through the switch area at top speed with complete safety. Failure to extend the wheels is not serious since the vehicle will pass through the switch without danger. Premature wheel extension is precluded by means of a dynamic pressure activated linkage, similar to that used on aircraft.

3.4 ALTERNATE PROPULSION SYSTEMS

If necessary, the Revenue TMLV can be propelled electrically - by any one of a number of systems currently in various stages of research and development. These include the single-sided linear induction motor (SLIM), the linear synchronous motor (LSM) and a superconducting rotary electric motor (REM) used in conjunction with ducted Q-fans. The guideway cost for all of the electric systems studied is substantially larger than the basic (non-electrified) guideway required with the Ducted Fan/Gas Turbine system. The effect of this increased cost, however, can be reduced if very high passenger capacity is achievable and/or the cost of chemical fuels becomes large in comparison with the cost of electricity. Cost comparisons are given below.

The SLIM has the most development effort behind it; it is reasonably efficient but is excessively heavy if onboard power conditioning is used. This results in high energy consumption, but the problem can be partially alleviated by employing wayside power conditioning with an associated 50% reduction in onboard propulsion system weight. Although not yet demonstrated, wayside power conditioning is probably feasible. High-speed power pickup is still necessary, however, and the motor appears difficult to switch - at least under the switch criteria established for all the propulsion concepts. Preliminary analysis indicates that the narrow-gap motor cannot be suspended from the large-gap vehicle without the suspension forces adversely affecting vehicle ride quality and/or stroke (stroke is the vertical motion of the vehicle). However, this problem is resolvable in principle by operating the motor as a tug, i.e., with its own separate suspension system which could be an air cushion or a stiff, short-stroke repulsion magnet system. However, this approach seems overly complex and the dynamical incompatibility between the single-sided linear induction motor and the vehicle is not likely to be easily resolved. For this reason, the SLIM does not appear attractive for a Repulsion MAGLEV system.

The LSM is at a very early stage of development, but appears to have substantial potential for Repulsion MAGLEV applications. Thrust forces are developed by interaction of onboard superconducting magnets with a moving electrical field generated in "meander" coils inbedded in the guideway and carrying large currents, appropriately phased and switched. The principal advantages of an LSM are that it is a large-gap (~ 30 cm) device with good power transfer efficiency (~ 70%), and no power pick-up is required. In principle, the LSM can provide for vehicle ride control as well as for propulsion. Preliminary analysis, however, shows that this would require additional active guideway surfaces with some increase in guideway cost and complexity. Also, there is no clear system advantage connected with LSM control of vehicle dynamic motion. A major difficulty brought out in this study is the large weight of the propulsion magnets and associated cryogenic cooling system, which results in relatively high energy consumption. Preliminary analysis also indicates increased guideway cost; Nevertheless, the LSM has good potential for improvement and merits further study.

The REM-driven ducted fan concept is a lightweight propulsion option for MAGLEV if the superconducting motors can be developed at the target values of weight and volume used in this study. Current U.S. Navy development efforts on superconducting motors and generators should provide early verification of these estimates. However, energy consumption is the highest of all systems studied which is due to the combination of low fan/duct efficiency and low efficiency for the electric generation, distribution, and collection process. Nevertheless, no reaction rail is required and the total guideway cost is the lowest of all the electric systems. Also switching is made easier by the system's ability to provide propulsion for off-line as well as on-line operations. From a systems viewpoint, an additional advantage could result from using this concept as a back-up to the baseline Ducted Fan/GT system. For example, if the Revenue system is initially implemented with gas turbine drive, the superconducting REM drive could be substituted with minimal design change at such time that electric power is deemed necessary.

An advanced concept propulsion system - the superconducting paddle wheel - was also considered and shows long-term potential. With this concept, an onboard circular array of superconducting magnets is rotated about an axis perpendicular to the longitudinal axis of the vehicle. Both thrust and lift forces (or even drag for deceleration) can be developed by interaction of the moving magnetic field with the aluminum guideway elements, depending upon the peripheral speed of the magnets. Thus an integrated propulsion/levitation system is possible; propulsive efficiency is high (~ 65%), and when driven by regenerative gas turbines the concept has the lowest energy consumption of all the systems studied. Basic feasibility has not been demonstrated, however, and this concept cannot be considered a realistic candidate for near-term application.

A breakdown of comparative costs for the various propulsion systems is given in Table 1 for an 80-seat vehicle and a design cruise speed of 134 m/s (300 mph). Some of the component costs, such as the paddle wheel and superconducting motor, are very approximate at this time. Total system specific costs for the various propulsion options are shown in Table 2, with comparable values for the 140-seat vehicle shown for comparison. Conservative figures for energy were used, i.e., 10.6¢/liter (40¢/gal) for JP fuel and 3¢/kW-hr for electricity.

TABLE 1. COMPARATIVE 80-SEAT VEHICLE COST

(V_C = 134.1 M/S)

SUBSYSTEM	FAN/GT	FAN/ REM	SLIM(1)	LSM	PADDLE WHEEL/GT
LEV-GUIDE MAGNETS + HARDWARE	$102 X 10^3	98	100(2)	112	101
CRYOGENICS	36	40(6)	40(6)	55(6)	50(6)
RIDE CONTROL	272	272	272	272	272
STRUCTURE	150	140	149(5)	179	148
FURNISHINGS(3)	140	140	140	140	140
AUXILIARIES(4)	25	25	25	50	25
WHEELS, BRAKES	91	85	87	110	90
PROPULSION	1,200	1,450	9000	868	1,500
COMMUNICATIONS	70	70	70	70	70
ASSEMBLY, CHECKOUT	230	230	230	230	230
TOTAL (THOUSANDS OF $)	2,316	2,550	2,013	2,086	2,626

(1)WITH WAYSIDE PCU

(2)INCLUDES LEVITATION-GUIDANCE MAGNETS FOR PROPULSION TUG

(3)INCLUDES CREW COMPARTMENT

(4)INCLUDES AIR CONDITIONING, APU, ETC.

(5)INCLUDES PROPULSION TUG STRUCTURE, THRUST BEARING, STRUTS, ETC.

(6)INCLUDES CRYOGENICS FOR PROPULSION OR SLIM TUG SUPPORT SYSTEM

TABLE 2. COMPARATIVE SYSTEM SPECIFIC COST(1)

(80-SEAT VEHICLES)

	FAN/GT	FAN/REM	SLIM	LSM	PADDLE WHEEL/GT
GUIDEWAY(2)	2.194 ¢/PASSR-KM	2.518	2.784	2.675	2.194
GUIDEWAY MAINTENANCE	0.042	0.161(3)	0.161(3)	0.161(3)	0.042
VEHICLES	0.344	0.378	0.299	0.309	0.390
VEHICLE MAINTENANCE	0.220	0.242	0.191	0.198	0.250
OTHER(4)	1.045	1.045	1.045	1.045	1.045
SUB-TOTAL	3.845	4.344	4.480	4.388	3.921
ENERGY(5)	1.106	1.048	0.886	0.842	0.860
TOTAL, 80-SEATS (¢/PASSR-KM)	4.951	5.392	5.366	5.230	4.781
TOTAL, 140-SEATS (¢/PASSR-KM)	3.30	3.55	3.495	3.406	3.169

(1) FOR 2 MINUTE HEADWAY, 16 HOUR/DAY OPERATION, 750 KM ROUTE

(2) INCLUDES BASIC GUIDEWAY, GUIDEWAY EQUIPMENT, ELECTRICAL SYSTEM AS APPROPRIATE

(3) INCLUDES ELECTRICAL MAINTENANCE AT 0.119¢/PASSR-KM

(4) INCLUDES CREW AT 0.333, FACILITIES AT 0.188, TERMINAL OPS AT 0.0277 AND IOC = 0.50 ¢/PASSR-KM

(5) JP FUEL AT 10.6 ¢/LTR (40¢/GAL), ELECTRICITY AT 3 ¢/KW-HR

4.0 CONCLUSIONS

The results of the program demonstrated that the Repulsion MAGLEV is a feasible concept for future high-speed ground transportation. Further analyses and experimentation are necessary to optimize various design parameters and test key components such as the levitation/guidance magnets and ride control system. Important conclusions are as follows.

VEHICLE

- Levitation/Guidance Magnets - The proposed design is basically state-of-the-art, but verification of performance is required in an actual high-speed vibratory field environment. The magnetic field is held to low levels with shielding. The lift-to-weight ratio and other performance parameters are within the desired range, but improvement should be possible if development work continues.

- Ride Control - The vehicle meets all DOT-specified ride quality requirements for all modes even for curves and hills at speeds to 134 m/s (300 mph), without the necessity for a very smooth guideway or a secondary suspension system. Several control strategies are available which meet the requirements; final selection awaits a more detailed route-specific analysis. A major feature of the work was the development of a five degree-of-freedom (5 DOF) vehicle dynamics computer program which permits the analysis of the vehicle ride for realistic conditions.

- Propulsion - The Ducted Fan/Gas Turbine is the best near-term solution due to its high degree of development, its light weight, good efficiency, good acceleration, and compatibility with the guideway. Solutions to the noise and emission problems are available, and alternate fuels can be used if desired. Other systems such as the LSM and superconducting paddle wheel have potential for the future, but much more work is required. Most of the power at cruise conditions goes to overcome aerodynamic drag (~ 2.5 times greater than magnetic drag), thus careful attention must be paid to aerodynamics.

GUIDEWAY

- Configuration - Several guideway configurations are acceptable, but the hat-shape (wide inverted Tee) is preferred. It provides for good vehicle ride, facilitates switching, is equally applicable to at-grade or elevated use, and can be easily fabricated with conventional construction techniques and equipment. Cost is reasonable compared to other configurations.

- Roughness - The guideway vertical roughness level achievable with conventional techniques is actually better than used in the analysis, and the lateral roughness of the central spine or curb is expected to be even lower. Thus there is the potential of better ride quality than predicted without resorting to expensive or exotic construction techniques. Reasonable-cost elevated guideways can be designed to have a minimal effect on vehicle ride.

OVERALL

- System Utilization - The system has high passenger capacity, and coupled 140-seat vehicles are required for peak capacities greater than 5,000 passengers per hour. Even a system with single 80-passenger vehicles can nearly meet the demand predicted for the Northeast Corridor in 1990.

- Energy - The system has relatively low energy intensity, ψ, which is considerably better than conventional short-haul aircraft and automobiles. Although ψ is not as good as for busses and trains, these systems operate at speeds much lower than MAGLEV. The optimum speed as far as minimum energy cost concerned is between 80 and 95 m/s (179 and 212 mph), the speed for minimum total system cost is about 30 mph higher.

- Cost - Total operating costs for a 3-coach train is quite low; from 1.7 to 2.1¢/passenger-km. Total investment cost for a complete corridor is reasonable, particularly with respect to other systems with comparable passenger capacity. The baseline Fan/GT propulsion system has a lower specific cost than any of the electric propulsion systems (Table 2).

5.0 RECOMMENDATIONS

- The 5 DOF program should be used for an in-depth parametric evaluation of vehicle ride for various control schemes and a specific route profile.

- Much more testing is required to obtain reliable aerodynamic data of typical MAGLEV configurations.

- Self-generated (aerodynamic) noise data are lacking and tests are needed to define this noise source.

- More analyses of propulsion systems should be carried out, with careful attention to overall systems aspects.

- A field experimental program is necessary to ascertain the performance of the superconducting magnets and the control system in a realistic environment.

- Work should continue on the development of superconducting magnets to improve lift to weight ratio, current density, etc.

- The use of a MAGLEV system to haul freight in off-hours (i.e., at night) should significantly improve the system utilization, and should be investigated.

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22nd September 1976

Dr. J.T. Harding,
U.S. Department of Transportation,
Federal Railroad Administration,
400 7th Street, S.W., Room 5416A,
Washington, D.C. 20590,
U.S.A.

Dear Dr. Harding,

I would be grateful if you would send me a copy of your report on the 'Conceptual Design & Analysis of the Tracked Magnetically Levitated Vehicle Technology Program (TMLV) - Repulsion Scheme' which I understand has been issued in three volumes.

We are continuing our research on the maglev scheme in a small way because of financial difficulties and I enclose a copy of our last report and some reprints of our more recent papers which I trust may be of some interest to you.

I would also be interested to learn of any further developments in this area of 'repulsive maglev' in the U.S. and I look forward to hearing from you.

Yours sincerely,

R G Rhodes

R.G. Rhodes (Dr)

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