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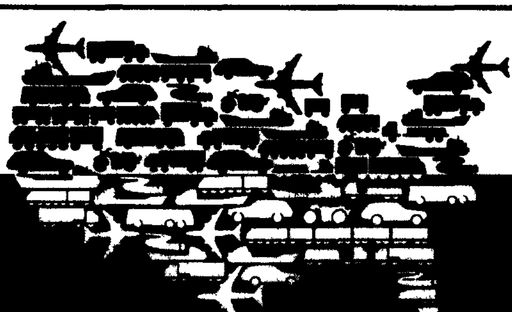
Maglev Vehicles and Superconductor Technology: Integration of High-Speed Ground Transportation into the Air Travel System

L. R. Johnson, D. M. Rote, J. R. Hull, H. T. Coffey,
J. G. Daley, and R. F. Geise



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MAGLEV VEHICLES AND SUPERCONDUCTOR TECHNOLOGY: INTEGRATION OF HIGH-SPEED GROUND TRANSPORTATION INTO THE AIR TRAVEL SYSTEM

by

Larry R. Johnson, Donald M. Rote, John R. Hull,*
Ioward T. Coffey, James G. Daley,* and Robert F. Giese

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After our initial evaluation of maglev technology and the potential contribution of high-temperature superconductor materials, we examined the market potential of maglev systems in the United States. Because we found that maglev systems appear to be most economically attractive if integrated into airport/airline operations, we wanted a very extensive external review of our work. The concept of maglev trains as a competitor to commercial airlines is the traditional view; the concept of maglev as a system of individual vehicles linking major hub airports with other airports and their cities is a new concept. We felt that a wide variety of reviewers should examine our ideas. Therefore, we are especially grateful to the following individuals for either commenting on a portion of our work or providing thorough comments on our earlier drafts.

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MAJOR FINDINGS OF THIS STUDY

Potential Market. The potential speed of magnetically levitated (maglev) vehicles (300 mi/h), combined with severe and growing air traffic congestion and limitations on major new airport construction, makes the airline market -- rather than the train market -- the primary application for maglev vehicle systems. If maglev vehicles were to operate from existing hub airports, their trips could substitute for 100- to 600-mi flights, thereby substantially reducing air traffic congestion. The market potential for maglev transportation could be further enhanced by integrating long-distance commuter service into the systems and by serving downtowns and other high-density areas such as major amusement parks.

Energy. Short- and medium-distance airline flights are much more energy-intensive than longer flights. Maglev vehicles consume as little as one-third of the total energy used by aircraft over short distances. Consequently, maglev vehicles could save 8-11% of the energy used by domestic passenger airlines. Just as important, electrically powered maglev systems would reduce the nation's consumption of imported petroleum, a major component of the U.S. balance-of-trade deficit.

Superconductivity. With the expected availability of high-temperature superconductors (HTSCs) cooled by liquid nitrogen, improvements in maglev system reliability and performance should enhance the technical aspects of maglev systems, reducing electricity and maintenance costs as much as 5 to 10%. Further, for the large-scale applications of HTSCs that are frequently discussed, maglev systems have one of the lowest threshold design requirements. In other words, HTSCs should be available for maglev systems before they are ready for other large-scale superconducting applications such as transmission lines, generators, magnetic separators, or energy storage devices.

Economics. In the past, many U.S. intercity corridors have lacked sufficient traffic densities to support maglev systems. However, rapid growth in travel is now generating densities high enough for maglev systems to be economical, as illustrated in this study by the example of the Chicago-Detroit corridor. Over the next 20 years, more than 2,000 mi of maglev system networks, radiating from major airports, could be built for the equivalent cost to airlines and their passengers of current air traffic delays (estimated by the Federal Aviation Administration at $5 billion annually). The West German maglev transportation consortium has identified more than 50 potential markets worldwide. Further, a Japanese survey found that maglev transportation systems represent the largest market for HTSCs, that is, one-third of a total $12 billion market for 32 HTSC devices.

Environment. Substituting electrically powered maglev vehicles for medium-distance aircraft would reduce aircraft emissions of air pollutants, a particularly severe issue around major airports. In addition, noise and vibration would be reduced in these same locations.

MAGLEV VEHICLES AND SUPERCONDUCTOR TECHNOLOGY: INTEGRATION OF HIGH-SPEED GROUND TRANSPORTATION INTO THE AIR TRAVEL SYSTEM

by

Larry R. Johnson, Donald M. Rote, John R. Hull,
Howard T. Coffey, James G. Daley, and Robert F. Giese

ABSTRACT

This study was undertaken to (1) evaluate the potential contribution of high-temperature superconductors (HTSCs) to the technical and economic feasibility of magnetically levitated (maglev) vehicles, (2) determine the status of maglev transportation research in the United States and abroad, (3) identify the likelihood of a significant transportation market for high-speed maglev vehicles, and (4) provide a preliminary assessment of the potential energy and economic benefits of maglev systems. HTSCs should be considered as an enhancing, rather than an enabling, development for maglev transportation because they should improve reliability and reduce energy and maintenance costs. Superconducting maglev transportation technologies were developed in the United States in the late 1960s and early 1970s. Federal support was withdrawn in 1975, but major maglev transportation programs were continued in Japan and West Germany, where full-scale prototypes now carry passengers at speeds of 250 mi/h in demonstration runs. Maglev systems are generally viewed as very-high-speed train systems, but this study shows that the potential market for maglev technology as a train system, e.g., from one downtown to another, is limited. Rather, aircraft and maglev vehicles should be seen as complementing rather than competing transportation systems. If maglev systems were integrated into major hub airport operations, they could become economical in many relatively high-density U.S. corridors. Air traffic congestion and associated noise and pollutant emissions around airports would also be reduced. Further analysis is needed to determine whether the foreign technologies being developed are amenable to U.S. transportation requirements. If significant improvements are needed in the foreign systems, the United States is still well positioned to undertake further development of maglev transportation technologies.

SUMMARY

STUDY APPROACH

This study began as an evaluation of one potential use for high-temperature superconductors (HTSCs), that is, magnetically levitated, or maglev, transportation along ground-based guideways. The analysis examined the benefits of HTSCs (cooled by liquid nitrogen) over conventional low-temperature (liquid-helium-cooled) superconductors for this application. Maglev system design requirements were also compared with those of other large-scale superconductor applications.

Expected improvements in the technical and performance characteristics of HTSCs are very promising for maglev transportation and are generally reflected in reduced costs and greater system reliability. However, this is only one aspect of a larger picture that would be used to determine the commercialization potential of maglev systems.

Consequently, this study went on to examine the potential market for maglev transportation. Current interest in high-speed ground transportation was reviewed. Analysis of congestion and intercity travel demand for both airline and highway traffic revealed a large potential market for maglev systems integrated into the airline network serving short- and medium-distance cities around major hub airports. Benefits of reduced air traffic congestion were estimated and savings in petroleum consumption were calculated. Developments in maglev technology were summarized to provide a perspective on international competitiveness.

MARKETS FOR HIGH-SPEED MAGLEV TRANSPORTATION

Although the benefits of HTSCs -- as discussed subsequently -- should be significant in improving the reliability and costs of superconducting maglev systems, they will be meaningless without a market. Ultimately, a new technology will be accepted in the market only when testing has verified its performance, cost, and reliability. Potential market size, however, can be identified by the predicted characteristics of the new technology.

Current Regional Markets for High-Speed Ground Transportation

The increase in travel, especially the explosive growth in air travel, has caused several states or regions to consider high-speed ground transportation as a component of a balanced transportation system in their areas. Independent initiatives have begun in Florida, California-Nevada, Pennsylvania, the Northeast Corridor (Boston-New York-Washington), Ohio, Michigan-Illinois, and Texas. In each of these regions, maglev transportation -- although still in the prototype-development stage -- has been seriously considered, encouraged, and/or favored as a technology alternative. Other states, including Missouri, Washington, Georgia, upstate New York, New Mexico, and Louisiana, are showing concerted interest in significantly improved rail passenger service.

Successful commercialization of maglev transportation in one area of North America will likely cause it to become a legitimate alternative in other areas.

Regional interest in maglev systems has generated sustained marketing initiatives by large German and Japanese firms and their governments, as well as U.S. entrepreneurs attempting to develop the technology on their own. An objective examination of U.S. intercity travel patterns, however, indicates that the problem in need of a solution is not rail passenger congestion, but air traffic and airport congestion.

Maglev Transportation as Airline Technology

Air traffic delays are costly to both airlines and travelers. The Federal Aviation Administration calculated that air traffic delays in 1985 cost the major (scheduled) airlines $1.8 billion, or 7% of their total direct costs. Cost to passengers was an additional $1.1 billion in lost time, exclusive of higher fares paid because of increased airline costs. By 1986, costs of all delays had climbed to nearly $5 billion. Additional delays were experienced by general aviation and commuter air traffic, both of which use the same facilities as the scheduled carriers.

Much of the delay occurs at the nation's major hub airports, eleven of which already have more than three million hours of passenger delay annually. Chicago's O'Hare International Airport, the nation's busiest terminal, has more than 12 million hours of passenger delay per year -- the equivalent of 1,400 people standing idle around the clock, all year. By 1996, 22 airports are expected to exceed three million hours of passenger delay annually.

Several methods are available to increase air traffic capacity, but their implementation introduces additional problems. Reducing the horizontal separation of aircraft has limited potential because of obvious safety concerns, even with the use of more sophisticated electronic equipment. Rationing of takeoff and landing slots is already used at some major airports, but does not improve capacity. Larger aircraft are already employed for longer-haul flights. However, as airlines continue to use hub airports to transfer passengers from short- and medium-distance cities to longer-haul portions of trips, more-frequent service is sought, rather than less-frequent service with larger aircraft.

Of the current alternatives, only the construction of major new airports and the expansion of existing airports (i.e., adding runways) would permit significant expansion of capacity. Public opposition to new airports, however, has meant that no new major airport has been built since the Dallas-Fort Worth facility in 1974. Planning for a new Denver airport has already taken 10 years and ground has not yet been broken.

Substituting maglev vehicles in the short- to medium-distance markets (100-600 mi), however, would increase the capacity of existing airports while reducing noise and air pollution. With speeds of 250-300 mi/h, maglev vehicles have a logical market in trips under two hours, thus allowing the airlines to retain their familiar hub-and-spoke systems. Consequently, whenever a major capital investment is needed to improve a city's airport capacity, a maglev transportation network should be examined as a potential alternative.

Maglev vehicles could operate from the terminals of existing airports, just as Lufthansa operates a train system between its Frankfurt airport and Düsseldorf. The systems could be built along existing interstate highways or abandoned railroad rights-of-way, a significant advantage in urban centers. Even though maglev systems can be used as airline technology to connect airports, they can also connect downtowns and major suburban developments as a part of intercity travel. Further, it is clear that maglev systems could dramatically change residential and commuting patterns as longer distances become possible for daily travel.

POTENTIAL ENERGY BENEFITS

Maglev vehicles offer energy savings in four ways: (1) petroleum savings by replacing short-haul commercial flights and intercity highway vehicle trips, (2) reduced aircraft fuel use associated with the congestion at airports, (3) reduced energy intensity compared with alternative transportation modes, and (4) reduced energy intensity for HTSCs compared to low-temperature superconductors (LTSCs).

Flights of up to 600 mi account for 45% of all energy consumed by commercial aircraft. An estimated 50-60% of these short-haul flights (i.e., the majority of those from major hub airports) could be replaced by maglev trips. Assuming a 50% share of potential market by 2010 leads to a net petroleum saving of 0.23-0.27 quad, or 11-13.5% of total aircraft fuel use per year (one quad equals 10^{15}, or one quadrillion, Btu).

Reduced airport congestion will result in shorter taxiing and idling time. A system-wide reduction of about 25% in taxiing and idling time leads to an estimated aircraft fuel savings of 1-3% and reductions of almost 25% in carbon monoxide and hydrocarbon emissions. Net aircraft fuel savings, including the effects of displaced short-haul flights and reduced airport congestion, is 12-17%.

Commercial aircraft operating from major hub airports spend a considerable fraction of their total trip time and energy on the ground and in low-altitude flight before heading for their destinations. For trip lengths of 200, 400, and 600 mi, roughly 81%, 72%, and 58%, respectively, of total trip energy is consumed in such inefficient operations. With a load factor of 60%, the corresponding energy intensity (EI) would range from 5,700 to 10,750 Btu/passenger mile (Btu/PM) for a 200-mi trip and 4,100 to 8,000 Btu/PM for a 600-mile trip. For a long-haul flight, say 2,000 mi, EI ranges from 3,550 to 6,200 Btu/PM. Variations in equipment and operating procedures are responsible for the variability in these numbers.

The analysis indicates that the EI of maglev vehicles is approximately 1,000 Btu/PM with a load factor of 60%. If electric power generation and transmission losses are included, EI is about 3,000 Btu/PM. This value should be compared with approximately 8,000 Btu/PM for short-haul commercial aircraft and roughly 2,000 Btu/PM for personal highway vehicles. Hence, aside from the potential petroleum savings by displacing riders from aircraft and autos, the potential exists for an absolute energy savings of up to 6,000 Btu/PM.

Intercity highway vehicle trips in the range of 100-600 mi account for 10% of all passenger-miles of travel, or about one quad of energy. An analysis of those trips suggests that by 2010, roughly 13% of that petroleum-based energy, or 0.14 quad, could be replaced by central-station electrical energy sources that provide power to maglev vehicles.

The fourth source of energy savings arises from potential efficiency improvements due to substituting HTSC technology for LTSC technology. A rough estimate suggests that a vehicle weight reduction of 9.5% is possible in some vehicle designs. Depending on the nature of the maglev vehicle technology, that weight savings could translate into a net system energy savings of about of 3-9.5% (due to reduced electromagnetic drag and acceleration energy requirements). Improved system efficiency and better power factors may be possible, leading to small additional energy savings.

ECONOMICS OF MAGLEV TRANSPORTATION

Because high-speed maglev systems are still under development, their capital costs are difficult to compare with those of existing transportation systems. However, a number of detailed cost studies have been performed, especially for the Las Vegas-southern California route. These have been reviewed and updated in this study for comparison with other studies. A useful first-order approximation is that for a typical intercity corridor, a double-track maglev system would cost about $15 million/mi, including terminals, vehicles, design work, and contingencies of 20-30% that represent uncertainties in system components based on prototype development. HTSCs can reduce operating costs (electricity and maintenance) perhaps 5-10% and capital costs by a smaller percentage. However, advances in civil engineering and automated fabrication of guideway components provide perhaps the greatest opportunities for cost reductions relative to earlier cost estimates.

By comparison, U.S. interstate highway segments often cost more than $30 million/mi in urban areas, $15-25 million/mi in suburban areas, and $5-10 million/mi in rural areas. New airports, if they can be built, are expected to cost $2-3 billion each. Short-haul aircraft cost $30-60 million each, while maglev vehicles are estimated at $2.5-5 million each. Dedicated new high-speed steel-wheel railway systems like the all-electric French TGV or the Japanese Shinkansen are expected to cost almost as much as maglev systems, but will have higher operating costs, lower ridership potential, and greater environmental impact through increased noise and vibration.

Two detailed economic studies have been conducted for the Las Vegas-southern California route. Both concluded that a maglev system would be economically viable, with revenues sufficient to repay capital costs, cover operating expenses, enable equipment replacement, and provide a return to stockholders.

Although a detailed revenue cost study was beyond the scope of this study, a preliminary analysis of the Chicago-Detroit corridor contributes to an understanding of the important economic parameters. Although travel density in this corridor was too low in 1985 to make maglev economically competitive, projected travel growth will make maglev systems -- if integrated into airline service -- competitive by the year 2000, given both constant dollar revenues and costs. This is significant because it is unlikely that a maglev system could be operational much before the end of the 1990s. However, if maglev transportation technology is developed only as improved rail passenger service, the economics do not look favorable even when extended to 2010.

An example will put the costs of maglev systems in better perspective. If the costs of air traffic delays remained constant over the next 20 years at $5 billion/yr (unlikely, given the increase in air travel demand) and if maglev alleviated less than one-third of all airport congestion, a savings of $1.5 billion per year would be achieved. That would be enough to build 2,000 mi of maglev systems during the same 20-year period, thereby providing a network of maglev facilities around several major hub airports. Also, if the initial 2,000-mi network is constructed, an estimated 500 maglev vehicles will be needed, creating a $2.5 billion market for the vehicles.

TECHNOLOGY STATUS

Although maglev transportation may still be considered by some to be in the context of futuristic science fiction, French engineer Emile Bachelet levitated and propelled a model vehicle with magnetic forces in 1912. Since the 1960s, considerable maglev development has been conducted in the United States, Japan, West Germany, England, Canada, and Romania. Japan and West Germany are the most active, each having built several prototypes, and both are proposing specific markets for their commercialization. Between them, they have carried many thousands of passengers and logged more than 60,000 mi of test runs. The United States is seen as perhaps the major maglev market by West Germany and as the second most important market, after its own domestic market, by Japan.

In the United States, the federal role in developing high-speed maglev technology ended in 1975. Although the United States pioneered in the theoretical approaches and development of propulsion, levitation, and guidance systems, the administrative decision to eliminate research in this area was based on the premise that the United States had adequate air transport and highway systems to accommodate the anticipated growth in intercity travel.

LARGE-SCALE APPLICATIONS OF HIGH-TEMPERATURE SUPERCONDUCTORS

The recent discovery of materials that are superconducting above the boiling point of liquid nitrogen has affected economic projections of large-scale applications of superconductivity. Among the frequently discussed potential HTSC applications are maglev vehicles, generators, magnetic separators, transmission lines, ship propulsion systems, and magnetic energy storage coils. The threshold current density for maglev vehicles is among the lowest of all these applications. Consequently, it is reasonable to expect materials suitable for this application to be among the earliest to be developed.

Raw material costs for new magnets may be lower for HTSCs than for LTSCs, although the costs of fabricating these materials into magnets are not yet known. The potential for quenching (a sudden shift to the "normal," nonsuperconducting mode) should be greatly reduced with the new superconductors, which operate at 77 K and have critical temperatures above 100 K. Should a quench occur, however, protection must be provided for the magnet because hot-spot propagation times are estimated to be longer.

A liquid-nitrogen cryogenic system for the magnets will (1) simplify design; (2) reduce costs, weight, size, and energy consumption; and (3) improve maglev reliability. Improved system reliability, (relative to that of liquid helium systems), although difficult to quantify, may have the most significant effect in maglev system acceptance and eventual commercialization.

The potentially larger fields associated with HTSCs could compensate for the increased inductance of the linear synchronous motor due to longer block lengths, which in turn would allow use of fewer power conditioning units and less aluminum in the linear motor while permitting operation at a higher power factor. However, the higher field strengths would require additional shielding. Maglev capital costs may be reduced, but at the expense of operating cost; these trade-offs, however, may be worth further examination.

Although many of the effects of the new HTSC materials will be specific to vehicle design and therefore difficult to quantify at this time, taking advantage of all of the attributes of HTSCs creates the potential for at least marginal reductions in operating and perhaps capital costs of maglev transportation. Because vehicles can be magnetically levitated using conventional electromagnets or LTSCs, the HTSCs should not be viewed as enabling technology. Nonetheless, future HTSCs should be an enhancing technology for maglev transportation.

CONCLUSIONS

The study has demonstrated the potential for a significant transportation market -- both domestic and foreign -- for high-speed maglev vehicles. Focus has been mainly on the domestic market, which consists primarily of replacing short-haul aircraft flights that connect major hub airports with regional cities and airports.

The potential exploitation of the airline market means taking maximum advantage of 300-mi/h maglev vehicles in the trip range of 100-600 mi. That exploitation provides many potentially important benefits, including substantially reduced congestion at major hub airports and in surrounding airways (a problem recognized by both the West Germans and Japanese, as well as by U.S. transportation planners), reduced delays and attendant costs to airlines and customers, and reduced fuel waste and air pollution emissions. Petroleum is saved by replacing some aircraft fuel with utility-generated electric power. Additional petroleum savings, as well as reduced air pollution emissions, are also expected because some intercity ridership will be diverted from the highway to maglev vehicles.

The potential benefits of replacing LTSCs with HTSCs have been identified and evaluated to the extent possible, given the present uncertainties in eventual HTSC properties. The two principal benefits of HTSCs for maglev vehicles may be (1) reduced weight of the magnets and cryogenics, which could result in a 3-9.5% reduction in energy use, and (2) improved system reliability due to decreased quench probability and use of a liquid-nitrogen cooling system in place of one with liquid helium.

The status of maglev technology in various countries has been comprehensively reviewed in an appendix, together with the perspectives of the major maglev developers with respect to worldwide maglev markets. Both the West Germans and the Japanese have brought low-speed attractive-force levitation concepts to the commercial stage (M-Bahn in Germany and HSST in Japan). Both countries also have developed high-speed maglev technologies (the attractive-force Transrapid System in Germany and the repulsive-force Linear Motor Car in Japan). The West Germans have already announced their first route and an alternate, although neither is expected to begin revenue service before the late 1990s. The Japanese are currently selecting their first domestic route; the decision is expected by 1990, and a revenue system could be ready for operation in the 1995-2000 time frame, depending on whether their current "Miyazaki technology" or a refinement thereof is used.

1 INTRODUCTION

1.1 OBJECTIVES

This study reported here had several objectives: (1) identify the extent of the transportation market for high-speed magnetically levitated (maglev) vehicles, (2) provide a preliminary assessment of the energy and economic potential of maglev technology, (3) evaluate the potential contribution of the new high-temperature superconductors (HTSCs)* to the technical and economic feasibility of maglev systems, and (4) determine the worldwide status of maglev technology research. These objectives are interdependent, e.g., successful developments in superconductivity will have little effect on maglev vehicles if no market exists; similarly, if the full market potential is not exploited, there will be little energy or economic impact.

The rapid growth in air travel in the United States, coupled with the inability to expand airport capacity (either through construction of new airports or expansion of existing facilities), has caused significant delays and capacity constraints at major hub airports. Continued constraints on airport construction are expected to exacerbate the problems of air traffic congestion and delay. One of the themes developed in this report is that maglev transportation could be implemented *as an integral part of the air travel system*, using aerospace technology.

1.2 MAGNETICALLY LEVITATED VEHICLES

Many of the major problems with conventional high-speed electric rail systems are due to the contact required between the vehicle and the guideway (i.e., rail or catenary). Such contact is difficult to maintain and results in intermittent electrical power to the vehicle and unreliable tractive force applied to the rail, among other problems. Maglev vehicles are supported and guided on magnetic fields so that there is no "physical" contact between the vehicles and their guideways at high speeds.

Magnetic levitation can be achieved in several ways, as discussed in App. B. In practice, however, only two approaches have been seriously considered. The first uses repulsive magnetic forces between the vehicle and the guideway, but is practical only if superconducting magnets are carried aboard the vehicle. Levitation is effected by the opposing magnetic field generated by eddy currents induced in a passive electrically conductive guideway strip or series of short coils (Fig. 1). This approach is generally referred to as the repulsive-force or electrodynamic system (EDS)

The second approach uses conventional electromagnets on the vehicle, which are attracted upward toward ferromagnetic (laminated iron) rails above the magnets. Distance between the rail and magnet is sensed, and magnet current is dynamically adjusted to maintain a constant spacing (Fig. 1) This approach is referred to as the attractive-force or electromagnetic system (EMS).

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*See App. A for a listing of abbreviations used in this report.

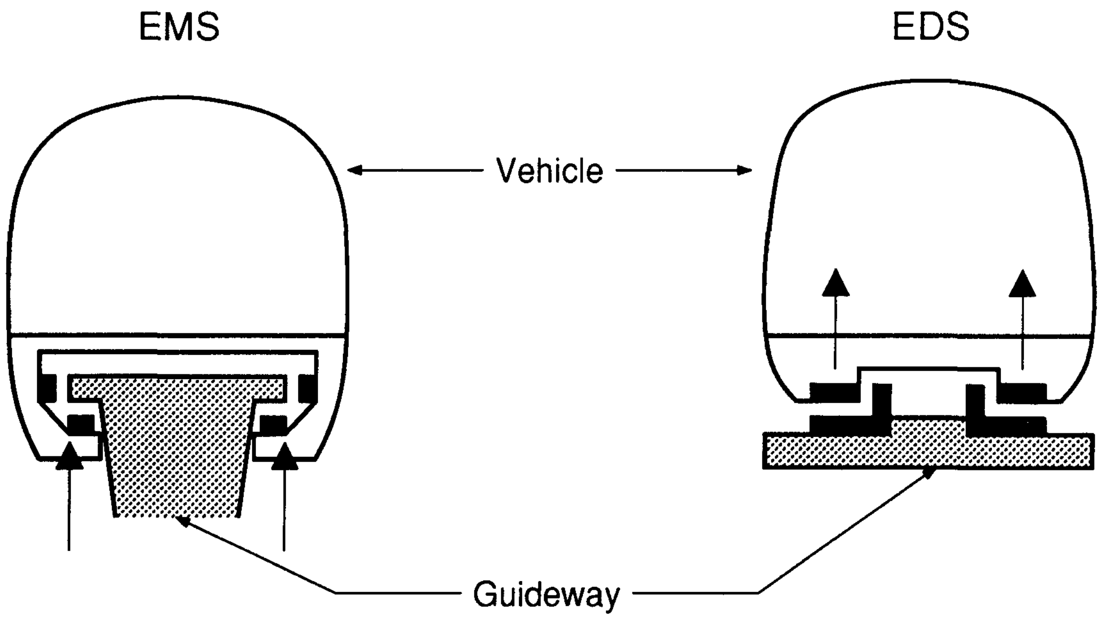

FIGURE 1 Schematic Diagram of Attractive and Repulsive Levitation Approaches

The EDS typically suspends the vehicle 4 to 6 in. above the guideway at sustained speeds greater than those realistically obtainable by "contacting" ground transportation. The EMS (attractive system) typically supports the magnets with a spacing of about 0.4 in. below the ferromagnetic rail. The air gap, i.e., clearance between guideway and vehicle, influences the designs of the vehicle guideway, propulsion systems, and damping or secondary suspension systems.

1.3 U.S. ROLE IN MAGLEV DEVELOPMENT

The concept of using superconducting magnets for magnetic-levitation transportation was developed and proven in the United States. An alternating-current (AC) repulsion system was first conceived by Emile Bachelet (1912), a French engineer working in this country. He built a model vehicle in 1912 using magnetic forces for levitation and propulsion. Bachelet's concept, incorporating conventional electromagnets, required very high levels of power, however, and the idea lay dormant until the mid-1960s when James Powell and Gordon Danby, both of Brookhaven National Laboratory, proposed that superconducting magnets in combination with linear synchronous motors would make the concept practical (Powell 1963; Powell and Danby 1966, 1967). Their concepts were followed by their invention of the low-drag, null-flux guideway using discrete coils, an approach that is still viable and a variant of which is being used by the Japanese. Powell and Danby presented papers to the railroad and mechanical engineering communities, but the concept seemed to stimulate little interest.

Atomics International and Stanford Research Institute* evaluated the work of Powell and Danby for its use in a nontransportation application (a Mach-10 rocket sled) in 1967-68 (Guderjahn et al. 1963). This work established the concept of a continuous-sheet guideway and the use of the Fourier transform method of analyzing lift and drag forces. The continuous-sheet guideway concept was soon applied to high-speed ground vehicles (Coffey et al. 1969). These papers drew the attention of the superconductivity community, which has conducted most U.S. maglev analysis since then. By the end of 1969, nine papers or presentations had discussed magnetic levitation; with the exception of Bachelet's original work, all were by U.S. authors. By 1970, the Japanese announced plans to extend their research on linear induction motors to maglev technology for an eventual maglev system between Tokyo and Osaka.

The U.S. Department of Transportation (DOT) funded maglev feasibility projects at Stanford Research Institute and Ford Scientific Laboratories in 1971. These studies were directed at establishing the feasibility of magnetic levitation for high-speed vehicles. At about the same time, the National Science Foundation funded work at Massachusetts Institute of Technology (MIT) on the magneplane concept, which had additional support from AVCO and Raytheon (Kolm and Thornton 1972, 1973). In West Germany, Seimens, together with AEG-Telefunken and Brown-Boverie, began work on the EDS approach. Work on the EMS system was reported to have been underway for some time at Messerschmitt-Bölkow-Blohm, and both 6- and 10-ton vehicles were said to have operated at speeds of 50 and 93 mi/h.

At the 1972 Applied Superconductivity Conference, results were reported on all concepts being evaluated. The Japanese National Railway levitated its linear synchronous motor test vehicle in July 1972 and its ML-100 demonstration vehicle later that year. These vehicles were physically guided by contacting slippers but were levitated and propelled magnetically. In November, SRI levitated an 800-lb vehicle that was supported and guided magnetically but propelled and braked by an endless cable.

By 1974, the feasibility of EDS maglev technology had been thoroughly proven, and 30 papers in three sessions were presented at the 1974 Magnetics Conference sponsored by the Institute of Electrical and Electronics Engineers. Analysis was extended and confirmed by Stanford Research Institute in experiments with an 1,100-lb vehicle levitated by four superconducting magnets, by experiments at Ford with a large rotating aluminum wheel, and by the 600-ft, 1/25th-scale model magneplane developed at MIT. Analyses of alternative guideway concepts, superconducting magnets, dynamic effects, damping mechanisms, etc., were made by all three groups. The SRI levitated vehicle, which now had complete on-board dynamic instrumentation, successfully measured the dynamic performance with both passive and active damping mechanisms and established vehicle stability with very large perturbations in the guideway. Ford made extensive tests with its wheel, including edge and corner effects of guideways, and analyzed damping for full-scale vehicles. The MIT research included static simulation of vehicle levitation and rotating-disk simulation for lift and drag effects, as well as towing tests to verify vehicle/guideway interactions and dynamics. An operational 1/25th-scale magneplane was developed after the initial research. All three groups concurred that a

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*Later known as SRI International.

full-scale system was practical. Ford was awarded a contract by DOT to develop a baseline vehicle and to construct and evaluate a 300-mi/h test vehicle, but the entire U.S. maglev program was dropped in 1975 and the vehicle was never built.

Work on U.S. high-speed ground transportation ended for two reasons. According to the tenth and final report on the High-Speed Ground Transportation Act of 1965, the large federal expenditures (in the billions of dollars) for improvements in conventional rail service made it necessary to curtail "less critical programs such as the Advanced High-Speed Ground Transportation R&D" (U.S. Dept. of Transportation 1977). Also, growth in transportation demand appeared too be slowing, so that the urgency in addressing air traffic congestion was "diminished -- at least for a decade." This decision effectively ended U.S. research on magnetic levitation and initially slowed research in Canada, the United Kingdom, West Germany, and Japan. However, both Japan and West Germany, with substantial support from their governments, continued at a slower pace to develop their systems and are currently marketing their technologies in the United States. U.S. entrepreneuers continued to pursue their concepts despite the lack of government support.

1.4 RECENT ADVANCES IN SUPERCONDUCTIVITY

The 1986 discovery of a new class of superconducting materials by Georg Bednorz and Alex Muller at IBM's Zurich Research Laboratory has stimulated considerable activity in this field of physics. Although superconductivity has been known since 1911, few commercial applications have exploited the unique property of current passing through a material with no resistance. This is chiefly because, until 1986, superconducting materials only operated at temperatures near absolute zero. After decades of research (from 1911 to the mid-1980s), the critical temperature increased by only 20 degrees Kelvin (Argonne National Laboratory 1987). The enormous potential benefits of superconductivity have been realized primarily in the field of high-energy physics, e.g., in particle accelerators, and more recently in the commercial application of magnetic resonance imaging for medical diagnostics.

The potential for operating superconductors in the comparatively simple environment of a liquid-nitrogen coolant (or eventually even at room temperature) has broadened the commercial possibilities. Interest has been stimulated in many potential large-scale applications such as generators, energy storage, transmission lines, levitated vehicles, and fusion generation of electricity. The shift to HTSCs might lead to reduced capital costs, lessen the complexity of the cooling system, and improve the overall reliability of any application that could benefit from either the transmission of electricity without energy loss or the generation of strong magnetic fields.

These recent advances in superconducting materials have caused a reexamination of several large-scale applications. One of the most obvious potential applications for HTSCs is maglev vehicles. Interest in high-speed ground transportation has been particularly intense in those regions with highly developed intercity train systems, i.e., Europe and Japan. High speeds have always allowed premium prices to be charged for transportation, and thus speed has had an enormous influence on the choice of mode for both passenger and freight movements. In the United States, intercity passenger travel is dominated by automobile and air travel, both of which require relatively high energy intensities to achieve personal convenience and speed. Similarly, trucks and aircraft dominate the transport of high-valued, time-sensitive freight. Among the issues that this report addresses are (1) whether a form of high-speed ground transportation has become a legitimate alternative to satisfy a portion of future intercity travel demands in the United States and (2) whether maglev vehicles can be enhanced by using HTSCs and thus enable maglev systems to become a technologically preferred choice in some intercity corridors.

2 MARKETS FOR HIGH-SPEED MAGLEV TRANSPORTATION

The market for a new product or service includes the current market in which similar goods are bought and sold, the near-term market in which the attributes of the new product can create a larger demand, and the long-term expanded market created by the performance characteristics or costs of the new product or service. These distinctions are especially important for new technologies because if the full market potential is not examined, the market may be perceived as too small to pursue. Maglev technology already has a current market, even though that technology is not yet ready for commercialization. This section summarizes this current interest in maglev technology, along with the factors that have stimulated it. In addition, the intercity transportation market is examined to determine if maglev performance has the potential to create significant near- and long-term market demands.

2.1 ATTRIBUTES OF MAGLEV TRANSPORTATION TECHNOLOGIES

The attributes (e.g., performance characteristics and costs) of any product or service define its potential markets. Maglev system attributes and the implications for their markets are summarized below.

2.1.1 Speed

Maglev technology overcomes the principal limitation of wheeled systems, that is, the guideway precision required to avoid excessive vibration and rail deterioration at high speeds, which leads to high maintenance costs. In addition, maglev vehicles do not depend on contact for traction and therefore have a greater capacity for acceleration, braking, and grade climbing than do conventional steel-wheel trains. Whereas steel-wheel trains have been limited to sustained speeds below 200 mi/h, maglev vehicles (especially the EDS) have the potential to travel at speeds above 300 mi/h. With enclosed-tube designs in which aerodynamic drag is substantially reduced, speeds well beyond 300 mi/h are conceivable with EDS technology.

2.1.2 Revenue Potential

All marketing and ridership studies of high-speed ground transportation systems show that increased speed (which reduces travel time) results in greater ridership. It is principally the enhanced ridership (revenue) potential that has sustained interest in developing maglev technology.

2.1.3 Operation

Noncontact operation of a maglev vehicle reduces the effects of inclement weather (i.e., rain, snow, or ice) on safe and timely operation relative to steel-wheel trains, aircraft, or highway vehicles. This is particularly significant when comparing maglev travel to air travel, in which adverse weather is responsible for much of the delay. Adverse weather is expected to have relatively little effect on maglev operations.

2.1.4 Maintenance

In general, maintenance costs associated with maglev transportation (at least for the lightweight EDS technology) should be considerably lower than those for conventional rail systems. Because the stresses on a maglev guideway are distributed over large areas instead of being concentrated at contact points, there should be relatively little tendency for guideway misalignment or mechanical wear. Wear should also be minimal on vehicle suspension systems. Minor settling or other perturbations of the guideway structure are likely to require less correction with an EDS maglev system than with either an EMS maglev or conventional rail system. The high precision required for the EMS technology and the greater vehicle weight are likely to require more frequent guideway alignment and adjustment than needed for the EDS technology.

2.1.5 Energy

Maglev systems, being electrical, are not dependent on dwindling U.S. petroleum supplies, and their electrical energy needs can be provided by hydroelectric, coal-fired, or nuclear power facilities. Only about 5% of U.S. electric generating capacity is based on petroleum. Further, the energy intensity of a maglev vehicle would be about one-third that of short-haul intercity aircraft travel, on a passenger-mile (PM) basis (see Sec. 3.1). The level of electric power required for a maglev network depends on several factors. As a typical example, assume a 2,000-mi-long network of double guideway carrying an average passenger flow of 2,000 passengers/h in each direction; total propulsion power demand would be about 1,300 MW. This is equivalent to the output of one large nuclear power plant, but such a network would span the grids of many utility companies and would present a more smoothed-out demand pattern than would a power system concentrated in one place.

2.1.6 Environment

Noise and track-side vibration, which have been reported as major concerns with the Japanese bullet trains, should be considerably lower for a noncontacting maglev system. Air pollutant emissions would be confined to the central generating plants, where they are relatively easy to control (unlike aircraft emissions, which are uncontrolled and are concentrated at airports in urban areas). Electromagnetic interference caused by sparking between electrical contacts on very-high-speed trains would be eliminated with maglev systems.

2.1.7 Guideway Construction and Right-of-Way Selection

Most maglev technologies require some form of powered guideway, which makes the maglev system more complex and more costly than nonelectrified conventional steel rail systems. This increased complexity, however, is largely overcome by several advantages. First, because maglev vehicles are expected to be much lighter than conventional trains, they will place much less load on the guideway.* Second, because magnetic levitation distributes the vehicles' static and dynamic loads over a continuous length of track, rather than concentrating it at several points of contact, stresses will be much lower and the structure can be made with lighter-duty components. Third, the cross-sectional area of maglev vehicles is smaller than that of ordinary trains, allowing smaller tunnel dimensions to be used; moreover, ventilation of long tunnels is not required. Finally, because maglev vehicles will not rely on contact for traction, they have much greater accelerating and grade-climbing capabilities than do conventional trains. All of these advantages combine to increase the flexibility of route selection and reduce the cost of constructing tunnels and support structures, relative to those for high-speed trains.

Conceptually, maglev transportation is perhaps closer to the airplane than it is to conventional trains or highways, and it is possible to design systems with lightweight guideways. The lightness of the guideway means that it can be elevated less expensively than conventional rail lines or highways, leaving large tracts of space available beneath the guideway. Right-of-way costs and disruption can be minimized by using existing highway, railroad, and utility rights-of-way to the extent practicable.

2.1.8 Safety

Because monitoring of vehicle position and speed is required for system operation, the chances of collisions and other accidents could be virtually eliminated. The use of elevated structures will preclude problems of grade crossings and reduce the probability of objects being placed on or falling on the guideway. Standards for safe exposure levels of passengers to magnetic fields have not been established. However, magnetic fields generated by the levitation and propulsion magnets can be reduced, if required for passenger and crew protection, by magnet-design and field-shielding techniques. Fields external to the system should have little safety or environmental significance because they fall off rapidly with distance and because of their intermittent nature relative to any wayside reference point.

In a power failure, the EDS would glide to a halt in much the same manner as in its normal operation. The on-board magnets do not depend on a power source for their operation. The electromagnetic drag force generated by the magnets and guideway provide a natural braking action until the vehicle settles on its wheels. The EMS maglev vehicle is provided with skids to contact and slide on the guide rails if on-board power fails.

Substitution of maglev trips for short-haul aircraft flight will reduce the number of aircraft operations at congested airports and thereby reduce the probability of midair collisions. Similarly, substitution for intercity highway vehicle trips will reduce highway accidents, especially during inclement weather.

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*Mass (t) per passenger seat: French TGV = 1.0; West German ICE = 1.2; EMS = 0.52-0.63; and EDS = 0.21-0.45.

2.1.9 System Capacity

The capacity of a maglev line depends on the number of passengers per car, the number of cars per vehicle or "train," and the time interval ("headway") between vehicles. Assuming single-car vehicles, 150 passengers/vehicle, and headways of 1 min leads to a steady-state capacity of 9,000 passengers/h (each way). If paired cars were used, system capacity would be doubled. This can be compared with traffic on an expressway: according to the Highway Capacity Manual (Transportation Research Board 1985), the peak capacity of a single traffic lane under ideal conditions is 700 vehicles/h traveling at 60 mi/h (it is higher at lower speeds). Assuming an average vehicle occupancy rate of 1.8 for intercity travel (1.1 for urban travel) leads to a lane capacity of 1,260 passengers/h in each lane. Hence, a maglev system based on the use of single vehicles has a capacity in excess of seven lanes of expressway. Further, the highway vehicles are moving at 60 mi/h, but the maglev vehicles travel at 300 mi/h.

Comparing maglev capacity with aircraft runway capacity, roughly 40 take-offs or landings per hour can be handled by a single runway under ideal conditions. Assuming 150 passengers/short-haul aircraft leads to a capacity of 6,000 passengers/h. Thus, a maglev network of four to five routes for a major hub airport would be equivalent to six to eight all-weather runways.

2.2 POSSIBLE APPLICATIONS OF MAGLEV TRANSPORTATION TECHNOLOGIES

In principle, maglev vehicles may have a variety of applications, ranging from low- to moderate-speed people-mover systems to high-speed commuter systems and very-high-speed intercity transportation. Applications in each speed range would exploit various combinations of the attributes listed above. Low- and moderate-speed urban transit applications can take advantage of the low environmental impacts and the use of central station power. However, most conventional urban mass transit systems already employ all-electric systems that offer similar benefits to maglev, so the potential gains are relatively small for short-distance applications and may not offset the added costs of a new technology. Nevertheless, both the West German and Japanese maglev developers are exploring such applications for their own countries and for the United States.

Intermediate- to high-speed commuter applications connecting suburbs to central business districts and connecting nearby cities (within roughly 50 mi of each other) are another potential maglev market. However, for this application, the principal competitors are highway vehicles and conventional commuter rail technology. Introduction of a new technology into that market may provide some important benefits, especially the replacement of gasoline use or diesel fuel demand (of diesel locomotives) with central station power and the subsequent reduction in environmental impacts. However, commuter system fares are typically low (on a per-mile basis) relative to very-high-speed intercity fares, so long-distance maglev commuter systems may fit more logically into a very-high-speed intercity maglev system where commuter service uses off-line stations. This approach would add ridership at low incremental costs, but would not interfere with very-high-speed intercity maglev vehicles.

The high-speed intercity market (100-200 mi) begins to take genuine advantage of the speed capabilities of maglev technology. However, even in this market area, it is important to recognize two important points. First, state-of-the-art steel-wheel-on-steel-rail systems can reach speeds near 190 mi/h, with average speeds of 150 mi/h, making destinations 350 mi away within reach of a 2.5-h travel time. However, such train systems would require totally new track, electrification, and infrastructure. Second, any railway technology providing a trip range of 50-350 mi must compete with the dominant intercity transport modes, which in the United States are highway vehicles and aircraft. Competitors are therefore numerous, and the net benefits of 150-mi/h average speeds are not likely to attract sufficient added ridership to solve the nation's leading transportation problems or justify the costs of a new transportation technology.

The very-high-speed market is a different matter. At speeds of 300 mi/h, maglev technology has no ground-based competitors. Trips of up to 600 mi could be covered in two hours or less, making maglev competitive with aircraft over this distance and travel time range. Highway vehicles are still likely to be the mode of choice for trips significantly under 100 mi; but for longer trips, the high speed of the maglev system, together with its safety, convenience, and relative freedom from dependence on good weather, makes it a strong competitor. Hence, for very-high-speed applications at distances of 50 or 100 mi to as much as 600 mi (referred to in this study as the "maglev window"), maglev's full capabilities can be exploited. For trips within the maglev window, the system could be used very effectively for hauling passengers and high-valued freight. Freight could be carried on specially designed vehicles that are not as constrained as passenger-carrying vehicles with respect to magnetic-field shielding and ride quality. In addition, the technology can be used to achieve a number of significant national objectives, as is discussed in subsequent sections of this report. However, to take full advantage of those potential benefits, the system should be compatible nationally and should not compete with airlines. This aspect is discussed in detail in subsequent sections of this report.

2.3 REGIONAL INTEREST IN HIGH-SPEED GROUND TRANSPORTATION

Historically, a market niche has appeared entirely feasible for intercity trips of 100-600 mi (Rhodes and Mulhall 1981). Trips of under 100 mi will still be dominated by automobile travel, although there may be a maglev market for some business travel. Trips much beyond 600 mi will still tend to be served principally by aircraft. Within this context, a review of U.S. intercity travel demands has indicated that maglev vehicles are being seriously considered in a number of corridors. Active interest in high-speed intercity ground transportation service in the United States, including the potential for maglev systems, is described here.

Independently, initiatives developed in several states and regions are considering alternative high-speed ground transportation technologies as a component of a balanced transportation system for those states. The most serious maglev proposals, and subsequent analyses, have been in California-Nevada, Florida, and Pennsylvania. Elsewhere, consideration is being given to Illinois-Michigan, the Northeast Corridor (Boston, New York, and Washington), Ohio, and Texas.

Numerous other states (including Missouri, Washington, Georgia, upstate New York, and New Mexico) have begun analyses and are planning to improve their rail passenger service significantly (Speedlines 1988, and other issues). Successful commercialization of the technology in one of the corridors most advanced in its planning will likely cause the technology to become a legitimate alternative in the other states and regions as well. It is particularly noteworthy that maglev technology has been seriously considered in so many corridors, because it is still in the prototype development stage. As an indication that there is already a market for maglev transportation, the current status of several of the regions farthest along in planning are summarized below.

2.3.1 Florida

Two formal programs in Florida are related to high-speed ground transportation, both under the jurisdiction of the Florida High-Speed Rail Transportation Commission. The first was established by the High-Speed Rail Act of 1984, and the second by the Magnetic Levitation Demonstration Project Act of 1988.

The High-Speed Rail Act establishes a high-speed corridor serving Miami, Orlando, and Tampa. Applications for the high-speed rail franchise were submitted by Florida High-Speed Rail Corporation (associated with ASEA Brown Boveri) and TGV Company of Florida (associated with Alsthom and Bombardier, Inc.) in April 1988. The ASEA Brown Boveri group proposed a 150-mi/h steel-wheel train now under development in Sweden, while the TGV group proposed the 185-mi/h TGV Atlantique steel-wheel train. Extensive hearings will be held and reviews will continue until mid-1991, when a franchise will be awarded.

The Magnetic Levitation Demonstration Project Act does not specify a location, route length, or duration for the project, although interest in this project was originally stimulated by the desire of Japan Railway to build a maglev demonstration project from Orlando International Airport to Walt Disney World. Three other maglev groups have also expressed interest in this project (Speedlines 1988).

Both programs (i.e., the maglev demonstration and the high-speed rail system from Miami through Orlando to Tampa) would have access to property via eminent-domain proceedings and would be granted the use of public lands and highway rights-of-way. For economic incentives, the High-Speed Rail Act further grants development rights for contiguous lands and allows issuance of Florida State tax-exempt bonds for financing. However, state full-faith and credit bonds are not available for high-speed rail financing.

Active interest by several international high-speed-rail and maglev consortia continued until the time for filing of applications. Only two formally accepted applications for wheel/rail technology were received by the application date, and no maglev applications for the state-wide system were received. An international consortium representing Japanese financing and German maglev technology, called Maglev Transit, Inc., responded to the Florida Magnetic Levitation Demonstration Project Act proposal with a bid on March 2, 1989. This project is separate and distinct from the Miami-Orlando-Tampa corridor. The Florida High-Speed Rail Transportation

Commission will host hearings for selection of maglev applicants in late June 1989. Final selection of a maglev demonstration project applicant will conclude in April 1990. Finally, completion of the demonstration maglev project is currently projected for mid-1994.

2.3.2 California-Nevada

California and Nevada have ratified a "California-Nevada Super Speed Ground Transportation Compact," which creates the California-Nevada Super Speed Ground Transportation Commission and authorizes it to ". . . prepare a study, secure a right-of-way, and award a franchise for the construction and operation of a super-speed ground transportation system at no expense to the State of California, principally following the route of Interstate Highway 15 between the City of Las Vegas, Nevada, and a point in southern California." Although the commission is authorized to issue bonds, the bonds cannot be an obligation of the State of California. The speed of the system is required to be at least 180 mi/h.

The city of Las Vegas, in pursuit of this objective, has used Federal Railroad Administration grants to fund several technical, operational, and economic studies of the system. All of these studies have been positive, indicating that the system is technically and economically viable and will operate at a profit to the investors. One route evaluated is between Las Vegas and Ontario, California, to the east of Los Angeles. A TGV train system on this 230-mi-long route was estimated to cost about $2 billion, while a Transrapid maglev system would cost about $2.5 million. Annual ridership was projected at about 3.1-3.7 million passengers at the start. The maglev system was considered to have an additional 1 million passengers/yr due to the novelty factor, but this ridership is not included in the official estimation.

As in the Florida initiative, the technologies being studied include the EMS (attractive) maglev system and the high-speed TGV rail system. The Japanese EDS maglev system is also a candidate, but detailed cost estimates were not complete due to lack of data. However, the latter system is considered to be behind the TGV or Transrapid systems in terms of deployment schedule.

The newly formed commission met for the first time in mid-September 1988. Among its priorities is a petition for dual use of the interstate highway right-of-way and the preparation of a request for proposals for the system. It is intended that the system be installed and operational in 1995 (Johnson 1988). The objectives of the program are to benefit the state and local economies, reduce reliance on gasoline and diesel fuels, encourage use of alternative fuels, reduce congestion on the interstate highway, provide convenient transportation, and demonstrate a state-of-the-art system that could be useful in future commuter service.

2.3.3 Pennsylvania

Pennsylvania has funded a nearly completed $4 million study of a high-speed ground transportation system for use in the corridor connecting Philadelphia, Harrisburg, and Pittsburgh. The report is not yet available for review. The Pennsylvania High-Speed Rail Commission elected to restrict its considerations to two systems, a 160-mi/h steel-wheel train and a 250-mi/h maglev system. Four to 12 million riders per year are expected to use the system.

A separate study of the maglev transportation option, combining regional commuter service with maglev vehicle feeder service to the Pittsburgh airport, is under way at the Carnegie-Mellon Rail System Center. The maglev system would serve as a "super-speed" 150-mi/h commuter system with stops 7-20 mi apart. The same system would provide longer-distance "air" service between the Pittsburgh airport and Ohio, West Virginia, and portions of Pennsylvania (Uher 1988).

2.3.4 Illinois-Michigan

The Michigan Department of Transportation has current (Main Line 90) and near-term (Blueprint Beyond 1990) programs to upgrade train service. Beyond that is active interest in very-high-speed systems, such as maglev transportation, in the Chicago-Detroit corridor. A High-Speed Rail Commission has been established in Michigan, and legislation is pending in Illinois and Indiana.

In a 1984 study by the Federal Reserve Bank of Chicago (Baer et al. 1984), several high-speed rail corridors in the Midwest, including Chicago-Detroit, were examined. Demand modeling showed significant increases in ridership (by two to five times) for maglev technology compared to existing train service, due to both reduced travel time and frequency of trips. The report was cautious in drawing conclusions about maglev systems because of the lack of revenue-service data; it also did not examine the potential economic effects of integrating a maglev system into the airline service.

Air-traffic volume at Chicago's O'Hare and Midway airports has prompted some planning groups to examine the need for a third airport. Construction of a new airport is opposed by the City of Chicago and the airlines. While the concept of maglev as an airline technology has not yet surfaced, it may as the concept becomes better understood.

2.3.5 Texas

The Texas Turnpike authority has initiated a study of high-speed ground transportation alternatives in the Houston-Dallas-Ft. Worth-Austin-San Antonio corridor, with the goal of having a new system operational in 1998. The study, which is to be completed by the end of 1988, includes various high-speed rail and attractive-maglev transportation options. Repulsive-maglev technology is regarded as probably not sufficiently developed to be considered, but is not precluded in the study. Many existing rail routes have been evaluated, and the possibility of an entirely new right-of-way is being considered as an option. An earlier study of a portion of this corridor -- funded by a consortium of West German companies -- recommended installation of the German Intercity Express (ICE) system, which has a planned operating speed of 156 mi/h.

2.3.6 Northeast Corridor

This corridor, which connects Washington, Philadelphia, New York, and Boston, is regarded by many, including the Japanese developers of maglev systems, as the most promising for introduction of a maglev system. It motivated the initial studies of magnetic levitation for high-speed ground transportation in the United States.

The Japanese National Railway reportedly presented a proposal to the Coalition of Northeast Governors (CONEG) for a feasibility study of maglev transportation in this corridor. Need for additional transportation services here is so pressing, however, that CONEG staff are said to feel that time is not available to develop a new system and therefore only systems now in service are being considered (CONEG 1987). Service will probably be improved incrementally, which may preclude introduction of an entirely new, i.e., maglev, system.

2.4 POTENTIAL AIR TRANSPORT MARKET

Intercity travel is used for many business and personal reasons and makes use of privately owned automobiles and numerous common carriers, including aircraft, trains, and buses. The airlines have accounted for most of the growth in intercity passenger travel during the last decade. As shown in Table 1, air traffic (in terms of passenger-miles) more than doubled between 1976 and 1986, accounting for more than 90% of the travel by common carriers.

As a result of this rapid growth in air traffic, congestion has become a major concern. The Transportation Research Board (TRB) recently listed congestion as one of the 10 critical issues in transportation, noting that it is a major problem for "all forms of transportation but is particularly severe for air and highway transportation." Although larger aircraft and improved air traffic control devices have helped to reduce congestion, deregulation has had the opposite effect by increasing the level of aircraft activity. The

TABLE 1 Intercity Passenger Travel in the United States (10^9 passenger-miles)

Mode	1976	1985	1986
Common carriers			
Airlines	152.3	277.8	307.6
Amtrak	4.3	4.8	5.0
Buses	25.1	24.0	23.1
Total	181.7	306.6	335.7
Private automobiles	1,259.6	1,418.3	1,459.7
Total	1,441.3	1,724.9	1,795.4

Source: Air Transport Assn. of America (1987).

congestion problem is expected to be exacerbated further by the continued increase in demand for air travel. TRB concluded that the "projected growth in automobile and air travel may well exceed the ability of planners and engineers to get the most out of existing systems" (TR News 1987).

The United States has nearly 500 airports with scheduled air service; the largest 100 account for 95% of all passenger enplanements.* In 1985, there were 384 million passenger enplanements and more than 11 million aircraft operations‡ in the United States. As expected, the nation's major hub airports represent a disproportionate share of total air traffic activity: the top five airports (Chicago's O'Hare, Atlanta, Los Angeles, Dallas-Ft. Worth, and New York's Kennedy) produced 25% of the enplanements, while the top 14 airports accounted for more than 50% of all passenger enplanements (FAA 1987).

The considerable growth in air travel that has developed over the last 10-15 years is projected to continue, although at lower annual rates. Passenger enplanements, which have recently increased at 5-7% annually, are forecast to grow at an annual rate of 3-4%. Even this sharply lower growth rate in air traffic means that passenger travel will increase by 88% between 1985 and 2000 (see Table 2).

As illustrated in Figs. 2 and 3, some 12 airports already are considerably congested, a number expected to increase to more than 30 by the mid-1990s. Much of the delay associated with air travel occurs at major hub airports, and the projected increases in air travel -- unless airport capacity is increased -- will produce further congestion there and will extend the congestion to other air terminals.

TABLE 2 Projected U.S. Air Carrier Enplanements, 1981-2000

Period, Year	Enplanements (10^6)	Annual Increase (%)
Historical		
1981	282.0	
1982	293.2	4.0
1983	311.9	6.4
1984	334.8	7.3
1985	384.2	14.7
Forecast		
1986	409.7	6.6
1987	436.0	6.4
1988	458.0	5.0
1989	479.4	4.7
1990	501.4	4.6
1991	523.3	4.4
1992	544.8	4.1
1993	566.4	4.0
1994	588.3	3.9
1995	610.4	3.8
1996	632.8	3.7
1997	654.7	3.5
1998	676.8	3.4
1999	699.1	3.3
2000	721.7	3.2
Increase, 1985-2000	--	88.0

Source: FAA (1987).

*Enplanement is the aircraft boarding of originating, stopover, or connecting passengers.

‡An aircraft operation is one takeoff or landing.

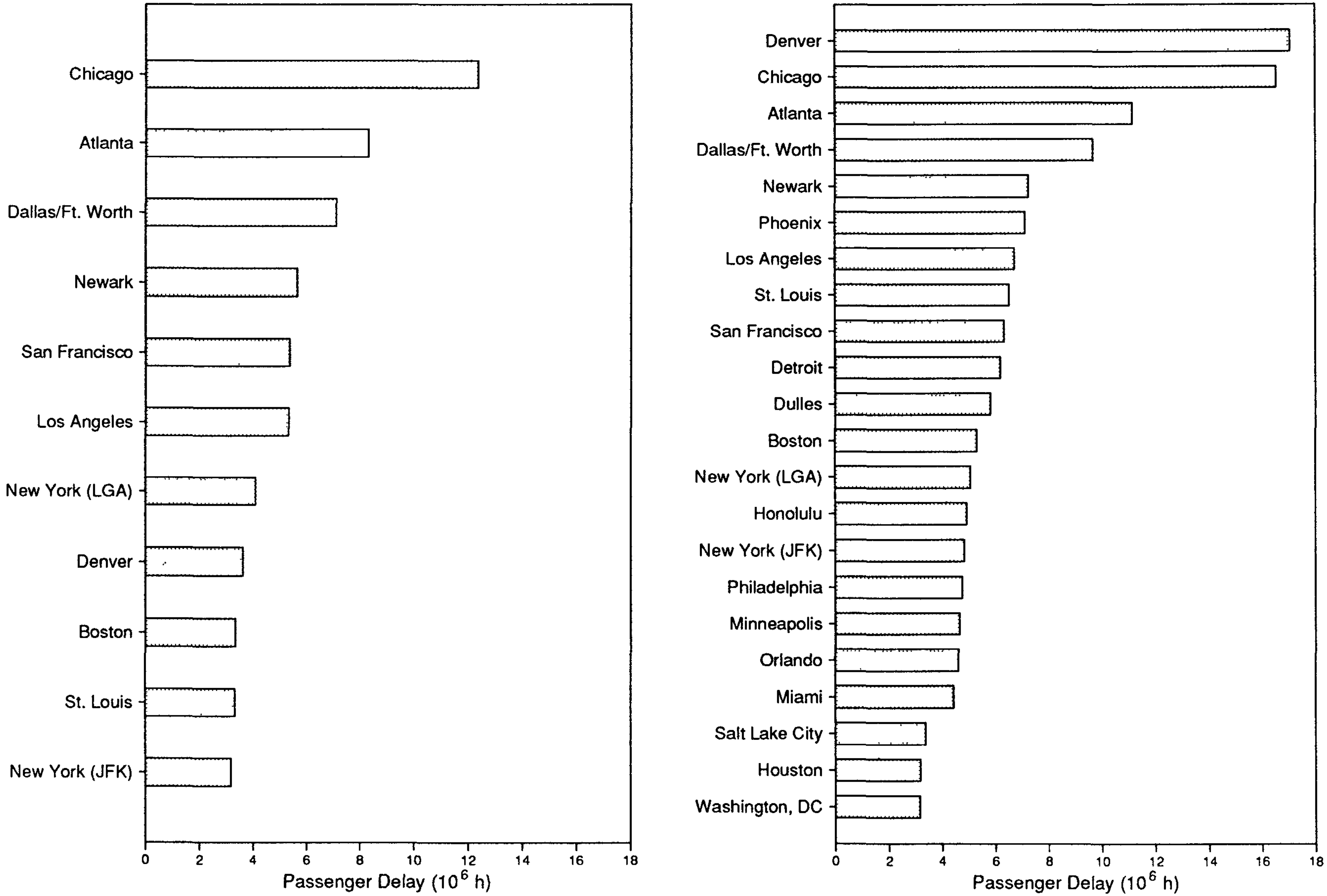

FIGURE 2 ***Left:*** **Airports Exceeding Three Million Hours of Passenger Delay in 1986;** ***Right:*** **Airports Forecast to Exceed Three Million Hours of Passenger Delay in 1996 (assuming no increase in capacity) (Source: Price 1987)**

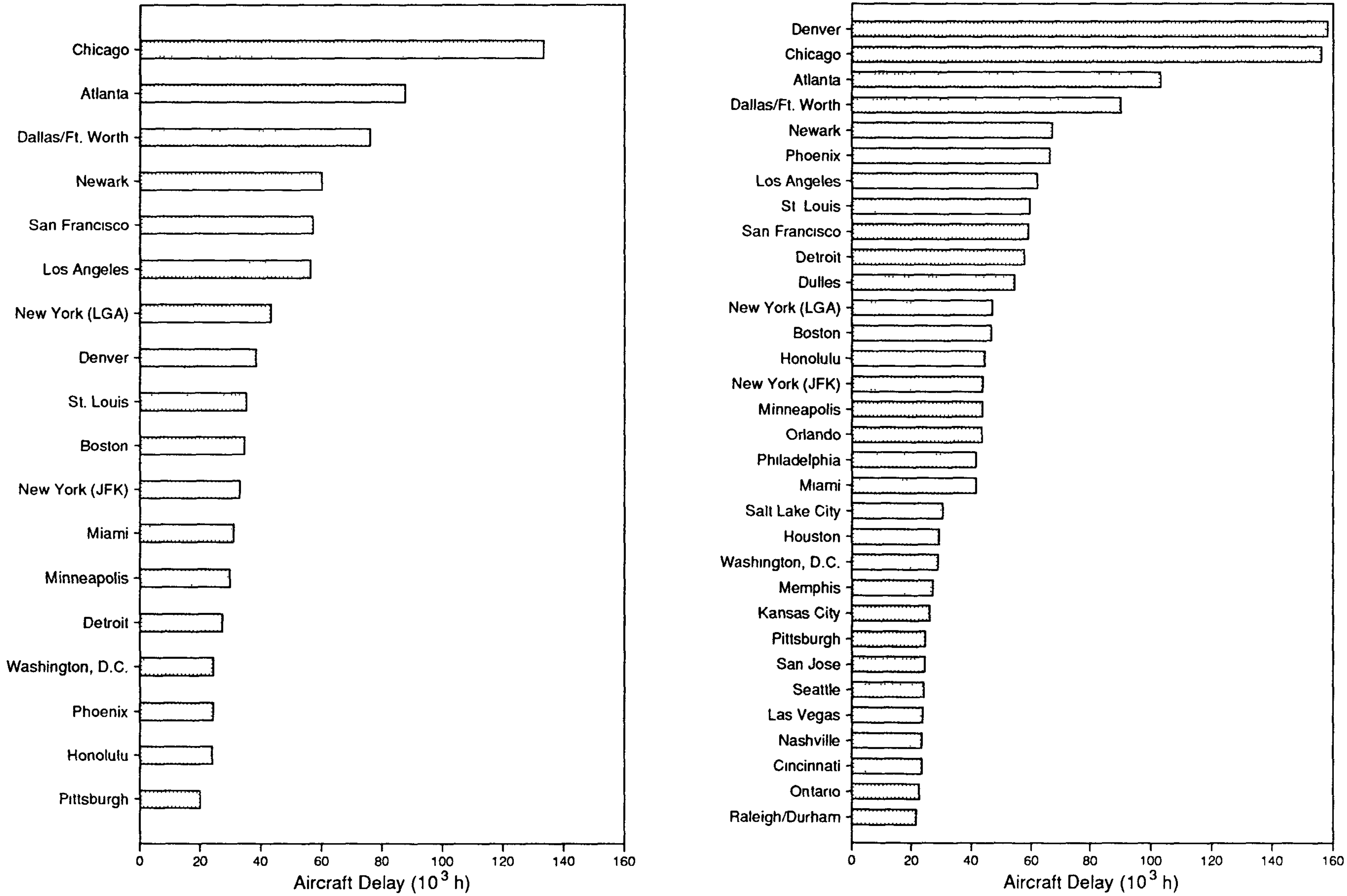

FIGURE 3 ***Left:*** **Airports with More Than 20,000 Hours in Aircraft Delay in 1986;** ***Right:*** **Airports Forecast to Exceed 20,000 Hours of Aircraft Delay in 1996 (Source: Price 1987)**

Congestion is not merely a matter of frustration, but entails costs to both passengers and airlines. Although an absolute value of congestion cannot be calculated because each individual or firm values time differently, rough estimates of the aggregate costs of air traffic delays have been made. The Federal Aviation Administration (FAA) estimates that cumulative delays in 1985 cost the scheduled airlines $1.8 billion, or 7% of their total direct costs. In addition, the delays cost passengers $1.1 billion in lost time, according to the FAA. Thus, the total cost of delays for both air carriers and passengers was almost $3 billion in only one year. By the following year, total congestion costs had risen to $5 billion. Because the costs apply only to scheduled air carriers, congestion effects for general aviation and commuter air traffic are not included; consequently, the total costs of air traffic congestion are underestimated (FAA 1988).

2.5 MAGLEV TRANSPORTATION AS AN AIRLINE TECHNOLOGY OPTION

The problems of airport and air traffic congestion can be addressed in ways other than building new airports. By substituting high-speed ground transportation for short- to medium-distance flights, airlines could make more efficient use of existing airport infrastructures and more cost-effective use of their fleets. High-speed ground transport radiating from major hub airports would increase airport capacity while reducing air traffic congestion.

The mixed use of airports for both aircraft and train service has been undertaken by Lufthansa at the Frankfurt and Düsseldorf airports in West Germany. Lufthansa's Airport Express, a 125-mi/h train operating since 1982, connects the two airports via Cologne and Bonn. By using existing airport terminal facilities, the train "augments and expands our flight schedules," according to Lufthansa's brochures. Travelers can choose between aircraft or train connections for the same price, and ridership is about the same in both modes.

Because U.S. airlines tend to operate on hub-and-spoke systems, passengers must often change planes at a hub airport for connections to short-distance cities. If high-speed ground transportation were available at the airport, little difference would be noticed by the passengers if they changed from an aircraft to a maglev vehicle, instead of to another aircraft.

Maglev systems may be the only high-speed ground transportation alternative that is reasonably available to U.S. airports because of the extensive development around airports. Although reduced speeds may be required on some sections, maglev vehicles generally should be able to use existing highway facilities and avoid extensive acquisition of new rights-of-way. This would also provide economical access to central business districts, which are obviously inaccessible to commercial jet airplanes.

2.6 WORLDWIDE MAGLEV TRANSPORTATION MARKETS

A number of possible routes in Japan, Western Europe, and North America that could be served by high-speed maglev vehicles have been described in the literature. Adding to these routes possible intercity links in such countries as Australia, Brazil, and

Argentina, as well as countries in eastern Europe, it is clear that a fairly large potential market exists. One source reported that "transportation experts foresee as many as 50 separate superconducting train lines worldwide" (Insight 1988). Whether that market will ultimately be served by normal-conducting maglev vehicles such as the German Transrapid or by superconducting maglev vehicles such as the Japanese Linear Motor Car, or by some altogether different technology, remains to be seen.

An estimate of the market size from the perspective of the Japanese research community appears in a recent issue of *Focus on Japan* (CSAC 1988), which reported that the Nikkei Industry Research Institute had forecast that nitrogen-cooled superconducting materials could create a $12.4 billion market -- of which the maglev train share would be $4 billion. The surveyed experts predicted a 100% probability that HTSCs would be part of maglev technology in 10 years. The report did not indicate if foreign applications were included in the projected market.

One point is clear. Both the Japanese and German maglev transportation developers continue to expend considerable resources to develop revenue versions of their system concepts for both domestic and foreign use. The extent of those domestic and foreign markets is discussed from both the German and Japanese perspective in the next two subsections.

2.6.1 West German Perspective

The West German government announced in July 1988 its plan to build the first commercial version of its Transrapid maglev system (using EMS levitation) on a 90-mi route between Hamburg and Hannover (New Technology Week 1988). An alternate 60-mi route linking Essen to Bonn was also announced. Initial revenue service would begin after 1999. According to the report, German officials see this technology "as a key means to solve air traffic saturation in their country by providing a ground-based alternative for short regional flights." Deutsche Lufthansa AG may participate in the financing of the $1.7-billion Hannover-Hamburg project. According to a recent communication from Kretzschmar and Wackers (1989), Deutsche Lufthansa AG and the Düsseldorf and Cologne airport authorities have proposed the incorporation of links to those two airports in the Essen-Bonn route. Another proposal, by other West German groups, calls for maglev connections between the seven major airports in West Germany; a feasibility study shows that these connections could be built entirely with private funds.

Maglev railway planning and testing in West Germany is conducted by the Versuchs und Planungsgesellschaft für Magnetbahnsysteme mbH (MVP) under contract to the Federal Minister for Research and Technology (BMFT). Interests in MVP are held equally by the Deutsche Bundesbahn (DB), Deutsche Lufthansa AG (LH), and Industrieanlagen-Betriebsgesellschaft (IABG). Included in the six major tasks of the MVP are operation of the test facility at Emsland and support of marketing efforts and assistance in introducing the Transrapid. According to an information brochure, both MVP and BMFT regard the Transrapid as a transport mode that will win back railway ridership lost in recent years to aircraft and highway vehicles (MVP 1985). A major objective of transportation planners is the transfer of passengers from short-haul aircraft flights to maglev systems to relieve Europe's air traffic congestion and to extend the travel radius for total trip times of under 3 h.

The MVP and its international marketing and promotional counterpart, Transrapid International, are identifying routes that might be served by its maglev technology. In addition to a number of domestic links, several European routes have been under negotiation, including Paris-Brussels-Cologne (which had been under discussion for several years). The MVP has also proposed a European maglev system network that would eventually link 26 metropolitan areas in eight countries. Outside continental Europe, proposed routes include a number of links between major cities and airports in Saudi Arabia; a Newcastle-Sidney-Canberra route in Australia; several routes linking U.S. and Canadian cities in the Great Lakes and New England regions; and other routes in Canada and the United States, including links between (1) San Francisco, Los Angeles, San Diego, and Las Vegas; (2) Dallas, Houston, San Antonio, and Austin; (3) Los Alamos, Santa Fe, Albuquerque, and Las Cruces; (4) Vancouver, Seattle, and Portland; and (5) Tampa, Orlando, and Miami. Also under consideration are relatively short links between urban centers and remote airports such as Washington's Dulles Airport and Ottawa's Mirabel Airport.

Even the possibility of applying the technology to Japan in direct competition with the Japanese maglev technology has not been overlooked. Transrapid interests in Japan are represented by C. Itoh & Co., Ltd., of Tokyo.

2.6.2 Japanese Perspective

Like the West Germans, the Japanese recognize the international market potential for very-high-speed ground transportation in general and for maglev technology in particular. In contrast, however, they have been somewhat less aggressive at the international level. There are several possible reasons for this. Unlike the European situation, Japan's population and economic activity tend to be concentrated in relatively few large urban areas, including Tokyo, Nagoya, and Osaka. A surprisingly small fraction of Japan has a choice between air, roadway, and railway transport. Almost half of the country is served by only one mode.

Strong political pressures are emerging in Japan to find solutions to this problem of excessive concentration and the attendant transportation problems of congestion and excessively long commuter times. Redistribution of government activities and development of very-high-speed ground transportation systems are just two of the strategies being planned to help redistribute Japan's economic activity and, of course, its population. A major goal is to bring all cities within a one-day round trip of each other; this travel time includes one hour between origin and trunk line and three hours of intercity travel.

The next development step for the "Linear Motor Car" (the Japanese name for the repulsive-force maglev vehicle funded by Japan Railway) requires extensive testing of prototype revenue-service vehicles at sustained full speed, testing of the effects of vehicles passing at full speed, passage through tunnels, and developing and testing of track-switching devices. These tests will require track lengths exceeding 20 mi; the present test track at Miyazaki is only 4 mi long. Several proposals have been put forward, including simply extending the Miyazaki test track or building a new track elsewhere that would subsequently become part of a revenue service route. The potential economic effect of such a facility has caused several prefecture governments to solicit the Ministry of Transport to become part of the first link in the high-speed maglev system.

This combination of strong local political pressure to build the first revenue maglev system in one or more prefectures and the need to solve the problem of excessive population concentration appears to give domestic application in Japan a much higher priority than does international market exploitation. In addition, from a technical standpoint, the program is still several years away from the revenue stage. Although the "Miyazaki technology" could be used as the basis for a trial revenue system within the next two or three of years, the technical experts would prefer several more years to refine and more completely test their technology. Of particular concern are questions of long-term component and system reliability, high-speed performance (ride quality and effects of passing vehicles at speeds of 250-300 mi/h), and economical methods of construction and operation.

The status of their development efforts suggests that the Japanese are not ready for international market exploitation, although they have participated in many international transportation and superconductivity meetings to keep the stage set and maintain their presence within the international community. Furthermore, while they did not participate in the bidding for the Los Angeles-Las Vegas route, they reportedly were the impetus behind the maglev system demonstration project in Florida to build a system between the Orlando airport and Walt Disney World (Speedlines 1988). In addition, they have conducted market studies in other parts of the world and have uncovered some interesting potential markets in Indonesia, where electric power is available but good transportation is lacking, and in South America, where the potential for petroleum savings could be exploited (Kyotani 1988a).

Because the Transrapid and Linear Motor Car concepts are based on fundamentally different technologies, they may eventually serve somewhat different markets. Many experts, particularly in Japan but elsewhere as well, believe that the Transrapid technology may be better suited to lower-speed applications (and to more stable ground conditions than exist in many parts of Japan). Transrapid promotional literature quotes 360 and 400 km/h (225 and 250 mi/h) as average and peak cruising speeds. Whether even this speed range can be sustained in North America without excessive maintenance costs is an unresolved question. On the other hand, the Japanese maglev system should, in principle at least, be capable of speeds up to 300 mi/h, which would make it more competitive with short-haul aircraft flights.

Maglev route development in Japan will undoubtedly lead to some redistribution of ridership from alternative modes, including short-haul airline flights and current high-speed railways (the Shinkansen, or "bullet" train, in particular). However, given that the fare structure, as well as route selection, is regulated by the Japanese Ministry of Transport, there is considerable opportunity to adjust the system to accommodate a new transportation mode, especially if it promises to help solve Japan's congestion problems.

The Ministry of Transport has doubled its contribution to the maglev development program during the past year, which suggests that the accommodation will be made.

Several possible maglev routes are under serious consideration in Japan, including two possible routes linking Tokyo with Nagoya and Osaka -- one east of Mt. Fuji (parallel to the present Shinkansen route) and one west (which has higher construction costs but lower land costs). Other possible routes include (1) a 28-mi link on Hokkaido Island between Sapporo and the airport at Chitose (half of the right-of-way is already owned by Japan Railway; (2) a semicircular route connecting Takasaki (north of Tokyo) to Toyama, Komatsu, and Tsuruga (along the north coast of Honshu Island), and Osaka; and (3) two routes on Kyushu Island linking Nagasaki, Fukuoka, Kumamoto, and Kagoshima.

The first maglev transportation route could be any one of these or possibly a link between Narita airport and Omiya (three options ranging in length from 43 to 62 mi are being considered) or simply an extension of the existing Miyazaki test track, as mentioned earlier. The Kyushu routes are particularly attractive because they could alleviate serious air traffic congestion. Routes on Hokkaido are attractive from the perspective of relocating of economic activity to that relatively remote area of Japan. A special study committee will investigate the route question, which has been given the highest priority in the maglev technology program; the committee is expected to reach a decision by 1990.

3 IMPACTS OF MAGLEV TRANSPORTATION

The potential energy-related and economic benefits of noncontact maglev systems are summarized in this chapter. Some of these benefits could be of crucial significance in the future (e.g., electric- rather than petroleum-based propulsion), but are widely enough understood that extensive discussion is unnecessary.

3.1 ENERGY

Despite the current unrestricted availability of petroleum in the world market, the energy effects of major new transportation technologies remain an important consideration. The limited U.S. petroleum reserves have fostered widespread acceptance of the conclusion that significantly higher oil prices are likely in the 1990s in spite of current low oil prices and that the potential for major petroleum supply interruptions is high (Millar and Vyas 1985; Singh et al. 1985). Transportation is particularly vulnerable to oil price shocks because it is almost entirely dependent on petroleum-derived fuels, unlike other end-use sectors.

Further, as petroleum demand increases, our dependence will increase. Since 1976, U.S. transportation has consumed more oil than is produced domestically (Santini 1986). Thus, if all other sectors of the U.S. economy could switch to nonpetroleum fuels, the nation would still have a petroleum problem. Much of the transportation energy research and development in the last decade has been appropriately focused on highway vehicles because they consume the majority of petroleum resources. Yet certain nonhighway modes may be particularly amenable to new alternative-energy technologies because of the limited potential for increased energy efficiency with conventional technologies.

3.1.1 Energy Consumption in Intercity Travel

Data on energy consumption for intercity travel in various transportation modes have been published by a number of authors for current years and have been estimated for future years, using various forecasting models. Table 3 lists some of these data for 1985 and projections for 2010.

3.1.2 Benefits of Maglev Technology Substitution

For the very-high-speed maglev concept, it is generally acknowledged that -- on the basis of traveler convenience and comfort -- trip lengths of 100-600 mi (the "maglev window") are likely to attract the greatest total ridership, including new passengers and those now using other transportation modes.

Within the maglev window, several benefits of very-high-speed maglev systems can be quantified. First, replacing a portion of short-haul aircraft flights (the most inefficient type of flights), would save a significant amount of energy and replace the demand for petroleum-based fuels with demand for electricity, which could be met

TABLE 3 Intercity Passenger Travel and Energy Consumption for 1984 and 2010, by Transportation Mode

Variable	Personal Vehicles[a] 1984	Personal Vehicles[a] 2010	Buses 1984	Buses 2010	Rail 1984	Rail 2010	Air 1984	Air 2010
Total vehicle-miles (10^9)	1,500	2,219	2.5[b]	--	0.36[c]	--	2.6	--
Total passenger-miles (10^9)	1,955[d]	2,885[d]	46.1[b]	--	14.6[c]	--	243	407
Intercity passenger-miles (10^9)	391[e]	577[e]	27.1[b]	--	4.2[f]	3.6	243	407
Total energy (quads)[g]	11.30	10.68[h]	0.10[b]	0.16[b]	0.05[c]	0.08[c]	1.36	2.04
Intercity energy (quads)	1.19[i]	1.12[h]	0.03	0.06	0.013[f]	0.01	1.36	2.04
Intercity energy intensity (Btu/passenger-mile)	3,030[j]	1,935	1,250	--	3,170[f]	2,780	5,183[k]	3,885

[a]Autos and personal light trucks.

[b]Sum of intercity plus transit bus operations.

[c]Sum of Amtrak plus rail transit operations.

[d]Assumes average occupancy of 1.3 persons/vehicle-mile.

[e]Assumes 13% of total vehicle-miles and 20% of total passenger-miles are intercity.

[f]Amtrak only.

[g]1 quad = 10^{15} Btu = 29.31×10^{10} kWh. Energy content of fuels: automotive gasoline = 1.25×10^5 Btu/gal; jet fuel (kerosene) = 1.35×10^5 Btu/gal; diesel fuel = 1.387×10^5 Btu/gal.

[h]Assumes average vehicle efficiency of 26.0 mi/gal, intercity vehicle efficiency of 32.3 mi/gal, and urban vehicle efficiency of 25.1 mi/gal.

[i]Assumes average fleet efficiency of 20.6 mi/gal for intercity travel.

$$E_{IC} = \frac{0.13 \times 1500 \times 10^9 \times 1.25 \times 10^5}{20.6} = 1.19 \times 10^{15} \text{ Btu.}$$

[j]Assumes 2.0 persons/vehicle for intercity travel. $EI = \frac{1.25 \times 10^5}{20.6 \times 2.0} = 3{,}030$ Btu/PM.

[k]Source: U.S. Dept. of Transportation (1987).

Sources: 1984 data are from Holcomb, Floyd, and Cagle (1987), unless otherwise indicated; 2010 data are from Mintz et al. (1987).

through various energy sources, including hydroelectric and nuclear power, coal, gas. Second, fewer aircraft flights means less neighborhood noise and air pollution and less airport congestion. Third, less airport congestion means less aircraft taxi-idle time, which, in turn, saves additional petroleum, further reduces neighborhood noise and air pollution, and -- perhaps most important of all -- effectively increases the capacity or extends the useful life of airports for the more-efficient, longer-haul aircraft flights. Finally, a maglev network could be expected to displace a reasonable percentage of intercity trips by personal highway vehicle, saving more petroleum and reducing highway congestion.

Displacement of Aircraft Petroleum Use. The energy equivalent of jet fuel that could potentially be saved (i.e., displaced) by maglev vehicles operating in the 100-600-mi maglev window is given by:

$$\Delta E_{ac} = F_1 \times F_2 \times F_3 \times E_{ac}$$

where:

ΔE_{ac} = saved or displaced aircraft energy equivalent,

F_1 = fraction of total aircraft energy consumed in domestic trips of 100-600 mi,

F_2 = fraction of such trips in locations where maglev systems might be built,

F_3 = expected degree of penetration of those markets in approximately the 2010-20 time frame, and

E_{ac} = total energy consumed by all domestic flights.

Estimates of commercial aircraft energy use as a function of trip length are given in Rose (1979). Table 4 summarizes the pertinent data as a function of trip length, with trip lengths aggregated into mileage blocks, while Table 5 lists energy intensity and available seat-miles (ASM) as a function of mileage block. The aircraft mix (regular and jumbo) assumed for this analysis is also given, although it is not critical. From the data in these two tables, the fraction of energy used in the accumulated mileage block of 0-600 mi (F_1) can be estimated; it is assumed that this energy percentage is essentially the same as that for the mileage block of 100-600 mi:

$$F_1 = \sum_{i=1}^{3} EI_i ASM_i / \text{total}$$

$$= 1778/3941$$

$$= 0.45$$

A suitable value for F_2 requires detailed market analysis that is well beyond the scope of this report. However, a relatively straightforward indication of its potential value can be estimated. From 1985 data published by the Air Transport Association of America (1985), 42% of airline passengers travel within the maglev window, and 15.4% of the passenger-miles occur within that window (the pasenger-mile data is skewed by long-range trips). Table 6 lists numbers of passengers traveling between major hub airports and nonstop destinations within the maglev window. Simply summing over this passenger data would result in an error because of multiple counting (trips are listed by city pair, e.g., a trip from Boston to New York would be counted under Boston and under

TABLE 4 Energy Use by Commercial Aircraft as a Function of Trip Length

Trip Length (mi)	Energy Use (seat-miles/gal)			
	Regular Aircraft		Jumbo Aircraft	
	Range	Average	Range	Average
0-200	12.5-25	18.8	--	--
200-400	18-31	24.5	--	--
400-600	22.5-34.5	28.5	--	--
600-800	24-37	30.5	42.5-47	44.8
800-1000	25.5-39.4	32.5	46.5-50.5	48.5
1000-1400	27-41.5	34.3	40-53	51.5
1400-1800	28-43	35.5	52-54	53.0
>1800	28.5-44	36.3	53-54.5	53.8

Source: Adapted from Rose (1979).

TABLE 5 Energy Intensities of Commercial Aircraft as a Function of Trip Length

Trip Length (mi)	Seat-Miles/gal	Aircraft Mix	Energy Intensity (10^3 Btu/seat-mile)[a]	% Available Seat-Miles
0-200	18.8	Reg.	7.2	6.7
200-400	24.5	Reg.	5.5	13.4
400-600	28.5	Reg.	4.7	11.9
600-800	34.1	75% Reg.	4.0	10.4
800-1000	36.5	75% Reg.	3.7	9.9
1000-1400	42.9	50% Reg.	3.1	14.5
1400-1800	44.3	50% Reg.	3.0	12.4
1800-3000	49.4	25% Reg.	2.7	19.6
>3000	53.8	100% Jumbo	2.5	1.2
Total	--	--	-	100.0

[a]Energy intensity (Btu/seat-mile) = $\frac{1}{\text{seat miles/gal}} \times 1.35 \times 10^5$ Btu/gal.

Source: Adapted from Rose (1979).

TABLE 6 Passengers Arriving at and Departing from Hub Airports, 1985[a]

Airport[b]	Passengers Traveling 100-600 mi (10^6)	Total Passengers (10^6)	% Total Passengers Traveling 100-600 mi	Subtraction to Avoid Multiple Counting (10^6)
Atlanta*	0.582	1.19	48.9	--
Boston+	0.674	1.47	-	0.383 to New York
Charlotte	0.197	0.280	-	--
Chicago*	0.872	2.41	36.2	--
Columbus	0.156	0.272	-	--
Dallas*	0.885	1.86	47.6	--
Denver*	0.265	1.24	21.4	--
Detroit+	0.483	0.978	49.4	0.131 to New York; 0.0909 to Chicago
Houston+	0.520	1.38	37.7	0.218 to Dallas
Los Angeles*	0.553	2.34	23.6	--
Nashville	0.113	0.242	-	--
New York*	1.54	4.83	31.9	--
Orlando	0.108	0.785	-	--
Philadelphia	0.192	0.755	-	--
Pittsburgh	0.363	0.565	-	--
San Francisco+	0.599	1.60	37.4	0.201 to Los Angeles
St. Louis	0.295	0.622	-	--
Washington, D.C.	0.859	1.52	56.5	0.321 to New York; 0.0826 to Chicago

[a]These data represent a 10% sample size and include inbound and outbound passengers. To convert to actual departures, multiply by 10/2. These data are for origin-destination city pairs only. Passengers using a city-pair trip as part of a longer trip (e.g., Detroit to Chicago may be part of a longer trip from Detroit to Los Angeles) are counted in the longer trip-origin and destination-pair only.

[b]Asterisk indicates a subset of six cities that are at least 600 mi apart; cross indicates an additional four cities that require some correction (see last column) to avoid multiple counting.

New York). Multiple counting can be avoided by selecting a subset of hub cities at least 600 mi from each other. That subset, which includes six cities, is indicated by asterisks.

The six-city subset accounted for 37.5% of all passengers traveling 100-600 mi. Expanding the subset to include the four additional cities marked with a cross, and correcting for multiple counting (see last column of Table 6) accounts for 50% of all passengers traveling within the maglev window. Optimizing the maglev network (i.e., selecting one that captures the maximal number of passengers with minimal guideway length) would require relatively sophisticated analyses. However, on the basis of the simple analysis given above, approximately 50% of the market can be represented by 10 hub cities. This subset of cities also contains those airports with the longest delays. Hence, by focusing on those 10 cities, 50% of the market and the key points of systemwide delays can be addressed simultaneously. Substituting maglev vehicle trips for short-haul flights at these major hub airports will therefore reduce delays at other airports feeding into these hub airports.

Based on this analysis, an F_2 value of 0.50 seems quite reasonable. Careful market optimization may lead to a value of 0.60 or higher. Use of the more conservative value (0.50) results in the following reasonable scenario for the year 2010: $F_1 = 0.45$, $F_2 = 0.50$, $F_3 = 0.50$, and $E_{ac} = 2.04$ quads. The value of $F_3 = 0.50$ is based on the assumption that maglev networks connected to the 10 hub cities will be in place in the 2000-20 time frame, while the value of E_{ac} is from projections in Mintz et al. (1987). Estimated value of ΔE is 0.23 quad, which corresponds to slightly more than 11% of the total energy projected for domestic aircraft. The more optimistic market size estimate of F_2 (0.60) leads to a 13.5% savings in domestic aircraft fuel.

Lower Petroleum Use by Reducing Congestion at Airports. As indicated in the previous subsection, a significant reduction in short-haul flights from major hub airports will result in correspondingly significant reductions in flight delays throughout the system. A 50% reduction in passengers traveling in the maglev window corresponds to roughly a 50% reduction in short-haul flights (provided the scheduling of maglev trips and flights is optimally managed). This latter reduction would in turn correspond to at least a 50% reduction in flight delays, especially if flight reductions occurred during rush hours. The percentage would probably be much higher, given the nonlinear dependence of delay time on activity. Furthermore, because of the relationship between delays at the key hub airports (e.g., Denver, Chicago, and Atlanta), a reduction of more than 50% in systemwide delays could reasonably be expected, because delays in key hub airports adversely affect other airports in the national air traffic system.

Reductions in delay translate into shorter aircraft operation time in the taxi/idle mode, which would in turn lead to reduced fuel consumption and reduced air pollutant emissions (see Sec. 3.2). Table 7 shows fuel savings per landing-takeoff cycle, assuming a systemwide 25% reduction in taxi/idle time.

In 1984, the average domestic flight was 761 mi (skewed by many short-haul flights by small aircraft), and total domestic flight mileage was 2.875×10^9 mi (Holcomb, Floyd, and Cagle 1987). There were therefore approximately 3.8×10^6 departures, and the amount of fuel saved annually by a systemwide 25% reduction in taxi/idle time becomes $3.8 \times 10^6 \times 31$ to $110 = 1.2$ to 4.2×10^8 gal. Given that approximately 1.09×10^{10} gal of aircraft fuel was consumed domestically, the potential savings are approximately 1.1-3.9%.

TABLE 7 Potential Fuel Savings and Resulting Drop in Emissions Due to Reduced Airport Congestion

Generic Aircraft Type	Taxi/Idle Fuel Consumption[a] (lb)	Taxi/Idle Fuel Reduction[b] (gal)	Reduction in Air Pollutant Emissions per Landing/Takeoff Cycle[c] (%)		
			CO	HC	NO_x
Jumbo					
Four engines	3013	110	47	48	4
Three engines	2260	83	47	48	4
Long-range	1511	55	49	49	4
Medium-range					
Three engines	1247	46	42	31	6
Two engines	831	31	42	31	6

[a]Fuel consumption per aircraft per landing-takeoff cycle (EPA 1985).

[b]Assumes system-wide 25% reduction in taxi/idle time (EPA 1985).

[c]Assumes 50% reduction in taxi/idle time at major airports only; CO is carbon monoxide, HC is hydrocarbons, and NO_x is nitrogen oxides.

Combining this savings (assuming that the percentage change due to reduced taxi/idle time remains the same in 2010) with that due to displacement of some short-haul flights by maglev vehicle trips leads to a total potential savings of about 12-17%. This analysis does not include savings due to reduced delays in international flights that use the same airport facilities and would be similarly affected by changes in congestion.

Displacement of Highway Vehicle Petroleum Use. A similar estimate can be made for the energy equivalent (ΔE_{pv}) of petroleum-based fuel used by personal vehicles on intercity trips of 100-600 mi. Taking into account differences between business and nonbusiness intercity travel,

$$\Delta E_{pv} = (F_0 \times F_1 \times F_2 \times F_3 \times E_{pv})_{business}$$
$$+ (F_0 \times F_1 \times F_2 \times F_3 \times E_{pv})_{nonbusiness}$$
$$= 0.135 \text{ quad},$$

where:

F_0 = fraction of total energy used for intercity travel for 2010,

F_1 = fraction of intercity passenger miles in 100-600-mi range,

F_2 = fraction of intercity-city personal vehicle travel that could be captured by maglev trips, and

F_3 = fraction of F_2 that would be captured in the 2010-20 time frame.

The following assumptions are made:

- For F_1: business = 0.0604; nonbusiness = 0.509; source is "POINTS" computer model calculation at Argonne National Laboratory.

- For F_2: business = 0.6; nonbusiness = 0.4; source is an assumption.

- For F_3: business = 0.5; nonbusiness = 0.5; source is an assumption.

- E_{pv} = 10.7 quads; source is Argonne National Laboratory projection; source is Mintz et al. (1987).

- F_0 = 0.105; source is Millar et al. (1982).

A small quantity of petroleum also may be saved by reducing highway congestion, but this is not estimated here. Further, petroleum displacements are likely if the maglev vehicles carry high-valued freight. Because freight requires neither the high quality of ride nor the magnetic shielding needed for passengers, lower-cost vehicles could be used to carry containerized freight, parcels, or mail. Such vehicles may be particularly attractive for high-speed transport of perishable goods. While the energy savings associated with freight transport are not estimated here, high-valued, time-sensitive freight is usually transported by energy-intensive modes for which maglev systems could be an energy-efficient alternative.

Energy Intensity Comparisons. Figure 4 shows the energy intensities (in Btu/seat-miles [Btu/SM]) of various transportation modes. All vehicles are fully loaded, and all data are for cruise only except for Amtrak, Rail Transit, and simulated runs, for which actual route data were used. Energy intensity (EI) values for maglev vehicles are calculated by

$$EI = \frac{P \times 3.41 \times 10^6}{V \times N \times \eta_{PCU} \times \eta_{LSM}}$$

where:

EI = energy intensity (Btu/SM),

P = required output tractive power (MW),

V = cruising speed (mi/h),

N = number of passengers (i.e., 145 for Canadian_1, 276 for Canadian_2, and 192 for German TR06-2),

η_{PCU} = efficiency of power conditioning unit at wayside substation,

η_{LSM} = efficiency of linear synchronous motor, and

$P = V \times F_D \times 2.78 \times 10^{-4}$, where F_D is total drag force in kN (i.e., aerodynamic plus electrodynamic) at speed V.

The values of F_D are from Hayes and Tucker (1984) for the Canadian vehicles, from Miller (1987) for the TR07 vehicle, from Ford Motor Co. (1975) for the Ford maglev, from Kolm (1988) for the Magneplane, and from estimates based on data obtained from Tanaka (1988) and Japan Railway (1988) for the Japanese vehicles. For the Canadian vehicles, the published value of η_{LSM} is 0.75, and the value of η_{PCU} was assumed to be 0.85. These same values are used for the Magneplane and for the Ford vehicle driven by a linear synchronous motor (LSM). For the Japanese vehicles, the values, $N_{LSM} = N_{PCU} = 0.925$ were used (from Tanaka 1988). For the German vehicle, the values of η_{LSM} and η_{PCU} were assumed to be 0.75 and 0.80, respectively. The power conditioning unit contains a step-down transformer and a solid-state power electronics package that includes rectifiers, frequency converters, switching circuitry, and equipment for power-factor correction. Published LSM power factors for the Canadian vehicles (1 and 2) are 0.93 and >0.90 at cruising speed, respectively (Hayes and Tucker 1984).

The power factor at cruising speed was not available for the German TR07. It is assumed to be lower than that for the Canadian vehicles because the lower field strength available in the attractive-force levitation system generally results in a larger lagging reactive power term in the long-stator circuit of the LSM. This in turn requires more power factor correction and therefore greater losses in the power conditioning unit for the attractive-force system. Also, acceleration of the TR07 vehicle (0.03 to 0.07 g) is significantly lower than that of the conceptual Canadian vehicles (0.1 g).

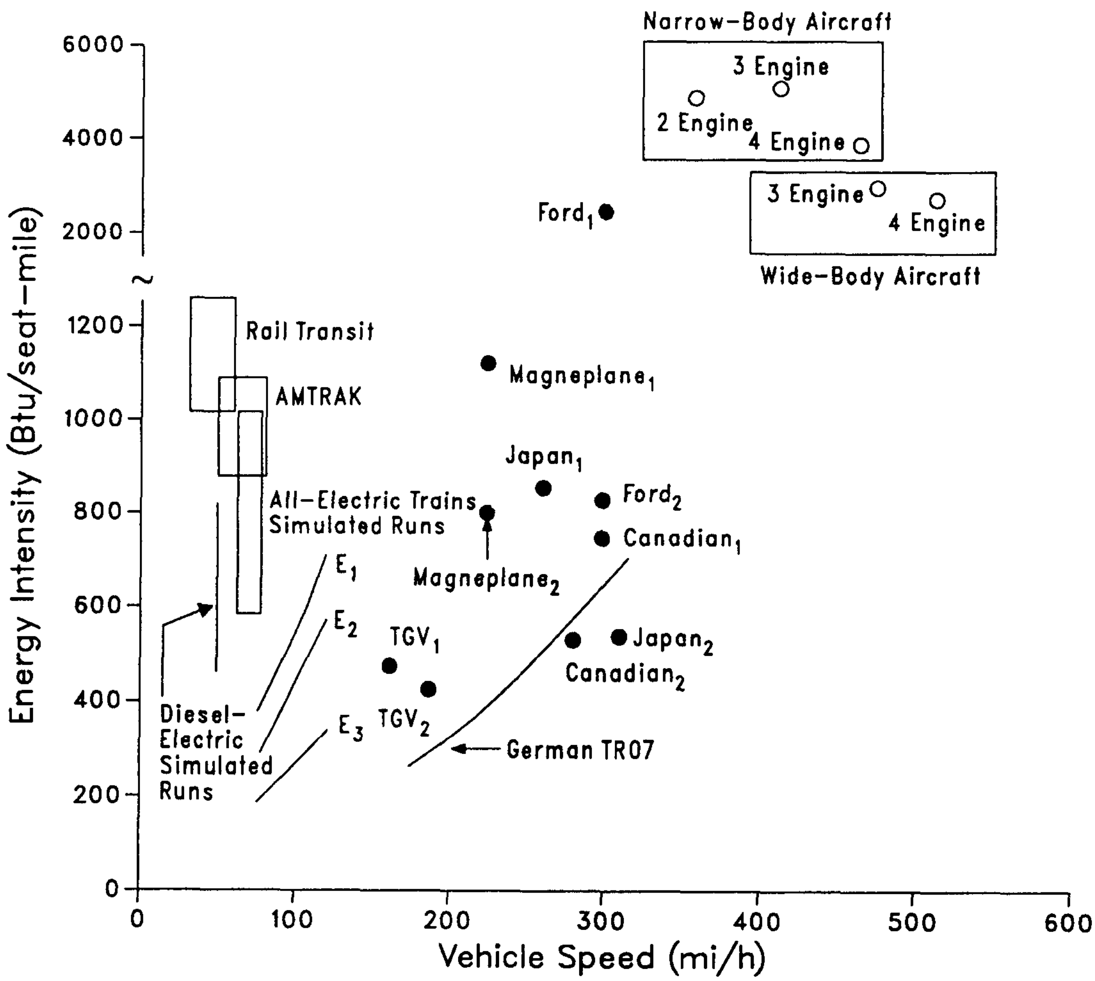

FIGURE 4 Energy Intensities of Alternative Transportation Modes, Based on Fully Loaded Vehicles (thermal efficiency of diesel engines and efficiency of electric power generation and distribution not included) (see sources below)

All-electric trains simulated runs, New York-Washington route (Mittal 1977).
AMTRAK, 1984 data (Holcomb et al. 1987).
Canadian$_1$ and *Canadian$_2$*, first- and second-generation conceptual designs, respectively, of Canadian maglev train (Hayes and Tucker 1984).
Diesel-electric simulated runs, trains over New York-Albany route (Mittal 1977).
E_1, *E_2*, and *E_3*, respectively a French CC14500 consist, a standard metroliner consist, and a General Electric E60CP consist, all cruise only (Mittal 1977).
Ford$_1$ and *Ford$_2$*, respectively a 140-passenger design propelled by noise-suppressed ducted fan driven by gas turbine and an 80-passenger design propelled by an LSM (Ford Motor Co. 1975).
German TR07 Transrapid prototype revenue maglev train, cruise only (Miller 1987).
Japan$_1$ and Japan$_2$, respectively the MLU002 vehicle being tested at Miyazaki test track (Kyotani 1988b) and a hypothetical six-car maglev "train" using Miyazaki technology (Japan Rolling Stock Exporters' Assn. 1988).
Magneplane$_1$ and *Magneplane$_2$*, 100-passenger and 140-passenger versions, respectively, of Kolm and Thornton's proposed design (Kolm 1988, 1989).
Rail transit, 1984 data (Holcomb et al. 1987).
TGV$_1$ and *TGV$_2$*, respectively the original Train à Grande Vitesse (TGV Co. 1987) and the Atlantique version (Alsthom Co. 1988), both cruise only.

Because short-haul aircraft expend most of their trip energy for ground operations and airborne operations other than cruising at altitude, a more meaningful comparison between various transportation modes should be made for a trip of a given length. For the hypothetical 300-mi trip, a load factor of 0.6 is assumed. The EI for the TR07 vehicle is 689/0.6, or 1,150 Btu/PM at 310 mi/h (Table 8). If the efficiencies of electric power generation ($\approx$35%) and electric power transmission to the substation ($\approx$95%) are considered, net energy intensity (EI_N) is 3,450 Btu/PM.

Table 5 shows that the EI for a commercial airline flight of 300 mi is approximately 5.5×10^3 Btu/SM. Using a load factor of 0.6 results in an EI value of 9,170 Btu/PM. Data in Table 3 show that the EI for personal highway vehicles is projected to be about 1,935 Btu/PM by 2010. Hence, maglev vehicles consume about 30% of the energy of a short-haul flight and about 160% of the energy of a personal highway vehicle, on a PM basis. If electric power plant and transmission line losses are excluded from the calculation, the percentages are 12% and 60%, respectively. Results of this analysis are summarized in Table 8 for reader convenience.

Summary of Petroleum-Based Fuel Savings. The savings in petroleum-based fuels (and energy equivalents) are summarized in Table 9.

3.2 AIR POLLUTANT EMISSIONS IMPACTS

Reduced aircraft taxi/idle time due to lessened airport congestion also reduces air pollutant emissions from aircraft near airports. Because carbon monoxide (CO) and hydrocarbons (HCs) are emitted predominantly during taxi/idle, a 50% reduction in ground time at major airports reduces these near-airport emissions by almost 50% (see Table 7). Nitrogen oxides (NO_x), on the other hand, are emitted primarily at high engine thrust settings, e.g., during takeoff, so that a NO_x reduction of only about 18% accompanies a 50% reduction in aircraft ground time (taxiing and idling). Emissions of CO, HC, and NO_x are further reduced because some short-haul flights are replaced by maglev trips; these emission reductions are in direct proportion to the number of flights eliminated at the hub and spoke airports and are the same for all three pollutants. Further reductions in emissions are expected because of reduced highway congestion and displacement of some highway trips by maglev vehicle trips. These reductions were not estimated.

On the other hand, because fossil fuels account for approximately 70% of the energy consumed by electric utilities, emissions (primarily sulfur oxides [SO_x] and NO_x) from fossil-fuel central stations will likely increase. Of course, these emissions can be controlled more easily than can those from myriad small mobile sources. Moreover, pollutants emitted from mobile sources contribute to local air quality problems such as high CO levels and photochemical smog in urban areas, whereas central stations contribute to large-scale problems such as acid rain and the greenhouse effect.

TABLE 8 Energy Intensity Comparison for a 300-mi Trip with a Load Factor of 0.6[a]

System or Mode	Cruising Speed (mi/h)	Energy Intensity (Btu/PM) Base	Net[b]
West German TR07 Maglev	310	1,150	3,450
Canadian second-generation maglev	280	890	2,680
Japanese MLU002 maglev test vehicle	260	1,420	4,260
Japanese six-car maglev revenue train	310	890	2,680
Magneplane (MIT)	225	1,340	4,020
Ford Motor Co. Maglev			
Base case (80-pass)[c]	300	5,540	6,250
Modified (140-pass)[c]	300	4,190	4,730
3-Car train[c]	300	3,380	3,810
Base case with LSM	300	1,390	4,180
Aircraft	400-500	9,170	10,300
Personal highway vehicle[d]	65	1,940	2,190

[a]Data are for cruising only, except for aircraft, which include all gate-to-gate operations.

[b]Includes power generation and transmission efficiencies for electricity, foreign crude oil shipment, and petroleum refinery efficiencies.

[c]Uses gas-turbine-driven, noise-suppressed ducted fan for propulsion.

[d]Assumed efficiency = 32.3 mi/gal.

TABLE 9 Summary of Energy and Fuel Savings Associated with Maglev System Implementation

Reduction[a]	Energy (quad)	Fuel Savings (%)
Aircraft fuel demand		
Replace 25% of short-haul flights	0.23	11.25
Replace 30% of short-haul flights	0.28	13.50
Cut taxi/idle time by 25% due to reduced airport congestion	--	1.1-3.9
Net petroleum (estimate)	--	≈12-17
Highway vehicle fuel	0.13	1.26

[a]All values are for 2010, except that reduced airport congestion is calculated from 1984 figures.

3.3 ECONOMIC POTENTIAL

The conventional practice in analyzing the economic viability of high-speed ground transportation has been to compare alternative ground transportation systems (e.g., steel-wheel and maglev systems). Section 3.3.1 reviews the relative costs and performances of three types of alternative ground transportation systems: (1) intermediate-speed rail systems, (2) very-high-speed rail systems (Shinkansen and TGV), and (3) maglev systems (both EMS and EDS). The financial analysis is based on train economics, i.e., a system of physically linked vehicles traveling between central business districts of cities. Rarely have maglev vehicles been compared with aircraft for the types of trips in which maglev systems are competitive or substitutable. Section 3.3.2 examines the economic implications of integrating maglev systems into the airline networks rather than replacing conventional rail passenger systems.

3.3.1 Review of Previous System Cost Studies

Intermediate-speed U.S. rail systems are usually diesel-powered and share track with other trains. In most cases, intermediate-speed rail systems use existing track and signal systems that have been upgraded to allow for higher speeds. Such systems realize average speeds of 70-90 mi/h, depending on the number of stops, and top speeds of more than 100 mi/h. High-speed rail systems are generally electric-powered and may use dedicated tracks. Their top speeds are 120-130 mi/h. Very-high-speed rail systems are powered by electricity, use dedicated tracks, and offer higher average speeds (100-160 mi/h) and top speeds of 185 mi/h.

Maglev vehicles can achieve speeds rivaling short-haul aircraft; depending on the technology, cruising speeds are estimated to be 200-300 mi/h. Tables 10-12 summarize cost and performance of high-speed rail, very-high-speed rail, and maglev systems, for both actual and proposed systems. All of these systems have high capital costs, 80% or more of which are related to the track or guideway and power delivery. The vehicles themselves account for only a small fraction of total costs. Capital costs for the high-speed rail system range from $2.5 to $6.6 million per mile, depending on the required upgrading of track. Very-high-speed systems are more capital-intensive, with costs ranging from $4.7 to $29.3 million per mile.* The high end is represented by the Tokyo-Osaka line, which employs the Shinkansen technology. For this line, the Japanese prefer construction of a near-level roadbed, which requires many tunnels. The maglev systems are projected to have costs comparable to those of very-high-speed rail systems, but these costs are much more uncertain because designs for revenue service systems have yet to be finalized and tested.

Operating costs are in three categories: (1) guideway and vehicle maintenance, (2) power, and (3) miscellaneous items such as insurance, ticketing, and vehicle crews. For wheel-on-rail systems, these categories are approximately equal in magnitude. As speed increases, track and vehicle maintenance costs rise rapidly because of the need for tighter track tolerances and the increase in dynamic forces between the wheel and track. Because of heavy traffic and unstable ground conditions, the Japanese Shinkansen system requires a crew of about 1,000 working daily from midnight until 5:00 a.m., checking and realigning the rails (Kyotani 1988).

In contrast, both types of maglev systems should have much lower guideway and vehicle maintenance costs despite their much higher speeds. On the basis of test track experience, these costs are anticipated to be 25-50% lower for the Transrapid system than for wheel-on-rail systems. Because of their greater track clearances, softer primary suspensions, and lower vehicle weights, EDS systems should have even lower guideway and vehicle maintenance costs, especially in areas subject to frequent earth tremors. However, these projected costs savings have yet to be demonstrated for a near-revenue-service prototype vehicle.

Power is consumed in accelerating, climbing grades, and overcoming rolling resistance (or magnetic drag, in the case of maglev systems) and aerodynamic drag (which dominates at very high cruising speeds). Because aerodynamic drag is proportional to the square of vehicle velocity, a Transrapid vehicle cruising at 250 mi/h would be expected to have nearly 80% more aerodynamic drag than a TGV vehicle cruising at 186 mi/h, provided the vehicles were aerodynamically equivalent. Actual energy consumption also depends on the magnitude of the other components of tractive resistance, as well as on vehicle design, the time spent accelerating, climbing grades, and cruising, and the extent to which regenerative braking is used.

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*Considerable caution is required in extrapolating the costs of foreign systems to U.S. corridors. For example, the dramatic decline in the dollar relative to the yen in the past two years has given the appearance of a doubling in the costs of the Japanese technologies, which is not an accurate reflection of the costs.

TABLE 10 Cost and Performance of Intermediate-Speed Rail Systems (Metroliner)

System	Route	Distance (mi)	Average Speed (mi/h)	Annual Ridership (10^6 round trips)	Cost (1987 $) Vehicle Unit ($\$10^6$)	Capital ($\$10^6$/mi)[a] Guideway	Total	O&M (¢/PM)	Revenue (1987 $) ¢/PM	Per $ Invested (¢)
Actual										
Amtrak	Boston-New York-Washington, D.C.	456	70	1.3	NA[a]	NA	6.6	13.7	18.3	7.2
Proposed										
Amtrak	Chicago-St. Louis	282	80	0.7	10.2	2.0	2.6	10.9	17.0	9.0
Amtrak	Chicago-Detroit	279	77	0.7	10.2	2.0	2.6	9.0	14.9	7.7
Amtrak	Chicago-Milwaukee	85	88	0.2	10.2	1.6	2.5	24.0	28.8	5.3

[a]NA = not available.

Sources: Actual data from Thompson (1986); proposed route data from Baer et al. (1984).

TABLE 11 Cost and Performance of Very-High-Speed Rail Systems

System	Route	Distance (mi)	Average Speed (mi/h)	Annual Ridership (10^6 round trips)	Cost (1987 $) Vehicle Unit ($\$10^6$)	Capital ($\$10^6$/mi)[a] Guideway	Total	O&M (¢/PM)	Revenue (1987 $) ¢/PM	Per $ Invested (¢)
Actual										
TGV	Paris-Lyon	265	100	9.3	NA[a]	NA	7.3	2.9	8.0	20.3
Shinkansen	Tokyo-Osaka-Hakata	668	130	19.6	NA	NA	29.3	8.0	14.5	19.4
Proposed										
Shinkansen	Los Angeles-San Diego	132	127	6.8	NA	NA	27.0	5.8	30.6	15.4
TGV	Los Angeles-Las Vegas	230	160	3.0	15.1	6.8	9.8	5.2	14.2	8.7
TGV	Chicago-Detroit	279	95	0.7	10.2	4.4	5.3	11.9	20.7	5.3
TGV	Chicago-St. Louis	282	100	0.7	10.2	4.4	5.2	12.9	16.9	4.8
TGV	Chicago-Milwaukee	85	113	0.2	10.2	3.6	4.7	29.0	33.3	3.4
TGV	Tampa-Orlando-Miami	314	123	0.7	NA	NA	9.4	16.0	21.5	3.2

[a]NA = not available.

Sources: Actual data for Shinkansen and TGV (Tampa-Orlando-Miami) proposed system from Thompson (1986); TGV (Los Angeles-Las Vegas) system from CIGGT (1986); remaining TGV estimates from Baer et al. (1984).

TABLE 12 Cost and Performance of Proposed Maglev Systems

System	Route	Distance (mi)	Average Speed (mi/h)	Annual Ridership (10^6 round trips)	Cost (1987 $): Vehicle Unit ($\$10^6$)	Cost (1987 $): Capital ($\$10^6$/mi)[a] Guideway	Cost (1987 $): Capital ($\$10^6$/mi)[a] Total	Cost (1987 $): O&M (¢/PM)	Revenue (1987 $): ¢/PM	Revenue (1987 $): Per $ Invested (¢)
Transrapid[a]	Los Angeles-Las Vegas	230	184	3.6	17.7	6.5	10.3	4.3	28.3	6.3
Transrapid	Los Angeles-Las Vegas	230	184	3.6	20.4	7.7	12.2	5.0	28.3	5.3
Transrapid	Chicago-Detroit	279	152	0.7	20.5	9.4	11.1	11.4	26.4	3.3
Transrapid	Chicago-St. Louis	282	160	0.8	20.5	9.4	11.0	12.3	25.3	3.5
Transrapid	Chicago-Milwaukee	85	175	0.7	20.5	6.0	8.9	18.8	19.6	3.2
Transrapid	Tampa-Orlando-Miami	314	196	0.7	NA[b]	NA	17.0	18.7	23.0	2.0
Attractive	Boston-New York-Washington, D.C.	438	NA	20	NA	27.2	29.3	NA	NA	NA
Repulsive	Boston-New York-Washington, D.C.	465	NA	17	4.0	10.5	11.7	7.1	NA	NA
Repulsive	Toronto-Ottawa-Montreal	375	NA	NA	NA	NA	24.3	NA	NA	NA
Repulsive	Japan	NA	≈250	NA	4.6	NA	18.5-30.8	NA	NA	NA

[a]EMS (attractive-force) system.

[c]NA = not available.

Sources: Transrapid Los Angeles-Las Vegas data from CIGGT (1986); Transrapid Chicago-Detroit, Chicago-St. Louis, and Chicago-Milwaukee data from Baer et al. (1984); Transrapid Tampa-Orlando-Miami data from Thompson (1986); attractive-system Boston-New York-Washington, D.C., data from Iwasa (1973); repulsive-system Boston-New York-Washington, D.C., data from Ford Motor Co. (1975); repulsive-system Toronto-Ottawa-Montreal data from Eastham (1988); and repulsive-system Japan data from Cirillo (1987).

Both the French TGV and German Transrapid systems were analyzed in detail for the Las Vegas-southern California corridor. Normalized for number of passengers carried, Transrapid power costs were only 31% greater than those for the TGV. Thus, for both systems operating at the same speed, power consumption by the Transrapid system could be up to 26% lower than that by the TGV system (CIGGT 1986).

Because of the EDS system's more efficient superconducting magnets, lower weight potential, and greater track tolerances, its energy consumption at 300 mi/h may be about the same as that of the EMS system at 240 mi/h. However, these conclusions depend on the final EDS design and in particular on the level of shielding required to reduce magnetic fields in the passenger compartment.

Because the various systems are similar in nature, miscellaneous costs per passenger for attractive and repulsive maglev systems are projected to be comparable. Thus, total operating costs per passenger-mile are projected to be 5-20% lower for the maglev system than for the comparable TGV system (CIGGT 1986). These conclusions for the maglev systems are based on projections from test-track data, whereas the TGV values are based on revenue-service data. However, the maglev system cost estimates were multiplied by a higher contingency factor to reflect the greater uncertainty associated with maglev system test data that are extrapolated to revenue-service systems.

Ridership has the single greatest effect on system economics. A simple example illustrates this maxim. The two train routes with the best financial performance in the world are the Tokyo-Osaka route with 20 million annual round-trip passengers and the Paris-Lyon route with slightly more than nine million. Both of these routes have experienced greater-than-expected ridership growth. There was a shift from other modes of travel, such as automobiles and airplanes, but there was also an increase of 10-30% in total travel (induced travel) along both corridors.

High-speed rail projects have been very successful in Europe and Japan. In the United States, however, even simple upgrading of rail systems has been difficult, and the passenger rail system, with few exceptions, is in a state of decline. The differences are due in part to demographics. Large cities in the United States are farther apart than large cities in Europe and Japan, and the United States has extensive interstate highways and an air system that greatly surpass those in Europe and Japan. In most industrial countries, fuel prices are two to three times higher than those in the United States, and intercity travel prices are often fixed by the government in favor of train service. These factors combine to cause train projects in the United States to be viewed with skepticism. Because a typical project will run into billions of dollars and because the ability to recover this capital plus a fair rate of return requires very high ridership, it is not surprising that no very-high-speed rail project has yet been undertaken here.

Several other factors work against such projects. First, Japanese projects are financed up to 90%, primarily with long-term debt. In contrast, U.S. projects are financed much more heavily with equity, which results in adverse tax consequences. Debt financing accounts for 50% of the borrowing in investor-owned utilities but only 30% in other industries. Second, recent tax law changes further penalize capital-intensive projects. The new tax law eliminates the investment tax credit, which was worth 10% of capital investment. Tax depreciation rates are also less favorable. Third, use of state-issued tax-exempt bonds has been curtailed. Previously, such bonds could greatly reduce financing costs. On a more favorable side, the Technical Corrections Act of 1988 gave high-speed ground transportation projects access to financing through tax-exempt industrial revenue bonds.

Despite the treatment of maglev technology as train technology, the economic analysis of the Las Vegas-southern California route (the U.S. corridor that has been analyzed in greatest detail) found that both maglev technology and very-high-speed steel-wheel technology would yield a reasonable return on investment. The Canadian Institute of Guided Ground Transport examined detailed cost data and ridership projections for both a Transrapid maglev system and a TGV train. Although the maglev system was estimated to have 25% higher capital cost, its higher speed produced 21% more ridership. In addition, its operating and maintenance costs were estimated to be 48% lower than those of the steel-wheel train. As a result, the two technologies had similar returns on investment over a 20-year period. The return was more favorable for the steel-wheel system in the early years because of lower capital costs, but then became better for the maglev because of its greater long-term ridership.

A second independent review of the Las Vegas-southern California route was made by Robert J. Harman & Associates (1987). The conclusion was that a "super-speed, ground transportation system" such as a maglev system was financially feasible. Such a project "is capable of generating sufficient revenue to (1) fully support operating costs; (2) repay capital costs, including credit enhancement; (3) provide for future maintenance and equipment replacement; and (4) provide an attractive long-term return on investment to the franchise and associated stockholders," according to the Harmon report.

3.3.2 Potential Economic Effects of Marketing Maglev Systems as Aerospace/Airline Technology

The problem of maglev system use in the United States is not so much the technology but how it is applied. U.S. intercity transportation problems concern (1) growing congestion at major airports and on highways, (2) impending higher air fares due to limits on expansion of air service, and (3) continued dependence on imported petroleum for transportation. A potential solution to these concerns is seen when maglev is treated as an aerospace/airline technology.

Many airline flights are short-haul trips that connect smaller airports to major hubs. For example, about 25 daily flights connect Chicago's O'Hare airport and Milwaukee, about 45 operate between O'Hare and St. Louis, and 50 link O'Hare and Detroit. All of these flights are under 300 mi; in fact, about 50% of all flights to O'Hare are under 500 mi. Such flights tend to be very inefficient because the aircraft spend a large fraction of their time taxiing, climbing, and descending. Fuel, time, and money are wasted, and the flights also tie up takeoff and landing slots and gate positions at busy airports. Maglev vehicles offer a partial solution for the airport capacity problem. At 300 mi/h on connecting or feeder routes, maglev vehicles could provide airport-to-airport service that is comparable to that provided by conventional airline service, thereby freeing airport slots.

Maglev vehicles can be modular, with each car containing its own levitation magnets that also serve as the vehicle-borne components of the linear synchronous motors for propulsion. The Japanese are developing EDS as an advanced train technology; each train would comprise 14 cars and carry a total of 950 passengers. Except in the most densely U.S. populated corridors, this train approach would be inflexible and consequently inefficient.

An alternate approach would be the use of smaller, unlinked (single) vehicles seating 100-150 passengers. With vehicles of this size (similar to mid-size commercial aircraft), maglev systems could be integrated into airport operations, as illustrated in Fig. 5. The relatively lightweight guideway would also mean minimal disruption to the existing infrastructure around airports. Each vehicle would be scheduled for point-to-point service. Off-line loading and unloading at intermediate stops would allow both express and local service without affecting the speed of long-distance vehicles. The smaller vehicle size would minimally affect per-passenger capital costs because vehicle cost tends to be a relatively small component of total system costs. Operating costs, however, may increase somewhat with unlinked vehicles, and the cost changes would have to be balanced against the potential for increased revenue with a more flexible system.

As an airline technology, maglev could generate ridership above that of an aircraft-only system because it can be integrated into the airport infrastructure and also serve destinations that the aircraft cannot (i.e., downtowns and other high-density employment areas). Airlines using a maglev system for short-haul trips would have a strong incentive to switch all of their short-haul flights in the corridor to the maglev system. By doing so voluntarily, they could retain their airline fare structure. Although fares are extremely competitive, airline fares are still significantly higher than railroad fares in most corridors.

3.3.3 Corridor Illustration of Maglev Economics

Although a detailed revenue-cost study is beyond the scope of this report, an illustrative example can help determine whether maglev technology appears promising and therefore worth further examination. The 275-mi-long Chicago-Detroit corridor was chosen to illustrate the differences between airline and railroad approaches to marketing maglev technology.* This analysis highlights the important parameters affecting ridership and profitability and can be used to evaluate the potential for costs or revenues as they may be perturbed positively or negatively.

The Chicago-Detroit corridor has about 500,000 round-trip airline passengers annually whose origins and destinations are these two metropolitan areas. Our analysis of available seat-miles indicates that an additional 1.3 million passengers fly this route, but their origins or destination are beyond the two metropolitan areas. Data from the

*This corridor was examined because of ready data availability. Other corridors, especially on the east coast, should have more favorable economics for maglev systems because of the greater concentration of large cities on the routes.

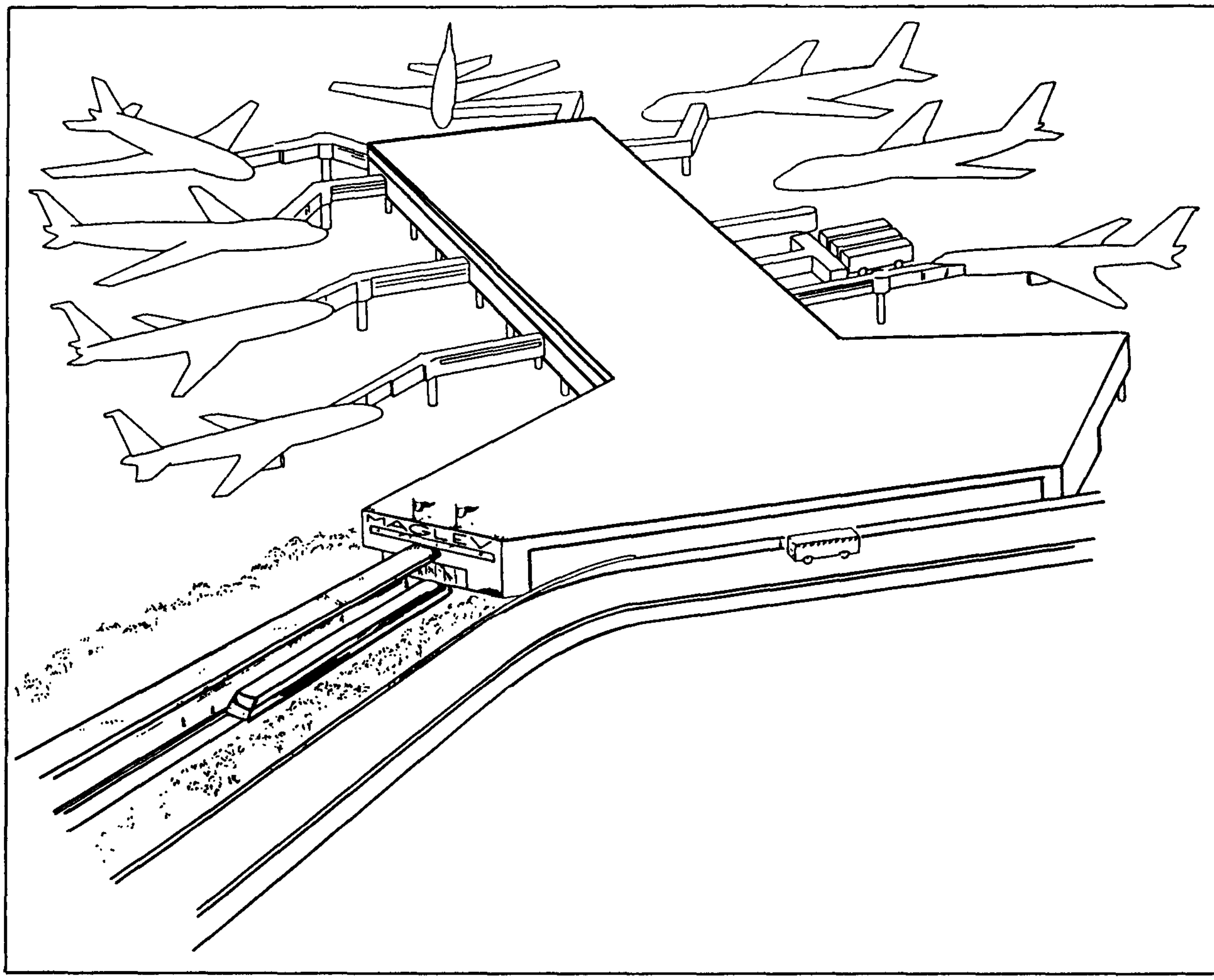

FIGURE 5 Integration of a Maglev System into an Airport

most recent national intercity travel survey (U.S. Dept. of Commerce 1979) reveal that, for trips of this distance, about 10 car-person trips are made for each air trip. These data indicate that about five million people take round trips by auto annually; passenger train travel accounts for about 100,000 trips per year. Table 13 summarizes the travel data and our projections.

The decision to build a new transportation project -- whether a highway, airport, or even a maglev system -- is not based solely on existing use, but rather is determined by expected long-term use. Systems requiring major capital investments should be examined over a 20- to 30-year period, or even longer. Total U.S. air travel is expected to increase by 90% by 2000 (Table 2); forecasting beyond this period is difficult. To keep our analysis conservative, we assume that air traffic grows at a slower annual rate during 2000-20, that is, at a 2.4% annual rate, rather than a 4.5% annual rate. Similarly, highway travel in the corridor is expected to continue growing at an annual rate near 2.7% until 2000; it is then assumed to increase at 1.7% annually until 2020. Conventional train travel is assumed to increase by 20% by 2000, a rate that reflects the growth in the corridor since 1980. Between 2000 and 2020, rail passenger travel is assumed to grow at a reduced rate of about 10%.

TABLE 13 Ridership and Economic Projections for Chicago-Detroit Corridor

Item	Intercity Travel (round-trips)			Maglev Integrated into Airline Network			Maglev as Upgraded Train Service		
	1985	2000[a]	2020[a]	1985	2000	2020	1985	2000	2020
Round-trip passengers (10^3)									
Air									
Chicago-Detroit (origin-destination)	500	950	1,520	400	760	1,220	200	600	1,000
Part of longer air trip	1,300	2,500	4,000	1,040	2,340	3,200	-	260	410
Train	100	120	130	100	120	130	100	120	130
Auto	5,000	7,500	10,500	500	750	1,050	750	1,125	1,575
Total Corridor Trips	6,900	11,070	16,150						
Maglev trips diverted from other modes	--	--	--	2,040	3,630	5,600	1,050	2,105	3,115
Induced maglev travel	--	--	--	306	545	840	160	315	470
Total maglev trips	--	--	--	2,346	4,175	6,440	1,210	2,420	3,585
Round-trip fare (constant $)	--	--	--	150	150	150	120	120	120
Revenue (constant $\$10^6$)	--	--	--	352	626	966	145	290	430
Financial analysis at $15 million/mi system costs (constant $\$10^6$)									
Capital recovery (10%/yr)	--	--	--	410	410	410	410	410	410
O&M costs (at $0.07/PM)	--	--	--	90	160	248	47	93	138
Total costs	--	--	--	500	570	658	457	503	548
Profit/loss	--	--	--	-148	56	308	-312	-213	-118

[a]Air traffic projections reflect the FAA forecast of a 90% increase in demand by 2000; growth is assumed to decline to 60% over the next 20 years. Passenger train demand is assumed to increase by 20% by 2000, but then level off to slightly less than 10% by 2020. Auto travel is expected to rise at a 2.7% annual rate until 2000; an assumed decline to less than 2% is used for 2000-10.

Sources: Chicago-Detroit air projection based on Air Transport Assn. of America (1985); 1985 train round-trip estimate and projections developed by Argonne National Laboratory, based on 1987 datum of 305,000 one-way trips between Chicago-Detroit-Toledo provided by Lanman (1988); part-of-longer-air-trip projection based on Argonne National Laboratory estimate of air traffic using available-seat-mile data; auto projection estimated from modal splits for trips in this distance range from 1977 National Transportation Survey data (U.S. Dept. of Commerce 1979).

Five airlines serve the Chicago-Detroit corridor, but three dominate the service by carrying 80% of the traffic. If these three airlines decided to substitute maglev vehicles for aircraft, 80% or more of the airline passengers could be diverted to maglev transport, carrying those traveling only between Chicago and Detroit and also those going beyond those points.

As either a train system or airline technology, a maglev system would likely replace all existing and future rail passenger service. Continuing subsidies of conventional train service would be highly unlikely. Highway trips would decline only slightly, e.g., 10%. Travel time would be reduced from five hours to one, but the pricing structure would still be important. Perhaps 10% of all highway trips could be shifted to the maglev system. Further, new transportation service, whether expressway links, airline service, or high-speed ground transportation, causes induced travel, i.e., that stimulated beyond the level that would exist without the new service. In the cases of the Shinkansen and TGV, induced (or new) travel accounted for 10-30% of total trips. Induced travel could add substantially to economic attractiveness because the cost of the incremental service is low (this is because the system's highest-cost item, the guideway, would already be substantially in place). Table 13 also shows the effects of 15% induced travel in ridership, revenue, and costs. This level of ridership would put the total number of maglev round trips at about 2.3 million annually if service were available in 1985. An average maglev system round-trip fare of $150 -- similar to the current, unrestricted airline fare not dependent on limited seat availability -- would generate revenues of about $350 million.

Implementation of a maglev system, i.e., construction and/or operation via private venture, public enterprise, or joint public/private partnership, has a major impact on economic feasibility. If the system can largely utilize portions of interstate highway rights-of-way (see discussion below), one plausible approach would be for the federal government to build the system and charge user fees to fully recover both capital and operating costs. System operation would be controlled at a central station, similar to that for aircraft but with substantially greater precision. Several alternative methods of financing and implementation are also possible. One approach, being used in Florida (see Sec. 2.3.1), would permit limited development rights around the stations to be assigned to the private-sector group that builds the system. This would substantially reduce the risks to the innovators and allow them to capture some of the external benefits that their transportation system would provide.

A maglev system (based on comparable Transrapid costs in the Las Vegas-southern California corridor of $15 million/mi for a complete double-track system with vehicles and stations) for the Chicago-Detroit corridor would cost about $4.1 billion. A capital recovery rate of 10% would require revenues of $410 million annually to cover the fixed expenses of loan repayment, taxes, and return to stockholders. Operating expenses for maglev systems are expected to be about of $0.05-0.10/PM; an average expense of $0.07/PM (using the Ford analysis of maglev systems) would result in operating costs of about $90 million annually. Total annual expenses for service at the present time would be about $500 million. Consequently, a maglev system available now at these costs would likely incur a significant annual loss. However, if the maglev system could be built for $10 million/mi, as some experts consider possible by minimizing guideway costs through use of lightweight EDS vehicles, this corridor would break even with current traffic under these same economic conditions. The addition of cargo revenues (high-valued, time-sensitive items currently transported by airlines) would further enhance the near-term financial picture.

Although traffic density in the corridor appears insufficient under present ridership and the higher cost conditions to support a maglev system, travel growth in the corridor makes a revenue-sustaining maglev system probable within the planning horizon being examined. By 2000, a maglev system integrated into the airport/airline network could have annual ridership of more than 4.2 million, which should make the system profitable, even using relatively high capital costs; this is an important conclusion, given that a maglev system for this corridor would not likely be available until then. Because maglev systems are capital-intensive, continued ridership growth increases revenue faster than operating costs; by 2020, a maglev system should be comfortably profitable, even if some of the assumptions had been overly optimistic.

If implemented as an upgraded railroad technology, maglev does not look as promising because of two important considerations. First, a maglev train system would compete with the airlines. Travel times would be comparable but because airlines are the established and dominant common carrier, the maglev train would have to offer lower fares to attract riders away from the airlines. In this example, a maglev train fare of $120 round-trip is used, which is 20% lower than the maglev fare as an airline system, but more than two-and-one-half times the present conventional train fare of $45. Second, and more important, maglev train systems using existing downtown train stations would not have access to the significant market of airline passengers traveling beyond Chicago and Detroit. Even assuming that maglev trains could take 60% of the airline market in the corridor and provide a shuttle service that would eventually gain them 10% of the connecting flights, total ridership as a train system would be only about two-thirds of its potential if maglev was integrated into the airline network. This is true even if the lower fare allows greater diversion of highway trips to maglev, assumed in this example to be 15% instead of 10%. Consequently, maglev as a railroad system, without access to the airline market, does not appear to be revenue-sustaining within the planning period unless system costs could be reduced significantly.

This corridor illustration highlights the importance of several parameters. First, traffic density is extremely important. Current traffic in this corridor is unlikely to be sufficient to make a maglev system profitable unless system costs could be substantially reduced. This may well explain the current reluctance by the transportation industry to include maglev systems in its planning. Yet, traffic in this corridor at present and in the foreseeable future appears sufficient to warrant closer examination of maglev potential. Because maglev technology is capital-intensive, research and development should be oriented toward designs that minimize or reduce system costs, especially capital costs for the guideway. Second, by combining the best attributes of both air and ground transportation, maglev technology should have significantly higher ridership than the air mode or the train mode developed independently. Third, ticket price is obviously important because fares that are too low would not cover costs, while fares that are too high would discourage ridership. Maglev systems integrated into airline networks allow revenue maximization while minimizing adverse effects on ridership potential.

The Chicago-Detroit maglev system could also provide additional service to intermediate cities such as Gary, Benton Harbor, Battle Creek, Kalamazoo, Jackson, and Ann Arbor, all of which have substantial populations. By using off-line loading and unloading at these other cities, the high-speed, nonstop service between Chicago and Detroit would not be impeded but additional revenue would be generated for the system at low incremental costs.

Adding the intermediate cities to the maglev network affects two types of travel. First, it provides additional feeder service, which could substitute for existing or potential aircraft flights. Second, the development potential in these cities (or even new cities) is significantly enhanced as travel time becomes comparable to that of a commuter system. For example, travel time from Battle Creek to either Chicago or Detroit would be about 30 minutes, similar to a typical suburban commute today. This additional ridership, either as airport feeder service or commuter service, was not considered in the Chicago-Detroit illustration. But both induced travel and intermediate city service could be important in improving the economic attractiveness of the system.

Three additional aspects of maglev implementation deserve further consideration. First, capital costs can be substantially lower if the guideway is built along existing interstate highways (Fig. 6). This multiple use of existing rights-of-way would not only reduce costs, but would minimize dislocations and environmental impacts.

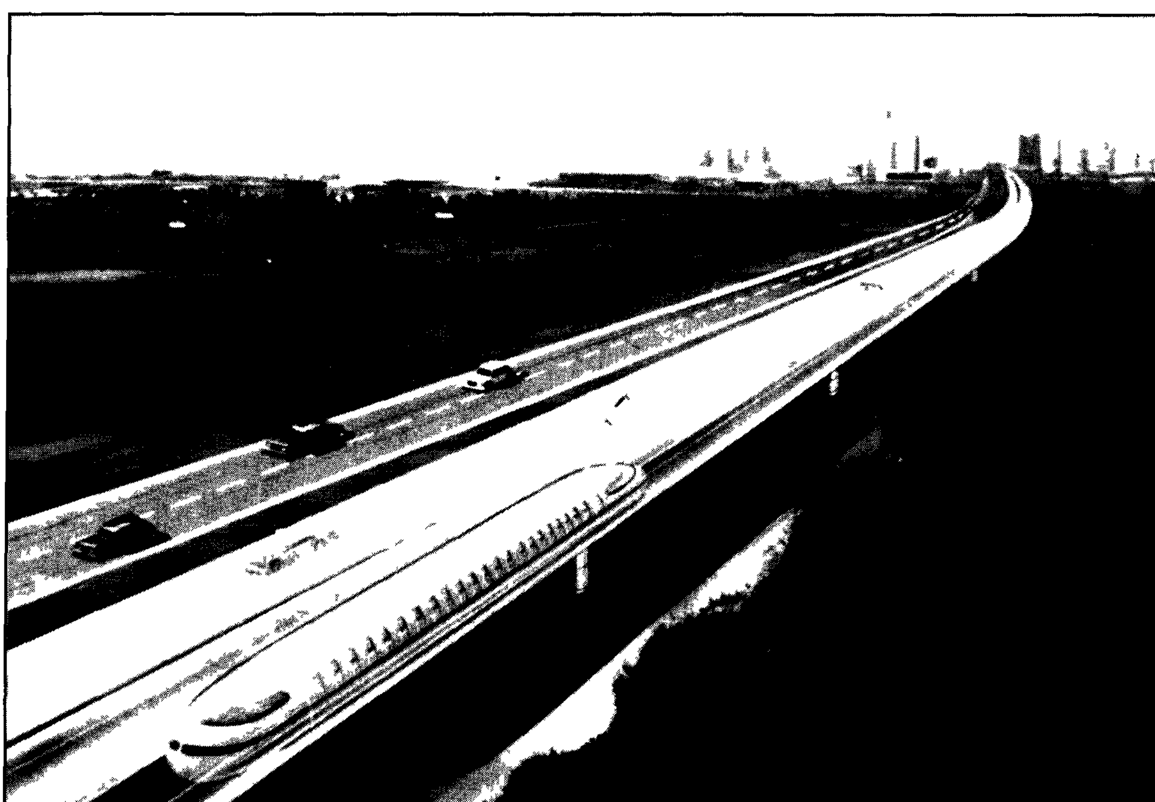

FIGURE 6 Use of Existing Highways for Maglev Systems (Source: Magneplane Corp.)

Second, new transportation systems (e.g., highways, subways, and airports) stimulate development. Yet those who pay for these systems rarely have access to development benefits. One group (often the taxpayers) pays for the transportation system link, while smaller groups (the developers) receive the benefits of improved access. In the Florida high-speed rail project, some of those development rights may go to the transportation system provider. No attempt has been made in this analysis to calculate the economic effect of including limited development rights, if a maglev system is privately financed, but such a provision could greatly offset construction costs.

Third, if maglev technology is to significantly reduce air traffic congestion at hub airports, the system must connect airports and also provide "through" connections. For example, service from Detroit to Chicago should also continue on to destinations beyond Chicago such as St. Louis and Milwaukee. Such service would further maximize ridership potential, but would require compatibility between maglev systems. If a regional or national maglev system is to be effective, a federal presence will be required to -- at a minimum -- standardize the configurations.

3.3.4 Implications of Air Traffic Congestion Costs

Economic activity often has costs, and sometimes benefits, beyond those that pay for the product or service. The considerable airport delays (see Sec. 2) have explicit costs for the airlines, which are reflected in higher costs for the consumer. However, there are also implicit costs for the traveler that are not counted in the ticket price, namely, the time costs of delay. These costs are substantial, and without additional airport construction they are expected to grow.

The FAA estimated the total cost of congestion delays in 1986 at $5 billion. This cost is expected to grow because new airports are not being built quickly enough. Even if the 1986 cost were held constant over the next 20 years, $100 billion of congestion costs would be incurred by airlines and passengers. If new maglev systems could could relieve one-third of this congestion, more than $30 billion in congestion costs would have been saved, or enough to build 2,000 mi of maglev systems during that 20-year period.

3.3.5 National Markets for Maglev System Components

Development of maglev systems will require components and materials from a number of economic sectors. To provide an understanding of the relative magnitude of these supplier markets, a conceptual 2,000-mi maglev network is examined. Specific components will vary somewhat depending on the design selected: the attractive (EMS) system, for example, uses $1.4-2.0 million in laminated steel per mile of rail, whereas the repulsive (EDS) system seeks to minimize the use of iron but incorporates $1.5-2.25 million in aluminum per route-mile. These amounts correspond to $2.8-4.0 billion in steel or $3.0-4.5 billion in aluminum for a 2,000-mi network.

The most costly portion of any maglev system is the basic structure prepared for the track or guideway. Some proposed designs rely on extensive earthwork in advance of installation of fabricated structures, whereas others prefer to use fabricated, elevated guideways while minimizing earthwork. Total costs do not differ radically, ranging from \$7 to \$10 billion. In the most probable case, most of these costs would be for construction and installation of a prestressed concrete guideway.

Such a maglev network would provide a market for about \$700 million in signal and communication equipment. If a linear synchronous motor were incorporated into the guideway, \$1.1-1.8 billion in power cables and switching stations would be required along the guideway, in addition to \$2.5-2.8 billion in fabricated stator windings and \$0.75-1.0 billion in power transformers. These estimates ignore the transmission equipment between the power station and the guideway.

An estimated 300-500 vehicles would be required for the system. On the basis of 300 vehicles in operation at one time (42,000 seats), with a power demand of 4 MW each, 1,200 MW of power (slightly more than the output of one modern electric power generating station) would be used. In one proposed concept, the vehicles would be propelled by turbine-driven ducted fans; this would provide a market for 300 turbines, drive trains, etc. The manufacture of 300-500 maglev vehicles, at an estimated cost of \$5 million each, would provide a \$1.5-2.5 billion market for aerospace-type manufacturing.

3.3.6 Conceptual Development of Intercity Maglev Systems

The 2,000-mi conceptual maglev system network initially was based on the possibility that resolving only a portion of air traffic congestion could pay for 2,000 mi of maglev system. Yet, there are reasons to anticipate that air traffic density alone will make many intercity corridors candidates for maglev system use, independent of whether the congestion costs would pay for the system. Figure 7 shows the top 50 air travel routes under 600 mi and reveals that substituting maglev trips for short flights out of New York and Chicago would relieve congestion in corridors with high volumes of flights. A triangular network between Chicago, Boston, and Washington and also linking New York, Philadelphia, Baltimore, Pittsburgh, Cleveland, and Detroit would have a total length of about 2,000 mi. The figure also shows significant short-haul air travel in California, Florida, and Texas, along corridors currently being examined for potential high-speed maglev routes. Thus, the market for maglev components could easily be larger than indicated here if the technology were to realize its full potential.

Figure 8 illustrates how maglev systems could connect major hub airport cities, allowing airlines to divert their passengers to maglev for short to medium-length trips. The maglev system would then provide both city-to-city travel and feeder service for long-haul flights. Two stages of development are shown. The heavy lines indicate where high traffic volume may support system implementation in the near term. The thin lines indicate where additional maglev systems could be built, depending on successes in the first phase. Both phases would contribute substantially to relieving airport congestion, as seen by comparing the system routes with the high-volume, medium-distance flight routes in Fig. 7.

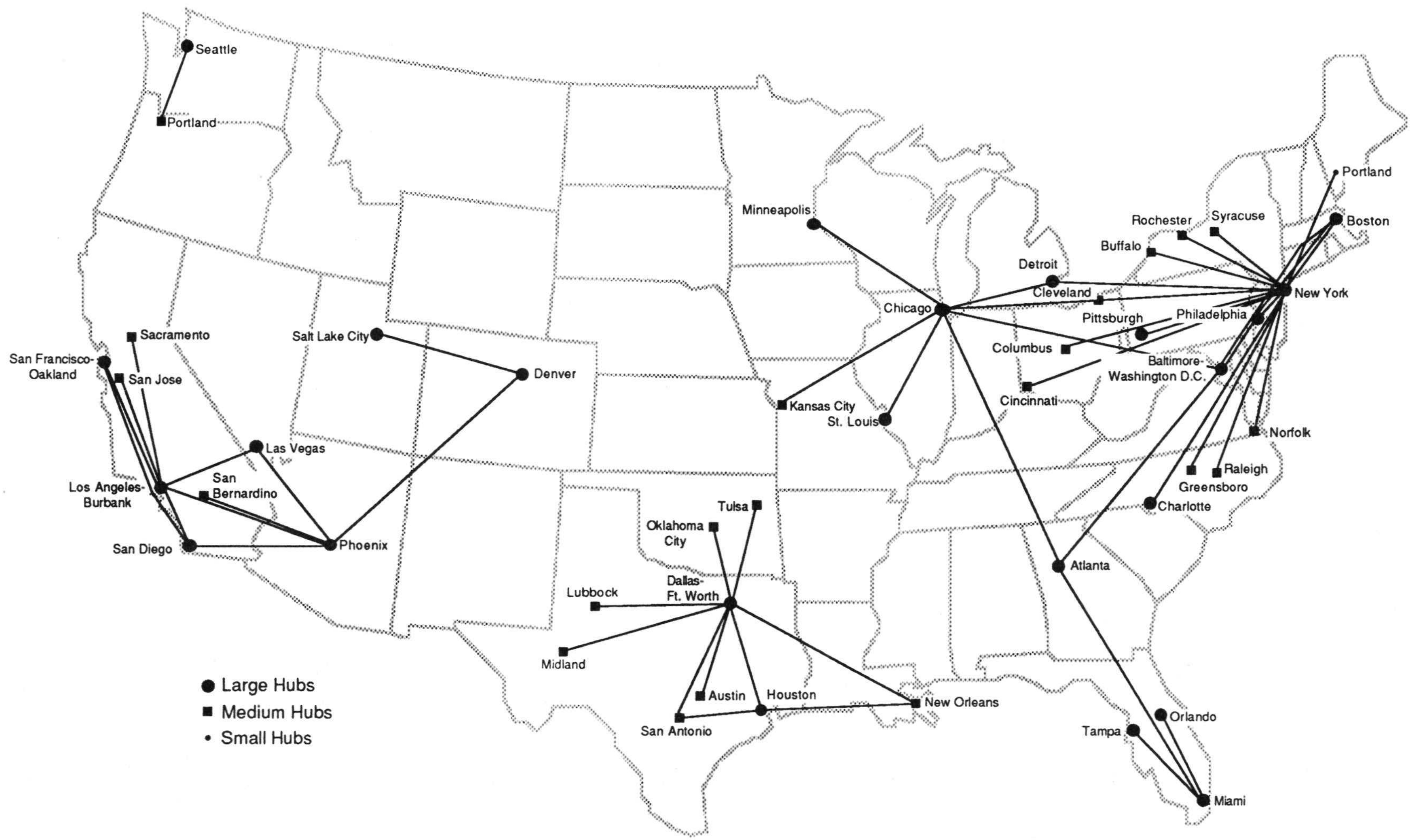

FIGURE 7 Top 50 Air Traffic Routes under 600 Miles (Source: Data from FAA 1986)

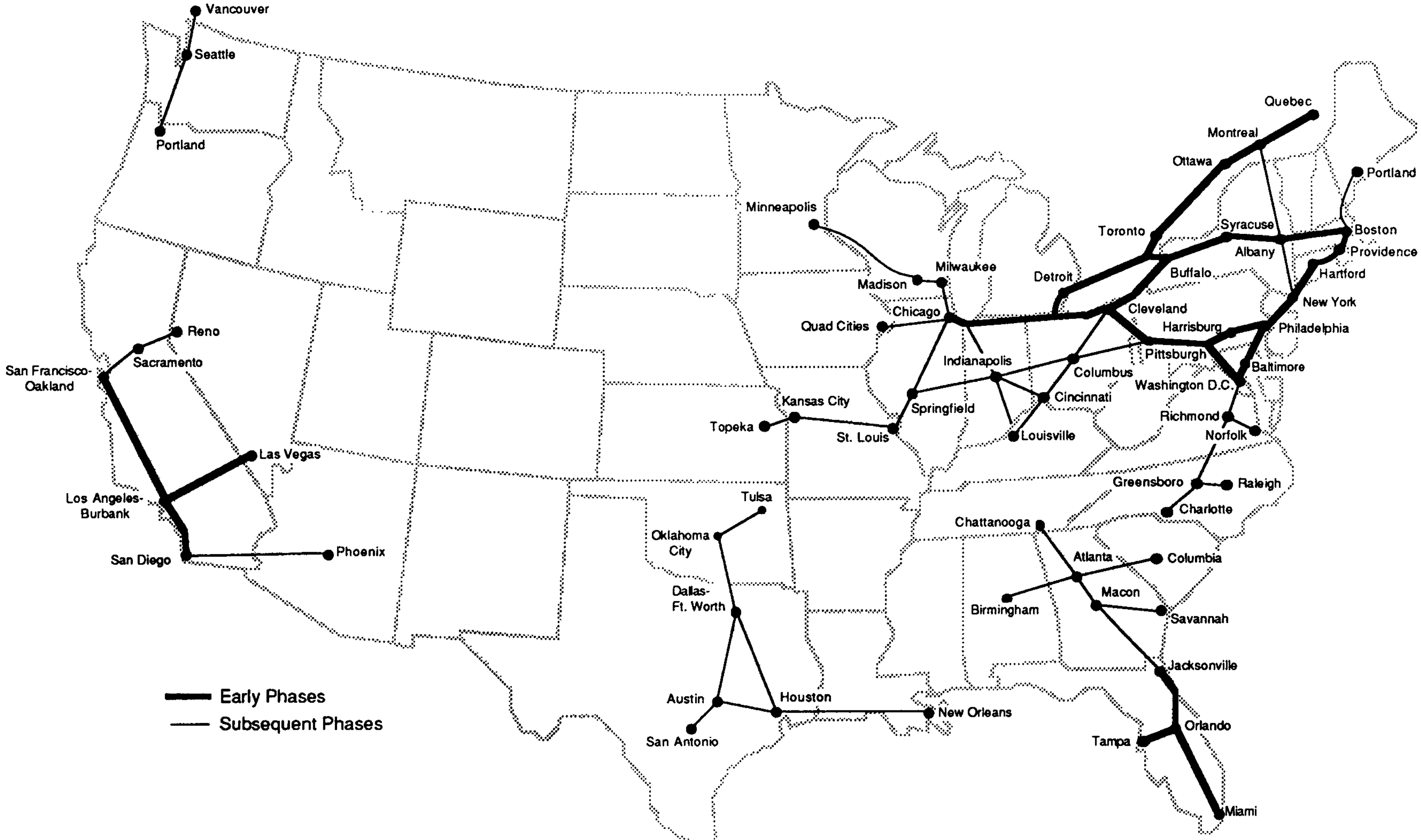

FIGURE 8 Conceptual Plan for Connecting Hub Airports with Maglev Systems

4 HIGH-TEMPERATURE SUPERCONDUCTIVITY AND MAGLEV SYSTEMS

The expected benefits from high-temperature superconductors (HTSCs) are sufficiently extensive to have prompted a presidential initiative to ensure that the United States participates appropriately. Frequently discussed as potential HTSC applications are maglev vehicles, generators, magnetic separators, transmission lines, ship propulsion motors, and magnetic energy storage coils. Maglev vehicles are expected to benefit from (1) the technical capabilities of the materials and their expected enhancement of performance and economics and (2) the modest threshold current density requirements, which appear to make them a candidate for early application of HTSCs.

Superconducting magnets must be used in the EDS (repulsive-force) system to achieve the large suspension heights that make this system so appealing; comparative merits of the EDS and EMS (attractive-force) systems are presented in App. B. Further, superconducting magnets would also be useful as the on-board portion, or "rotor," of linear synchronous motors, which might be used for propulsion. The extent to which EMS systems might benefit from HTSCs has not been discussed in the literature. Thornton (1989) has suggested that because of the ease with which they can be cooled, HTSCs could replace normal magnets in an EMS system, despite the expected high AC losses. One new EMS force levitation scheme made possible by superconductivity is described by Hull (1989).

The design goals for magnetic field strength are relatively modest, that is, generally in the range of 2-5 T or lower for most of these large-scale applications (requirements for fusion magnets would be higher). As Table 14 shows, however, threshold current density requirements are often substantially lower for maglev systems, which could operate with a current density of 10^4 A/cm^2 (see, for example, Moon 1988). Nonetheless, optimal performance may require significantly higher current densities to minimize magnet mass and volume. In other large-scale applications, the superconductor is a major cost item. Large current densities are required to minimize the need for superconducting materials. Because the superconductor is a relatively small cost item in maglev systems, smaller current densities (i.e., more superconductivity material) can be tolerated before costs are affected significantly. From a materials perspective, therefore, the new HTSCs should be available for maglev use, even though their properties may not be optimal, before threshold design requirements are met for the other potential uses. As of June 1988, Sandia National Laboratories reported current densities of 1.9×10^4 A/cm^2 in a 3-T magnetic field at 77 K (Superconductor Week 1988). A side benefit of these materials is that their basic components are less expensive than the niobium and titanium used in low-temperature superconductor (LTSC) magnets, both of which are strategic materials stockpiled by the United States. In addition, fabrication practices for these materials are less costly, although the final fabricated form cannot be foreseen at this time. Material with optimal properties may be quite expensive to prepare in a form suitable for coil windings.

TABLE 14 Design Goals for Selected Large-Scale HTSC Applications

Application	Current Density (10^4 A/cm^2)	Field Strength (T)
Maglev	1[a]	2-5
Generators (300 MW)	3	2
Magnetic separators	3	2-5
Transformers (1,000 MVA)	10	0.3
Transmission lines (10,000 MVA; 230 kV)	23	1
Magnetic energy storage (5,000 MWh)	60	1-5

[a]Threshold value; to reduce magnet size and mass, larger current densities would be required.

Source: Adapted from Wolsky (1988).

Superconducting magnets require a cooling system. Conventional superconducting magnets wound with niobium-titanium or niobium-tin conductors operate at 4.2 K (or higher) and use liquid helium as the coolant. Since the discovery of the new class of superconducting materials with transition temperatures (T_c) of 77 K and higher, conventional superconductors have become known as LTSCs. The HTSCs have sufficiently high critical temperatures that liquid nitrogen can be used as the coolant.

Several experimental and prototype EDS maglev vehicles have been built and tested using LTSCs. Demonstrably, they work. Now, however, the possibility of operating superconducting magnets at higher temperatures and potentially at more intense magnetic fields must be evaluated. Using HTSCs in place of LTSCs could, in principle, provide the following advantages:

- Less complex designs for the cryostat and components that transfer mechanical stress (given the same field strength). A single nitrogen-cooled cryostat would replace a helium cryostat enclosed in a nitrogen cryostat.

- Lower mass and volume for the coolant system.

- Much more reliable and less costly coolant system.

- Much cheaper and more abundant coolants.

- Reduced energy consumption by coolant system.
- Reduced maintenance costs.
- Lighter vehicle mass due to replacing liquid-helium cryostat, reservoir, and liquefier with a simplified liquid-nitrogen system.
- Smaller propulsion energy requirement (because of somewhat lighter magnets, cryostats, and refrigeration systems). This benefit would increase with current density.
- Potential for more efficient system operation and for reduced guideway costs.
- Potential for reduced costs for power conditioning unit (substation); may involve trade-offs with other costs.

Some of these potential benefits are discussed in detail below. Their relative importance depends to some extent on vehicle and system design. For example, using HTSCs may result in a weight reduction of, say, 2 tons; while this reduction may significantly affect the propulsion energy of a lightweight vehicle, it may be of little importance for a heavy one. This analysis assumes that HTSCs can supply the current densities and magnetic field strengths needed for on-vehicle magnets, once the materials are commercially available.

4.1 COOLING SYSTEMS

Of all the potential HTSC benefits, perhaps the most important for revenue operation is the relative simplicity and reliability of liquid-nitrogen vs. liquid-helium cooling and supply systems. The reliability problems of liquid-helium systems are well known (i.e., compressor difficulties, vacuum and helium leaks, and helium contamination). These problems are exacerbated when the systems must be used in the harsh environment of on-board vehicle operation. According to Tanaka (1988), the maglev research group at JR's Railway Technical Research Institute has struggled for several years to develop a highly reliable, self-contained, on-board liquid-helium system for their LTSC magnets. A liquid-nitrogen system would greatly simplify this task and eliminate the expense of the helium liquefier.

Liquid nitrogen is much less expensive than liquid helium (\$0.05/L vs. \$2.33/L), and the convenience, ease of handling, operational familiarity, and reliability of liquid-nitrogen systems are also significant advantages. Moreover, liquid nitrogen is also preferable because readily accessible resources of liquid helium may prove insufficient for economical and widespread implementation of all the LTSC applications now contemplated (Hull and Berry 1988).

Because liquid nitrogen is much less expensive than liquid helium, simply boiling off the gaseous nitrogen becomes an option and is likely to be more cost-effective than an on-board reliquefaction system. It may also be possible to avoid the use of a vacuum chamber for thermal isolation. In any case, liquid-nitrogen systems are less massive and more than 30 times more efficient than their liquid-helium counterparts.

4.2 MAGNET RELIABILITY

An important characteristic of any superconducting magnet is its stability, that is, its ability to remain in the superconducting state. If any part of a superconductor makes the transition into the normal state, it will immediately begin to undergo Joule heating. Unless the magnet system is designed to limit or dissipate this heat, the magnet's temperature will rise and lead to normalization of the magnet in a process called a quench. The magnetic energy stored in the field will be dissipated in heating the magnet. If enough energy is stored, the increase in temperature could melt the conductor, expand the epoxy (in which the windings are embedded) and break the conductor, or cause internal arcing. A quench may occur when enough energy accumulates in a superconductor to raise its temperature above the critical value. A variety of energy disturbances may perturb the system, but the most common are frictional heating due to conductor motion, AC losses resulting from magnetic field fluctuation, and elastic energy release due to breakage of filaments or other structural components.

One advantage of HTSCs over LTSCs is that magnets operating at liquid-nitrogen temperature (77 K) are less likely to quench than those operating at liquid-helium temperature (4 K). This is due to the higher heat capacity (several orders of magnitude higher) of materials at 77 K compared to those at 4 K (Hull and Berry 1988; Moon 1988; Laquer et al. 1988; Iwasa 1987).

Considerable effort has been devoted over the years to designing LTSC magnets that do not quench. Magnet designs have evolved to limit temperature excursions by restricting energy perturbations to about 10^4 J/m^3. If the same designs could be used to limit energy perturbations to the same degree at 77 K, the traditional spectrum of disturbances would cause only an insignificant temperature rise (Hull and Berry 1988). Thus, HTSCs should be much more stable than their low-temperature counterparts, i.e., the probability of a quench would be much lower. Nevertheless, the possible consequences of a quench must be considered in order to protect the HTSC magnets.

Tolerance of several-degree temperature excursions appears likely in the new ceramic HTSCs, especially in those with transition temperatures considerably above 100 K and that operate at 77 K. One outcome could be relaxed design constraints (e.g., allowing more motion in the conductors or using structural members with a lower elastic modulus). A second possibility is that the ceramic superconductors could be used in magnets that operate reliably at much higher magnetic field strengths without quenching (Hull and Berry 1988).

These arguments have been made by simplistic extrapolation of experience with LTSC magnets to a higher operating temperature. Conclusions must be tempered with the observation that other design constraints, such as those related to brittleness of the ceramic superconductor and high normal-state resistivity, may be present and may either constrain the design or require operation at lower maximum magnetic field strength. As noted by Rinek (1989), some current HTSC materials also exhibit excessive sensitivity of critical current density (J_c) to mechanical strain. Such design issues can only be discovered by analyzing and experimenting with HTSCs.

4.3 ENERGY SAVINGS

HTSCs provide at least two ways to reduce maglev energy consumption. First, because liquid nitrogen requires at least 30 times less energy to remove a given quantity of heat energy at 77 K than does liquid helium at 4 K, on-board power requirements may be significantly reduced. (This reduction may range from 10 to 25 kW or more, depending on vehicle design; however, hotel-power* demand is much higher than this.) Second, as already noted, the liquid-nitrogen system would be smaller and lighter.

Lightweight vehicles mean that less energy is expended in accelerating and cruising. Energy required for acceleration (to change the vehicle's kinetic energy) depends directly on vehicle mass, while power for cruising at a fixed speed depends on drag forces at that speed. Because the maglev vehicle does not touch the guideway (except at speeds below takeoff for repulsive-force levitation), the only drag forces are electromagnetic and aerodynamic. Whereas aerodynamic drag increases with the square of vehicle speed and reaches its peak value at maximum cruising speed, electromagnetic drag has a more complex dependence on speed and track thickness. For typical designs, electromagnetic drag peaks at relatively low speeds (30-60 mi/h) and diminishes at higher speeds.

Electromagnetic drag arises from the interaction (i.e., Lorentz forces) between the eddy currents in the guideway elements that conduct electricity and the on-board magnetic fields. This interaction produces the desired levitation, or lift, but also the undesired drag. For a given configuration, air gap, field strength, and speed, there is a characteristic ratio of lift force to drag force. For example, in the first-generation Canadian maglev design (Atherton et al. 1977), that ratio is 21:1 at 300 mi/h. If vehicle weight is reduced, the required lift force is reduced and so is electromagnetic drag, provided the lift-to-drag ratio remains unchanged. For higher lift-to-drag ratios, the effect is less important.

As an illustration, consider the effect of weight reduction due to replacing the LTSC magnets with liquid-nitrogen-cooled HTSCs; relevant parameters and results are given in Table 15. The approximate net effect is a 9.5% weight reduction and a 3.2% change in propulsion power at the maximum cruising speed of 300 mi/h. At lower speeds, for which the ratio of electromagnetic drag to aerodynamic drag is higher and the ratio of lift to drag is lower, the effect of weight reduction is substantially greater. In addition (as already mentioned), the savings in kinetic energy associated with accelerating a lightweight vehicle are directly proportional to the weight savings. Thus, in this illustration the net savings for a vehicle trip involving acceleration to and cruising at various speeds are 3-9.5%. For systems such as the Japanese MLU002, in which magnets make up a smaller percentage of total vehicle weight or in which the lift-to-drag ratio is larger, the effect would be smaller.

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*Hotel power is that needed for on-board functions.

TABLE 15 Example Calculation of Effects of Weight Reduction Due to Use of HTSC Magnets

Item	LTSC[a]	HTSC[b]
Weight (lb)		
Levitation magnets and cryostats	2,310	1,617
Linear synchronous motor magnets and cryostats	11,088	7,762
Vehicle suspension and structure	14,872	13,726
Magnet shielding	3,498	2,625
Subtotal	31,768	25,279
Total vehicle, including 100 passengers	63,360	57,321
Performance at 300 mi/h		
Aerodynamic drag (ton)	3.26	3.26
Lift-to-drag ratio	21	21
Electromagnetic drag (ton)	1.52	1.37
Net drag (ton)	4.78	4.63
Propulsion power (MW)	5.67	5.49

[a]Source: Based on data in Atherton et al. (1977).

[b]Assumptions: (1) Inner stainless-steel pressure vessels and all associated plumbing and liquid-helium storage tanks, together with liquid helium, are eliminated, and outer cryostat is reduced in size slightly; (2) some method, either with active or passive shielding, will be found to exploit the properties of HTSCs to reduce the shielding mass penalty by ≈25%; (3) mass reductions will propagate through the vehicle, causing reductions in suspension and structure mass of ≈7.7%.

4.4 POWER SYSTEM IMPACTS

As noted in App. B, most maglev propulsion systems use a linear synchronous motor (LSM) that includes on-board field coils and active stator windings on the guideway. The electrically active portion of the guideway is divided into sections or blocks that are individually energized and controlled by wayside substations containing power conditioning units. Power from the utility grid is delivered by high-voltage transmission lines to the substations where it is stepped down. The power conditioning unit receives information on vehicle speed and location from a sensor network along the guideway and produces a variable-voltage, variable-frequency output to match the speed and power requirements of the vehicle's levitation, guidance, propulsion, and service load demands.

Substation spacing and "block length" are selected to optimize both capital and operating costs (the latter include electric power charges, which are based on peak demand, low-power-factor penalties, and actual energy consumption rates). Although no detailed analysis has yet been made, superconductivity may play an important role in optimizing these costs. On the one hand, the fewer the power conditioning units and switching components required (i.e., the longer the block length), the lower the capital cost (within certain limits). On the other hand, the longer the block length, the greater the inductive reactance (and resistance) of the system load and the lower the power factor (and efficiency). Low power factors require the power conditioning unit and utility transmission system to be oversized relative to the useful power delivered. Hence, low power factors usually invoke an operating cost penalty from the utility, as well as a capital cost penalty for the power conditioning unit.

With the high field strengths available even with LTSCs on board, the voltage induced by that field in the guideway windings can be high enough to operate the LSM in the overexcited mode. In this mode, a repulsive normal force is produced along with the longitudinal propulsion thrust. Furthermore, the LSM then produces a capacitive reactance that compensates for the inductive reactance of the guideway windings. With a proper match, the power factor seen by the power conditioning unit in the substation can be close to unity, and the unit can be optimally sized to the amount of useful power delivered to the guideway and vehicle. This is how repulsive systems are usually designed.

HTSCs may be beneficial because the higher fields produced might allow a greater degree of compensation for the inductive guideway load and thus allow longer blocks. This problem is rather complex, however, and many factors enter into the choice of block length. Additional field strength may not provide a net benefit in this respect. For example, the use of higher field strengths in the vehicle coils may require additional magnetic shielding of the passenger compartment.

The operating losses from the relatively low-frequency LSM are typical of those from power transmission lines, where efficiency is already relatively high. Superconductors could, in principle, be used in the LSM stator windings of the guideways, in the transmission line, or in the power conditioning unit to reduce resistive losses. However, little or no advantage from this substitution is likely unless room-temperature superconductors are discovered, because the cost of cryogenic cooling over long guideway lengths would be significant.

4.5 GUIDEWAY DESIGN

HTSCs could benefit guideway design, but the effect is expected to be relatively small. As noted earlier, maglev vehicles are lighter than conventional trains (see Sec. 2.1.7), and their static and dynamic loads are distributed over relatively large surface areas. For example, attractive levitation (see Sec. 5) is an improvement over a steel-wheel vehicle because the total force is lower and is distributed along part of the lower surface of the vehicle rather than only where wheels touch a track. Repulsive levitation is a further improvement because the total force is still lower (the vehicles weigh less) and can be further distributed over a larger portion of the vehicle bottom.* HTSCs further reduce vehicle weight because of their lighter refrigeration systems, magnetic shielding, and magnets. These weight reductions and distributed loads are expected to affect maintenance costs significantly compared to those of a steel-wheel-on-steel-rail system.

If room-temperature superconductors become a reality (which seems doubtful at this time), systems employing superconducting guideways might be feasible if their increased material costs were offset by reduced energy costs.

4.6 AGGREGATE SUPERCONDUCTIVITY EFFECTS

Although repulsive-force maglev vehicles can use LTSCs -- and present economic studies of these systems indicate that they can be profitable -- HTSCs offer additional benefits that will further improve the economics and profitability of such systems, perhaps helping somewhat to justify their use in corridors now considered marginal. HTSCs are expected to provide numerous benefits because of reduced capital costs for certain elements, reduced operating expenses, and improved reliability of the levitation system. As noted by Moon (1988), liquid-nitrogen cooling may permit new economical designs for magnets and cryostats. For example, whereas the Japanese have tended toward large LTSC magnets separated from the passenger cabin by mounting on bogies, Moon suggests using small magnets to distribute the forces and reduce field strength in the passenger cabin.

In general, reduced capital costs can be expected because of decreased cryostat volume, weight, and complexity; lower refrigerant costs; elimination of liquefiers; and, possibly, lower magnet weight. Consequent reductions in weight and possible improvements in the power factor could reduce requirements for and costs of installed power in the system. Such cost savings, however, may represent only a small fraction of total system costs.

Operating cost reductions are anticipated because of the same technical merits. Gaseous nitrogen is inexpensive, and the cost of liquefying it for use in cryostats is minimal compared to the cost of liquefying helium. Nitrogen's heat capacity is such that on-board liquefaction will not be required, thus, the simplicity of the resulting system will reduce the maintenance required for fleet vehicles. Moreover, the weight reductions mentioned above could potentially reduce the operating power requirements by as much as 3-9.5%, depending on system design, and power-factor improvements could reduce penalties for low power factors or related operating costs.

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*This may, however, lead to an added weight penalty for mitigating the field strength within the passenger compartment, depending on vehicle design and exposure limits (which have not been set). Some vehicle designs seek to reduce passenger exposure to magnetic fields by concentrating the levitation magnets at the vehicle ends. This increases mechancial stresses on the guideway.

Liquid-nitrogen-cooled magnets are expected to be stable and to require less design engineering than magnets cooled by liquid helium. The relative simplicity of liquid-nitrogen systems (compared to liquid-helium systems) reduces the complexity, cost, and maintenance of virtually every portion of the levitation, refrigeration, and cryogenic storage systems. Because HTSCs that meet the needs of magnets for this application can use a low current density, at least initially, they should be developed earlier than HTSCs for some other large-scale applications. The maglev application should therefore be considered when determining the focus of applied HTSC research.

5 CONCLUSIONS

5.1 BENEFITS OF MAGLEV IMPLEMENTATION

This evaluation has shown that maglev vehicle technology could potentially benefit from liquid-nitrogen-cooled HTSCs when they become available. Potential benefits are seen in improved reliability, somewhat reduced cost (especially for maintenance), and reduced energy consumption for intercity transportation. In addition, the study discovered the existence of a potentially significant market for high-speed maglev vehicles in intercity travel. The market would likely require integrating maglev technology into the present airline system. Maglev systems would substitute for short- to medium-distance flights, serving as a feeder operation at major hub airports.

From an economic standpoint, maglev technology looks sufficiently promising to be examined as a system for heavily traveled corridors and as an alternative to major airport construction. The rationale in 1975 for discontinuing U.S. development of maglev technology no longer applies. Rather than enjoying adequate intercity transportation facilities, as anticipated, we are experiencing serious congestion and are facing problems unlikely to be solved by minor modifications to existing air and highway systems.

If maglev systems were implemented as an aerospace/airline technology, benefits would accrue to the economy generally, but also to airlines, aircraft manufacturers, and air travelers. The airlines could gain by using their facilities more efficiently. For each short- to medium-distance flight diverted to a maglev system, an airline could substitute a longer-haul or international flight at a hub airport with capacity constraints. Airframe manufacturers could supply the short- to medium-distance market with a new technology while allowing the market for longer-haul aircraft to grow without constraint from airport congestion. Because maglev vehicles are essentially fuselages without wings, aircraft manufacturers are their logical builders. Indeed, if airport congestion continues to worsen, the lack of sufficient airport capacity will adversely affect aircraft sales.

More-diffuse benefits will depend on the degree of maglev commercialization. Passengers will certainly benefit immediately and also over the long run from the new technology: their travel options will be expanded, their delays will be reduced, intercity travel safety should be enhanced, and travel costs will be lower than if the severe congestion had not been reduced. Local communities and the nation will benefit through improved intercity travel accompanied by reduced noise and pollutant emissions, as well as through greater energy efficiency and lessened dependence on increasingly scarce domestic and foreign petroleum.

5.2 INTERNATIONAL COMPETITIVENESS

The problems of air traffic and highway congestion are not unique to the United States, being common throughout the industrialized world and serving as part of the impetus for maglev technology development in Japan and West Germany. Transportation congestion in the United States actually sets the stage for a potentially large export market for Japanese- and German-manufactured maglev systems. Without a domestic program to develop maglev technology, the United States will likely be importing these systems by the late 1990s. Also, without a domestic program, the United States will lose even its ability to evaluate foreign technology options.

The country that develops and implements the technology first will have an obvious marketing advantage; however, the worldwide market for maglev systems appears large and diverse enough to sustain several manufacturers. Although the United States is now behind in prototype development, the first high-speed maglev system will probably not be commercialized for 8-10 years. Sufficient time is available for the United States to develop its own technology and compete successfully for the systems that will be built here and abroad beyond 2000.

5.3 TECHNOLOGY DEVELOPMENT

Whether the United States should independently develop maglev technologies and how that development should be structured were not addressed in this study. It is nonetheless clear from the analysis that the following broad considerations would be prominent in such decision making:

- *Maglev transportation applications provide perhaps the best opportunity to showcase U.S. developments in large-scale superconductivity.* Maglev systems could benefit substantially from HTSCs, and threshold design requirements for maglev systems could be met before those of other large-scale HTSC applications, although optimal system designs will probably require improvements in material properties.

- *Maglev technology development should be structured in parallel programs — one to develop a maglev system using LTSCs and the other to develop HTSCs that could be substituted when maglev systems are fully developed.* This is a rational approach because HTSCs do not constitute an enabling technology for maglev systems and are not yet at a practical stage of development. If HTSC development proves more difficult than now thought, an LTSC maglev system will still have been developed to meet U.S. needs and the international competitive challanges.

- *Development of HTSC components for maglev transportation will produce spin-off benefits applicable to other technologies, such as motors or magnetic separators.*

The optimal characteristics of a U.S. maglev system have yet to be determined. Decisions must be made about vehicle and system design, routes, and operating parameters. Existing foreign designs do not appear to meet U.S. needs. For example, current German and Japanese approaches to maglev technology development (i.e., using maglev "train" and heavy train sets) do not take advantage of the aerospace aspect of the technology and do not exploit the market niche identified in this study as possibly the most cost-effective. Consequently, even the existing technology may have to be substantially modified to meet U.S. requirements.

Further investigation is warranted. This assessment has defined a promising market niche for maglev systems. Yet the economic analysis is preliminary, having been conducted for only one corridor. A comprehensive examination of national intercity travel patterns and projections would better define the potential markets for maglev systems and identify the most cost-effective corridors. A broad look at financing options is very important because alternative financing mechanisms can vary widely in determining the economic feasibility of such a capital-intensive system. Identifying how the systems could be operated (privately, publicly, or as a joint public/private venture) is also critical for understanding potential markets and associated risks.

These systems studies look only at the demand side of the cost-effectiveness equation. Because the costs of the foreign maglev technologies are high, opportunities exist for U.S. industry to design a lighter-weight and less expensive system with greater flexibility to meet U.S. needs. However, the magnitude of system cost reductions will not be known until further research and development is conducted. At a minimum, detailed engineering designs of promising new approaches will allow greater precision in costing and more confidence in the ultimate benefits of U.S. maglev developments. Given that the United States developed the initial superconducting maglev systems and that commercialization of the technology is 8-10 years away, the nation is still well positioned, for a limited period, to develop a very-high-speed maglev system.

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APPENDIX A:

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

CO	Carbon monoxide
CONEG	Coalition of Northeast Governors
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EDS	Electrodynamic system
EI	Energy intensity
EPA	U.S. Environmental Protection Agency
EMS	Electromagnetic system
FAA	Federal Aviation Administration
h	Hour
HC	Hydrocarbon
HTSC	High-temperature superconductor
J_c	Critical current density
K	Degrees Kelvin
km/h	Kilometers per hour
L	Liter
LIM	Linear induction motor
LSM	Linear synchronous motor
LSUM	Linear synchronous unipolar motor
LTSC	Low-temperature superconductor
mi/h	Miles per hour
MW	Megawatt

NO_x	Oxides of nitrogen
PM	Passenger-mile
SO_x	Oxides of sulfur
TRB	Transportation Research Board

APPENDIX B:

STATUS OF MAGLEV TECHNOLOGY

B.1 SPEED LIMITATIONS: CONVENTIONAL RAIL VS. MAGLEV TECHNOLOGIES

Advances in conventional steel-wheel-on-rail technology in the United Kingdom, France, West Germany, and Japan have enabled revenue service systems to operate in the top-speed range of 125-185 mi/h. While the maximum operating speed for this technology has yet to be defined, the principal limiting factor in reaching higher speeds and in turn attracting more passengers seems to be track alignment and maintenance costs.

On the Japanese Shinkansen ("bullet") line, maintaining the essential accuracy of track alignment, even at operating speeds of 125 mi/h, was reported to be a growing problem a decade ago (Rhodes and Mulhall 1981). Wear and noise problems have forced the Japanese to limit top speeds on the very heavily used older Shinkansen line to 125 mi/h. On the newer Shinkansen lines, slab construction has replaced the tie method; this design allows speeds up to 160 mi/h. However, for safety reasons, daily inspection is still required. The noise and vibration of these and other steel-wheeled trains, together with the high cost of maintenance, have influenced the Japanese to examine other alternatives, such as maglev systems, for intercity transportation.

The U.S. Federal Railroad Administration (FRA) standards for conventional freight trains and commuter trains allow relatively large discrepancies, e.g., 1.25 in. for 80 mi/h operations, between the levels of the two rails relative to the plane of the track. However, the FRA standard drops to 0.5 in. for 120-mi/h operations. By comparison, the French TGV standard is 0.16 in. for the 170-mi/h portions of that system (Thompson 1986). Satisfying the standards for high-speed service is not impossible, but it is expensive.

The need to rely on traction between wheels and rails for propulsion in a conventional system could be eliminated by linear propulsion motors. Wheels would then be used only for suspension. This could, in principle, make higher speeds technically feasible. However, the high maintenance costs associated with the required track (or guideway) alignment, smoothness, and curvature specifications may still render this alternative economically unattractive.

Achieving significantly higher speeds (i.e., above 250 mi/h) may require substantial reduction in, or total elimination of, physical contact between the vehicle and the track or guideway. However, depending on the desired degree of reduction in physical contact, alternatives must be provided for the basic functions of suspension, guidance, propulsion, and energy collection (i.e., delivery of electric power to the vehicle). Maglev technology can, in principle, provide completely contactless vehicle operation at very high speeds limited only by the power required to overcome aerodynamic drag. Experimental EDS (repulsive-force) vehicles have been tested to 320 mi/h.

In the maglev transportation concept, primary vehicle suspension is provided by magnetic forces that levitate the vehicle 0.3-12 in. above the guideway, depending on the specific design concept. Magnetic forces can also be used to guide the vehicle (i.e., to keep it centered over the guideway), propel it along the guideway, and slow it. Electromagnetic induction can be used to transfer electrical energy to the vehicle and to assist braking. On-board batteries may be required for some electric energy storage.

Several maglev design concepts have been proposed, and some have been developed to the stage of near-readiness for revenue service. A low-speed, attractive-force maglev people-mover system has been in public service since 1984 in Birmingham, England (Dalgleish and Riches 1986). It travels 2,000 ft (610 m) at an average speed of 11 mi/h over an elevated guideway from the Birmingham airport to the British Rail station. The low-speed West German M-Bahn rapid transit system is operating in West Berlin. The high-speed system that is probably closest to commercialization is West Germany's Transrapid system, although actual revenue service is not scheduled to begin before 1999 in West Germany, according to one report. The two Japanese maglev systems (i.e., the high-speed Japan Railway [JR] maglev system and the slower HSST Corp. system) are close behind. A low-speed HSST system is scheduled to be operated as a licensed railway on an 1,800-ft-long single elevated track at the 1989 Yokohama Exposition beginning in March 1989, and the JR system could begin revenue service in the 1995-2000 time frame.

B.2 LEVITATION SCHEMES

Only a few of the numerous levitation mechanisms are candidates for use in high-speed ground transportation systems (Jayawant 1981; Coffey, Chilton, and Hoppie 1971, 1972a; Davis et al. 1972; Rhodes and Mulhall 1981). The most viable candidates are:

1. Permanent magnets on the vehicle interacting with permanent magnets in a guideway.

2. Permanent magnets on the vehicle interacting with image currents induced in a conductive guideway.

3. Conventional iron-core, copper-wire-wound electromagnets on the vehicle interacting with a ferromagnetic guideway (hereinafter referred to as EMS).

4. Superconducting air-core magnets on the vehicle interacting with currents induced in conductive-sheet or coil-type guideways (hereinafter referred to as EDS).

Methods 1 and 2, which use the repulsive force generated by permanent magnets, are generally not favored for high-speed applications because the suspension height is small and weights and costs are high (Coffey, Chilton, and Hoppie 1972a,b; Atherton and Eastham 1974). Consequently, Methods 3 and 4 are of the greatest interest.

B.3 DEVELOPMENTS IN MAGLEV SYSTEMS

B.3.1 EMS vs. EDS

Electromagnetic suspension (EMS) derives from the attractive force between an electromagnet and a ferromagnetic material. Electrodynamic suspension (EDS) derives from the repulsive force between a magnet and the electric currents (eddy currents) induced in a conductor moving relative to the magnet. As implemented in current design concepts, the two approaches have major differences. Each approach offers advantages and disadvantages, and certain applications might be better served by one than the other.

In EMS systems, the electromagnets used for vehicle suspension are generally fixed to the vehicle undercarriage, which is wrapped around an underlying guideway (see Fig. 1) so that the electromagnets are attracted upward toward steel rails fixed to the guideway. If the attractive magnetic force fails, the vehicle will come to rest on the guideway structure. Although not essential for vehicle operation, some type of wheel suspension is usually provided for maneuvering the vehicle when the power is off. Also, some type of skids must be provided to protect the vehicle, magnets, and guideway if the levitation and lateral guidance systems fail while the vehicle is in motion or the air gap between the magnets and rails is accidentally forced to zero. The wraparound design of the undercarriage is an important safety feature because it prevents the vehicle from leaving the guideway. To date, all reported EMS design concepts have used normal conducting coils with iron cores for the vehicle-borne electromagnets. Some low-speed designs use both electromagnets and permanent magnets.

An important aspect of attractive-force levitation is its inherent instability. No natural restoring force acts to automatically restore the vehicle to its equilibrium position if it is disturbed. For example, if the vehicle moves upward slightly, the air gap between the magnet and rail is reduced and the attractive force increased, which tends to pull the magnet even closer to the rail. Control of the air gap requires that it be monitored continuously and that the magnetic force of attraction be continuously adjusted. The power required to maintain the air gap is relatively modest, except for high-frequency and large-amplitude disturbances caused, for example, by large track irregularities. Energy consumption required to maintain the gap increases with the square of the gap. The magnetic drag and the energy used in the feedback circuits required for stabilization increase with vehicle speed.

Because of the relatively low field strength achievable with iron-core magnets and the high power required to maintain large air gaps, all practical systems are designed with air gaps limited to 0.3-0.4 in. This provides very little tolerance for fluctuations caused by wind gusts, passenger movements, rail misalignments, and debris on the guideway. Typical short-wave-length tolerances are about 0.08 in., and long-wave-length tolerances are about 0.06 in. in 50 ft (Raschbichler and Schwindt 1985). These small gaps may ultimately reduce maximum operating speed below the desired range of 250-310 mi/h. Atherton and Eastham (1974) calculate that, for a lift-to-weight ratio of 5:1, a 0.6-in. gap is achievable in a best case with a 1-T lift magnet, and a 1.2-in. gap is achievable with a 5-T lift. Thus, in principle, suspension systems with vehicle-borne electromagnets appear to be limited to a maximum clearance of 0.4-0.8 in.

The limited range of magnet motion in an EMS system results in a very stiff suspension system that is incompatible with the more resilient suspension required to meet ride quality criteria. The EDS suspension system is less stiff because of the larger track clearance. To meet these criteria, the West German EMS system design uncouples the primary suspension system from the vehicle via a secondary suspension system. In the analogous steel-wheel-on-rail system, the wheels are suspended from bogies by a system of springs and shock absorbers, resulting in a relatively heavy bogie and vehicle.

A major advantage of the repulsive-force levitation system is its use of direct-current (DC) excitation of the vehicle-borne electromagnets. This is ideal for superconducting magnets because small, lightweight superconducting magnets can produce intense DC magnetic fields over relatively large volumes with far less energy consumption than that of normal magnets. Superconducting magnets operated in the persistent-current mode maintain their field strength without energy consumption, except for energy used in refrigeration and for small energy losses associated with magnetic field fluctuations. On-board refrigeration is not needed if the liquid refrigerants are replenished periodically at wayside substations. Such systems can be operated for many hours between recharges. As noted by Thornton (1989), it might be possible to use HTSCs in EMS systems as well, because removal of heat generated in the superconductor by AC losses is much easier. See Sec. B.3.4 for a description of an attractive force system using superconducting magnets.

With superconducting magnets, air gaps of 3.9-7.9 in. have been attained with EDS test vehicles. Such large air gaps allow for additional vertical motion of the vehicle, reducing stresses on the vehicle and guideway and providing substantially greater tolerance for guideway misalignments and accumulations of ice and snow or debris on the guideway.

In the simplest form of EDS, superconducting magnets are placed on the vehicle so that eddy currents are induced in conducting strips on the guideway as the vehicle moves over it. Interaction between the eddy currents and the magnetic fields produced by the vehicle-borne coils produces a vertical repulsive force. At rest, there is no repulsive force (wheel sets are used to support, guide, and maneuver the vehicle at low speeds). As vehicle speed increases, the repulsive force increases until the vehicle levitates. After lift-off, the wheels can be retracted to reduce aerodynamic drag.

The interaction described above produces electrodynamic drag that must be overcome by the propulsion system. Initially, as vehicle speed increases, the levitating and drag forces increase. The levitating force remains constant after lift-off, although the suspension height increases slightly. Drag reaches a peak value at a relatively low speed -- depending on track thickness and magnet design -- and diminishes thereafter. With increasing speed, the aerodynamic drag force dominates.

In contrast to the speed dependence of the EDS levitating force, the attractive force in the EMS system exists whether the vehicle is moving or stopped. However, speed-dependent electromagnetic drag forces still arise in the EMS system due to induction of eddy currents in the rails; these forces can be reduced by laminating the rails (i.e., replacing the solid steel rails or plates with stacks of electrically insulated, thin vertical steel sheets fastened together).

Another EMS advantage arises from the use of iron-core magnets that tend to produce relatively small magnetic fields in the passenger cabin and near guideway components. The air-core superconducting magnets produce much higher external fields that generally require shielding of the passenger compartment and careful attention to selection of guideway structural materials to avoid excessive electromagnetic drag.

A major advantage of the EDS system is its inherent stability. The magnetic forces acting on the vehicle tend to restore the vehicle to its equilibrium position when it is disturbed by some influence such as a wind gust, guideway discontinuity, or passenger movement. For example, if the vehicle is pushed closer to the guideway, the repulsive force increases, tending to push the vehicle back to its original position. This eliminates the need for continuous air-gap monitoring and continuous field-strength adjustment. However, some air gap monitoring may still be required to control the lift force and the air gap for ride quality or to compensate for load changes.

B.3.2 Lateral Guidance

As mentioned earlier, in addition to suspension, a maglev system must provide not only suspension but also guidance and propulsion. Guidance can be provided by the same schemes used for levitation. For example, in the EDS system, retractable wheel sets can be used to keep the vehicle centered in the guideway at low speeds, while magnetic forces can produce the necessary lateral guidance forces at higher speeds. In the simplest form, the magnets used for levitation can also provide guidances forces, or guidance can be provided by separate superconducting magnets mounted vertically on the sides of the vehicle and used with conductors mounted vertically on the guideway walls.

Although this approach is workable, it produces additional electrodynamic drag that must be overcome by the propulsion system. Of the several schemes proposed, the one that appears to be most attractive and that has been adopted in various designs is the so-called "null-flux" concept (Powell and Danby 1969a). In brief, a passive coil configuration in the guideway intercepts zero net magnetic flux and generates no net guidance or drag forces when the vehicle is centered. Both the guidance and drag forces increase as the vehicle departs from its centered position. With this scheme, electrodynamic drag during high-speed operations is small compared to aerodynamic drag.

Another method of reducing electrodynamic drag (suggested by Powell and Danby in 1967) is the use of discrete passive coils in the guideway for levitation in lieu of conducting metal sheet (see, for example, the Japanese EDS system design based on this concept).

B.3.3 Propulsion

Several methods have been proposed for propelling maglev vehicles. The most compatible appears to be the long-stator linear synchronous motor (LSM). Stator windings in the guideway are driven with three-phase AC power and are energized sequentially, causing a magnetic wave to travel along the guideway. This traveling magnetic wave interacts with the vehicle-borne superconducting coils to propel the vehicle.

More efficient than the long-stator linear induction motor (LIM), which has also been considered, the LSM allows control of the system power factor, thus reducing the costly demand for large reactive power (large reactive power means that current-carrying conductors and power-conditioning equipment must be sized to carry large currents at high voltage while delivering relatively little useful energy). The main reason for the LSM's greater efficiency is that it uses magnetic fields produced by the superconducting magnets to interact with weaker fields produced by normal stator windings in the guideway. The long-stator LIM, on the other hand, produces the total magnetic field in the guideway and interacts with a passive reaction plate mounted in the vehicle.

With the LSM, only that portion of the stator winding near the vehicle or train needs to be energized. This substantially reduces system power requirements and also provides a fail-safe way to regulate vehicle headway. If for any reason headway falls below a safety limit, the power supplied to the portion of the guideway occupied by the errant vehicle can be reduced or shut off and, if necessary, electrodynamic braking can be applied. The sequential energizing of guideway sections (called "blocks") requires a network of wayside power substations connected by power transmission lines and control cables to switches that turn each block on and off. The optimal spacing of these stations and of the switches is a matter of balancing the costs of the individual components (such as power control components and cables) with the operating costs associated with continuous and peak-power demand and any required power factor correction.

In recent designs, two or more of the basic functions (suspension, guidance, and propulsion) have been combined into a single set of vehicle-borne coils. For example, the West German Transrapid system, which is based on the EMS principle, uses one set of vehicle coils for both lift and propulsion and a separate set for guidance. All three functions are performed by a single set of vehicle-borne coils in the proposed Massachusetts Institute of Technology (MIT) magneplane, the Warwick maglev concept (Rhodes and Mulhall 1981), and the Japanese MLU vehicle series. In all of these concepts, propulsion is provided by an LSM winding placed in the guideway and driven with three-phase AC power. A short-stator on-board LSM has been developed by Boeing Aerospace Co. (see Sec. B.3.4).

In the Romanian Magnibus concept, the LSM is carried on the vehicle. In their latest designs, both the Germans and Japanese favor the use of bogies with secondary suspension systems. However, the German Transrapid system uses a uniform distribution of magnets along bogies that extend the entire length of the vehicle, while the Japanese favor a design in which the magnets and bogies are concentrated at the vehicle ends. The MIT and Canadian designs do not use bogies. The MIT design uses a continuous distribution of magnets on the vehicle bottom, while the Canadians concentrate the magnets at each end and at the middle of each vehicle, using secondary suspension for the levitation magnets only.

Electric propulsion systems offer many advantages. However, the long-stator designs require active windings distributed along the entire length of the guideway and are subject to weathering and related deterioration. They also require extensive equipment for power transmission, distribution, and conditioning. The Ford propulsion concept, on the other hand, is entirely contained on board the vehicles themselves. It uses turbine-driven, noise-suppressed ducted fans. This would greatly simplify the guideway, allowing it to be optimized for ride quality, safety, aesthetics, and cost. The disadvantages are increased vehicle weight, noise, pollution, and reliance on fossil fuel. Noise from the turbo fan is lower than that of the vehicle body at full speed (Ford Motor Co. 1975), and the air pollution problem could be mitigated by the use of liquid fuels other than jet fuel.

B.3.4 Maglev Research in the United States

The concept of high-speed ground transport using maglev technology was discussed at least as early as 1907 (Bronwell 1980). Pioneering U.S. work on maglev vehicles was conducted at Brookhaven National Laboratory in the early 1960s. A feasibility study for a high-speed test facility for rocket-propelled vehicles was started at Sandia National Laboratories. In that study, Stanford Research Institute (SRI)* and Atomics International Division of North American Rockwell were asked in 1967 to examine the use of superconducting magnetic suspensions for Mach-10 rocket sleds operating in an evacuated tunnel (Barbee et al. 1968; Coffey, Chilton, and Barbee 1969a; Guderjahn et al. 1969b). An EDS levitation system using high-field superconducting magnets and a continuous-sheet guideway was suggested. Analogous to the null-flux design of Powell and Danby (1969b) of Brookhaven National Laboratory, the sheet guideway was folded around the superconducting magnets.

Powell and Danby (1969a) examined several schemes for repulsive levitation of vehicles and investigated techniques for reducing electrodynamic drag. They developed the first scheme for repulsive levitation of a high-speed vehicle using superconducting magnets and the aforementioned null-flux concept later adopted by the Canadians and Japanese for their guidance systems.

SRI used its own funds to continue its study of magnetic levitation, promoting the concept to the FRA (Coffey, Chilton, and Barbee 1969b). A 500-ft-long test track containing 400 ft of continuous sheet aluminum guideway was built in 1970 and later used to evaluate an 1,100-lb levitated test vehicle using superconducting magnets.

Ford Motor Co.'s research laboratories began studying maglev technology in 1969-70 (Reitz 1970). MIT researchers conceived of the magneplane concept in 1970-71; they subsequently built and tested a 1/25th scale model using superconducting magnets on a 400-ft-long guideway (Kolm and Thornton 1972). The magneplane was the first maglev concept that incorporated a self-banking feature.

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*Now known as SRI International.

In early 1971, Ford and SRI began parallel analytical and experimental studies of both attractive and repulsive levitation systems with funding from the U.S. Department of Transportation (DOT). This work continued until 1974 at SRI and until 1975 at Ford, when funding was stopped. Rohr Industries began a maglev technology development program in 1970, producing both top-suspended and bottom-supported vehicles; the latter was demonstrated at Transpo 72. Boeing Aerospace acquired the Rohr technology in 1978 and began to develop the linear synchronous unipolar motor in the mid-1980s under sponsorship of the Urban Mass Transit Administration (UMTA). Boeing completed its maglev technology program in 1986, and through an agreement with UMTA, transferred its technology in 1987 to Carnegie-Mellon for further development and commercialization. The Office of Technology Assessment (1983), in a report titled *U.S. Passenger Rail Technologies*, contends that "U.S. maglev research and development was on a par with similar foreign research programs at the time the U.S. Government canceled it in the mid-1970's."

Brookhaven National Laboratory Studies. Interest in the EDS levitation system for high-speed ground transportation was revived by James Powell and Gordon Danby of Brookhaven National Laboratory in the early and mid-1960s when they recognized that superconducting magnets could reduce the power requirements of such systems to practical levels. Powell in 1963 discussed a system with superconducting coils both in the guideway and on the vehicle. The cost of the guideway, however, made this system impractical.

Powell and Danby (1967) discussed a system using superconducting magnets on the vehicle and two sets of normally conducting coils in the guideway to provide both the electrodynamic lift and guidance force for a 300-mi/h vehicle. An important feature of this system was the use of very high currents in the vehicle magnets, in which no power is dissipated, and the incorporation of inductors to limit the current induced in the resistive guideway coils. The principle of this system is that the force between two conductors is proportional to the product of their currents and that because the current in the superconductor dissipates no power, that current should as high as possible while the current in the normal conductor, which does dissipate power, should be as low as possible. This limits power dissipation in the track and results in a very high lift-to-drag ratio.

Powell and Danby pointed out that electrodynamic drag decreases as vehicle speed increases, a characteristic that has since been extensively discussed. They also recognized the intrinsic stability of the system and the damping inherent in the guideway interaction that is still poorly defined to date. They recognized that this damping is insufficient and that other means would be required at high speeds. The system now under development in Japan uses many of the features described by Powell and Danby in their early work.

Later in 1967, these authors applied for a patent describing many optional methods of using on-board superconducting magnets with guideway-mounted, normally conducting coils to achieve the same and additional benefits (Powell and Danby 1969b). Included among these are the various "null-flux" systems for which Powell and Danby have received much acclaim (Fig. B.1). These include both vehicle- and guideway-based

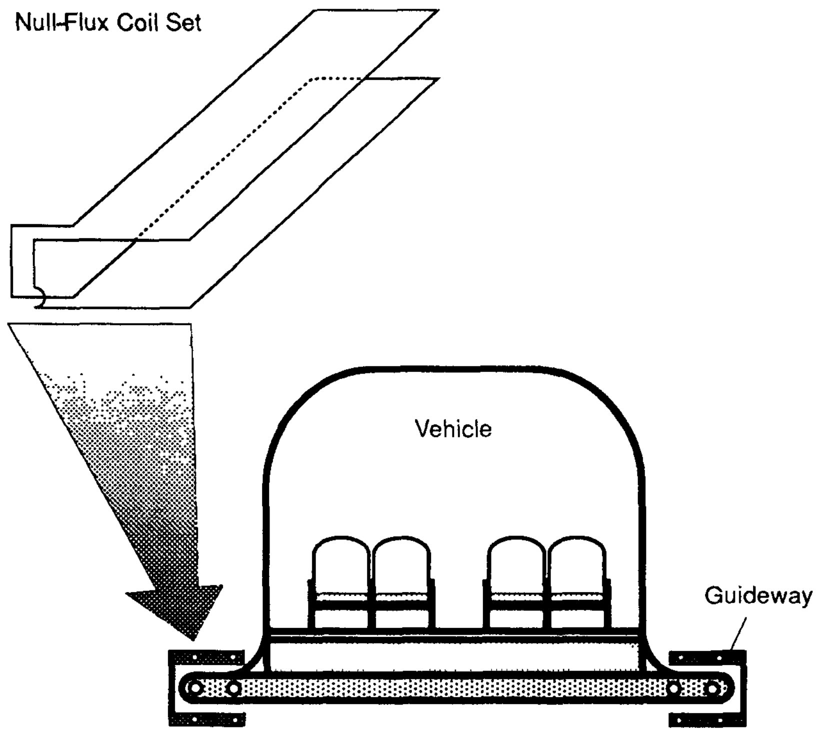


FIGURE B.1 Null-Flux Concept of Powell and Danby (One set of guideway-mounted coils is shown schematically at top. When centered between coils, the vehicle-mounted magnets generate opposing currents in the upper and lower coils, resulting in no induced current. Deviations from the center position result in high currents and restoring forces. Propulsion mechanism not shown)

double coils that induce no current in the guideway coils unless the vehicle-mounted coils deviate from a central position. These systems are capable of high lift-to drag ratios and very stiff restoring forces (i.e., forces with large gradients).

Together with J.W. Jackson, these authors later developed a concept for a system with a still higher lift-to-drag ratio and that included a ferromagnetic sheet above the null-flux coils to provide nearly drag-free lift (Danby, Jackson, and Powell 1974).

Ford Motor Co. Study. Starting in 1971, FRA's Office of High-Speed Ground Transportation sponsored cooperative feasibility studies of high-speed maglev ground vehicles at Ford Motor Co. and SRI. These studies focused on a 100-ft-long, DOT-specified vehicle weighing 100,000 lb and capable of speeds up to 500 mi/h. Davis et al. (1972) documented the results of the first part of the Ford study, which addressed the technical feasibility of magnetically levitated suspension of high-speed ground vehicles.

Both the attractive- and repulsive-force concepts were considered. A repulsive-force concept called "Magnefloat," using high-field-strength superconducting magnets and a continuous guideway, received the greatest attention. Also evaluated were the repulsive-force concept that uses discrete guideway coils, the attractive-force concept, the Powell-Danby null-flux concept, and a track suspension system incorporating permanent magnets. The attractive-force system provides a higher lift-to-drag ratio than all of the repulsive-force concepts (100:1 vs. 50:1) except the null-flux system, whose ratio could be as great as 400:1. Of the three attractive-force concepts considered, that using a continuous conducting sheet in the guideway required the smallest cryogenic system. All suspension concepts were found to have low inherent damping, requiring some method of increasing damping or movement control.

The comparison between the discrete and continuous guideway conductors showed that the discrete system has a characteristic pulsating lift but allows more efficient use of conductor material. The pulsating lift degrades ride quality and causes AC losses in the superconductor, increasing the cryogenic loading. Ford found that the null-flux suspension system -- which should not be confused with the similar null-flux guidance systems used in several maglev concepts -- was not a serious candidate for practical reasons.

The attractive maglev system was found to have some advantages (e.g., low magnetic drag and only moderate magnetic shielding problems), as well as some disadvantages (e.g., low tolerance for rough or misaligned track). Power consumption comparisons showed that the attractive system requires approximately 50 kW for levitation and control to support a 100,000-lb vehicle. Additional power is required for the active secondary suspension at 300 mi/h. The Magnefloat system (repulsive-force concept and continuous guideway conductor) uses no levitation power, but may require some control power and certainly some power for refrigeration (if used). If no secondary suspension were used, and no method for increasing the passive damping were developed, the Magnefloat would require approximately 20 kW of control to operate over a guideway with a specified roughness. With on-board refrigeration, approximately 50-70 kW would be required.

Aspects of the magnetic levitation concepts identified for further study include:

- Response to an operating vehicle environment of superconducting magnets operated in a persistent-current mode.

- Methods to increase damping.

- Magnetic shielding.

- Development of alternative propulsion systems.

- Failure modes and required redundancy.

The second year of the Ford study focused on selected critical technical problems in both attractive and repulsive levitation systems (Reitz et al. 1973). Included were (1) studies of AC losses in superconducting magnets; (2) magnet shake tests;

(3) damping and control studies; (4) assessments of magnet shielding requirements; (5) in the case of repulsive-force suspension, baseline design of a research vehicle, including a propulsion system; and (6) in the case of attractive-force suspension, baseline design of a research vehicle, including design and construction of two model electromagnets and their feedback control system, together with studies of magnetic saturation and eddy-current drag at high speeds, control requirements, criteria for maximum allowable track roughness, and need for a secondary suspension. Four alternative propulsion systems were evaluated: a double-sided LIM, two forms of newly proposed rotating superconducting motors, an LSM, and the "Q"-fan turbojet engine.

Ford's researchers concluded that either suspension system is acceptable and that magnetic shielding to below 0.02 T is attainable without excessive weight penalties. They also found, however, that with an LSM propulsion system, magnetic shielding was a greater problem and that a higher weight penalty could be expected. Laboratory tests on model superconducting coils operating under simulated vehicle conditions showed that AC losses were not a major problem, as first thought. Researchers concluded that the repulsive-force suspension system had inherent damping and that acceptable ride quality was probably possible with passive control and a secondary suspension. Superior ride quality was thought to be obtainable without secondary suspension, using active control (described in the next subsection). The reported power requirement is modest, i.e., 1.2 kW/ton of supported weight. Another recommendation in the Reitz et al. (1973) report was that serious consideration be given to a high-speed repulsive-force system using a quiet-fan jet engine for propulsion.

The next report on the Ford study (Borcherts et al. 1974) describes the development of a mathematical model used to predict the magnet-rail system behavior of an attractive-force system at high speed and to optimize magnet parameters. Various track geometries were also examined to reduce the aluminum requirements for a repulsive-force system. The model calculations indicated that, for the attractive system, long magnets perform better than short ones at high speed and that "small gaps between the elemental magnets making up a long magnet will not degrade performance appreciably." Calculations also supported an earlier conclusion that magnet performance can be improved by laminating the track, but that this would be very costly.

The final phase of the Ford work is described in an executive summary (Ford Motor Co. 1975). Of the two tasks described, the first was development of a conceptual design for a repulsive-force system using an 80-passenger vehicle with specified ride requirements at all speeds up to 480 mi/h (Fig. B.2). The second task, which was never completed, was the detailed design, construction, and testing of a high-speed test platform incorporating a scaled version of the Task 1 conceptual design and construction of a guideway at China Lake, California.

Stanford Research Institute Studies. Maglev studies at SRI began with the study of a Mach-10 rocket sled, as mentioned earlier, and continued in programs funded internally and by DOT. Many of the Ford studies were conducted in cooperation with and in parallel with SRI, and both organizations reached similar conclusions. Results of the SRI studies are reported in Barbee et al. (1968); Coffey, Chilton, and Barbee (1969a,b); Coffey, Chilton and Hoppie (1971); Coffey, Chilton, and Hoppie (1972a,b); Coffey,

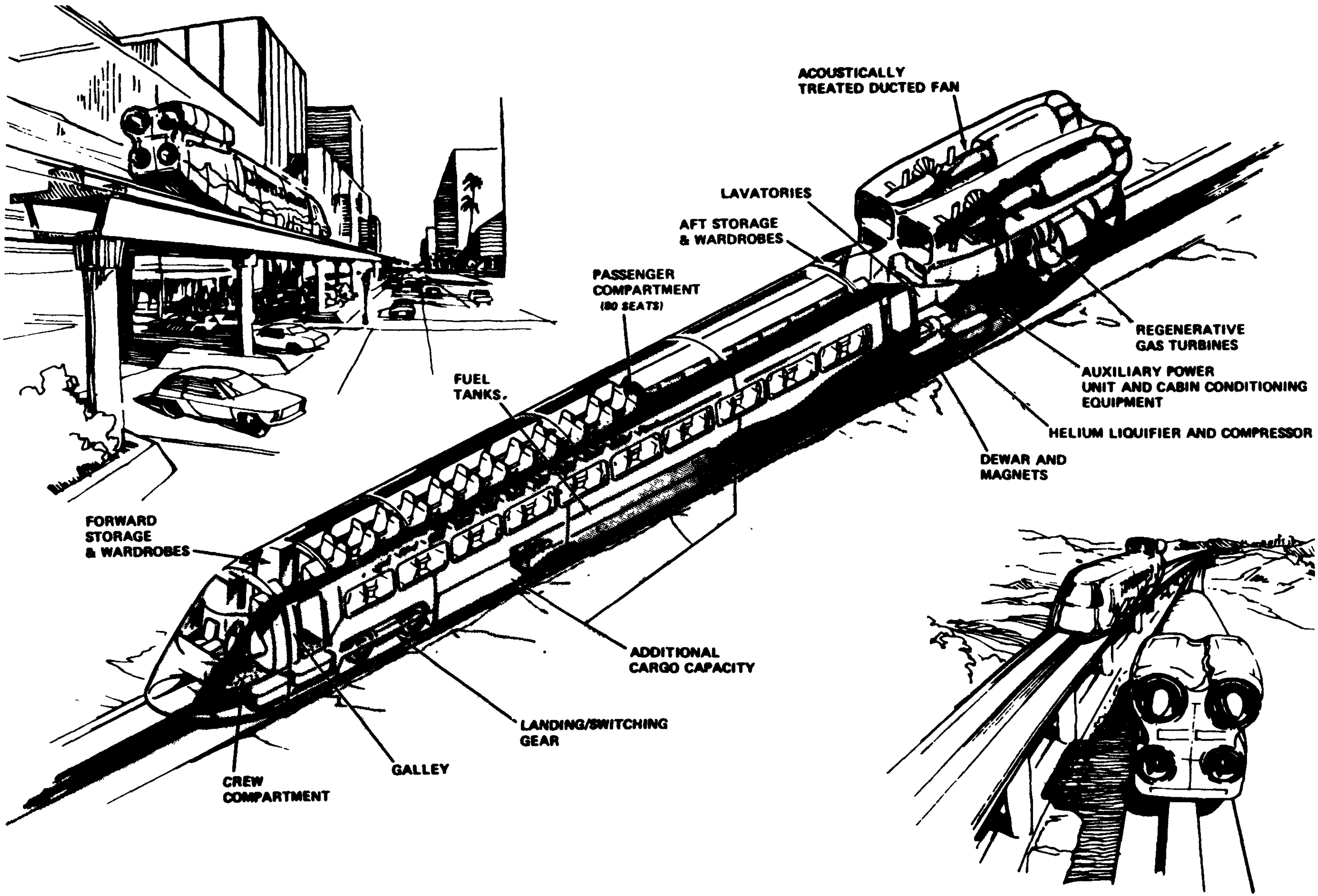


FIGURE B.2 Conceptual Ford Design for Maglev Revenue Vehicle System (Source: Ford Motor Co. 1975)

Colton, and Mahrer (1973); Coffey (1974); Coffey et al. (1974a,b); Chilton and Coffey (1971); and Hoppie et al. (1972). The first part of the SRI study examined six combinations of vehicle suspension and guideway designs: (1) permanent magnet suspension with both permanent magnet and conducting sheet guideways, (2) conventional magnet suspension with ferromagnetic rail guideway, and (3) superconducting magnet suspension with single- and double-layer coil and continuous conducting sheet guideways.

SRI found that all six combinations could suspend the 100,000-lb target vehicle specified by DOT. For nonsuperconducting systems, the air gaps were limited to 0.4-0.8 in. as practical parameter ranges. For superconducting systems, the air gaps could be 12 in. or more. All combinations were judged to be safe, except those using permanent magnets, which were judged marginally safe because of the possibility of demagnetization. That possibility could be avoided, according to the authors, by using cobalt rare-earth magnets with high coercive fields. At the time, such magnets were still under development and their cost and availability limited their usefulness.

The SRI authors concluded that choosing among the five "safe" alternatives was not possible on the basis of technical feasibility. Detailed cost analyses were judged necessary, but were beyond the scope of the SRI project. On the basis of subjective consideration of cost, ride comfort, and operational characteristics, the superconducting suspension systems were regarded as the most favorable for future study. The continuous conducting guideway was selected as the best alternative, primarily because it is simple and offered the best ride quality at the lowest cost. SRI's investigators felt that the advantage of higher lift-to-drag ratios with the coil-in-guideway designs was of relatively little importance at high speeds, where aerodynamic drag dominates. Furthermore, savings in material costs (if any) would probably be offset by the increased fabrication and installation costs of the coil-in-guideway system.

Extending the work begun with Sandia National Laboratories and continuing with SRI funds, SRI performed Fourier transform calculations of the lift and drag associated with a superconducting suspension system using an infinite, continuous-conducting sheet in the guideway. Approximate methods were used to account for the finite width of the guideway.

Early experiments used a small superconducting magnet that was moved in a U-shaped 500-ft-long guideway (Coffey, Chilton, and Hoppie 1972a). Forces on the magnet were measured as a function of vehicle velocity, suspension height, magnet current, and vehicle position in the guideway. Later experiments using a 14-ft-long test vehicle weighing as much as 1,100 lb are reported in Coffey, Colton, and Mahrer (1973), Coffey (1974), and Coffey et al. (1974a,b). This vehicle was both levitated and guided by 12.6 × 10.6-in. superconducting magnets located at the vehicle corners. Propulsion was by a glider-towing winch driving an endless cable. The propulsive force was applied at the vehicle's center of mass through a combination of spherical and linear bearings that permitted the vehicle to move freely in all directions except along the guideway. A telemetry system and position and acceleration instrumentation gathered simple vehicle performance data.

Early measurements verified the theoretical predictions of the dependence of lift and drag on velocity. Guidance, on the other hand, was found to depend critically on the electrical contact between the vertical and horizontal plates of the U-shaped guideway.

Theoretical calculations were modified to more accurately account for the guidance forces and predicted the magnitudes of the lift, drag, and guidance forces within a few percentage points.

In later experiments (Fig. B.3), the vehicle was completely instrumented for dynamic-motion measurements and an on-board recorder was incorporated for extensive data acquisition. Large perturbations were induced in the vehicle's motion by extra aluminum plates placed at various positions on the track and by simultaneously offsetting the vehicle laterally in the guideway. Perturbations were typically 0.75 in. in magnitude and 20 ft long. Passive damping occurred because of power dissipation in the guideway and a liquid-nitrogen-cooled, one-turn coil installed below the magnet. Active damping was the result of normally conducting electromagnets placed on the bottoms of the dewars and controlled dynamically by feedback from on-board accelerometers. The vehicle was stable in all cases, recovering from perturbations in about three cycles via passive damping and 1.5 cycles with active damping. Active damping was regarded as suitable for producing the desired ride comfort in a revenue vehicle.

A dewar insulated and strengthened with compressed fiberglass layered with aluminum foil kept the levitation magnets at liquid-helium temperatures. This design was relatively inexpensive and simple to install and provided adequate thermal insulation.

Massachusetts Institute of Technology Magneplane Concept. Work began on the magneplane concept at MIT in 1970 with support from AVCO Systems Division and Raytheon Equipment Division (Kolm and Thornton 1972). The National Science Foundation also provided support until February 1975, when the U.S. Office of Management and Budget terminated funding for all high-speed ground transportation research. Thereafter, the magneplane was mothballed (Kolm 1987).

Kolm and Thornton invented the magneplane concept in 1970-71 at MIT, which owns the three basic patents. The vehicle and guideway conceptual designs (Fig. B.4) contain several innovations and unique features. In the vehicle is a set of saddle- or pancake-shaped superconducting coils that interact with the semicircular metal guideway to produce repulsive levitation, lateral guidance, and propulsion. The unique semicircular guideway design consists of a central, shaped aluminum propulsion conductor driven by three-phase AC power and straddled by two passive conductor sheets (also of aluminum) that carry eddy currents induced by the moving vehicle-borne magnets.

The interaction of these induced eddy currents with the magnetic field of the vehicle-borne magnets produce the repulsive levitation and guidance forces that support the vehicle. This unique guideway design, plus the use of a 1-ft air gap, allows the vehicle to be self-banking, that is, it negotiates turns like an aircraft. The inventors noted that this latter feature was especially important because, even with a 45° bank, the tightest turning radius at 300 mi/h is 1 mi. Hence, unless turning radii were very much larger, departures of any vehicle's speed from the design speed for a given bank angle would result in unacceptable lateral forces on the passengers. Of course, even the self-banking feature does not eliminate the need for large-radius turns at high speed because even though the net force is normal to the passenger seat, that force cannot be made too large. Given the self-banking feature and the resilient ride made possible by

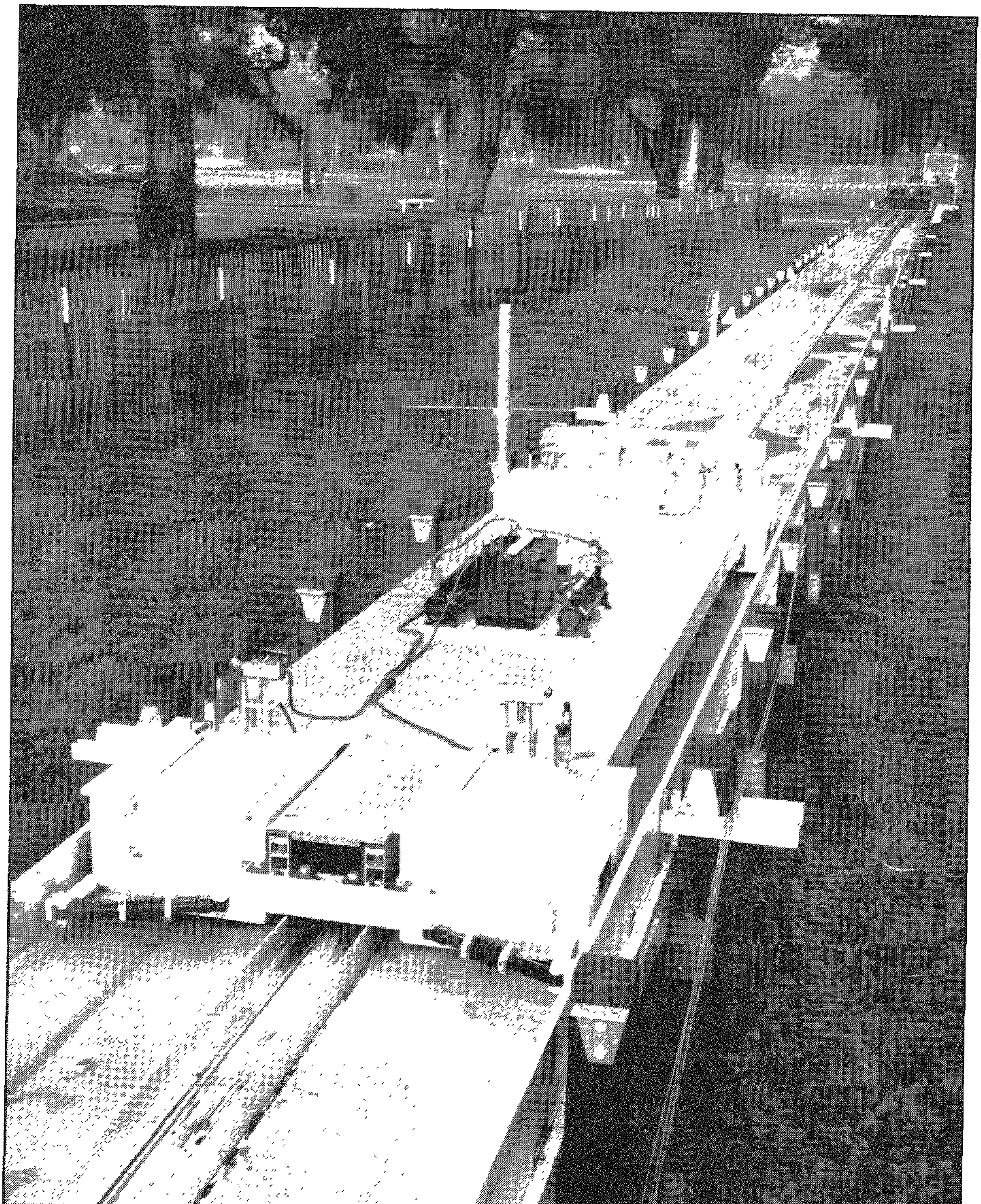


FIGURE B.3 SRI Test "Maglev Vehicle" on U-Shaped Aluminum Guideway (Courtesy SRI International)

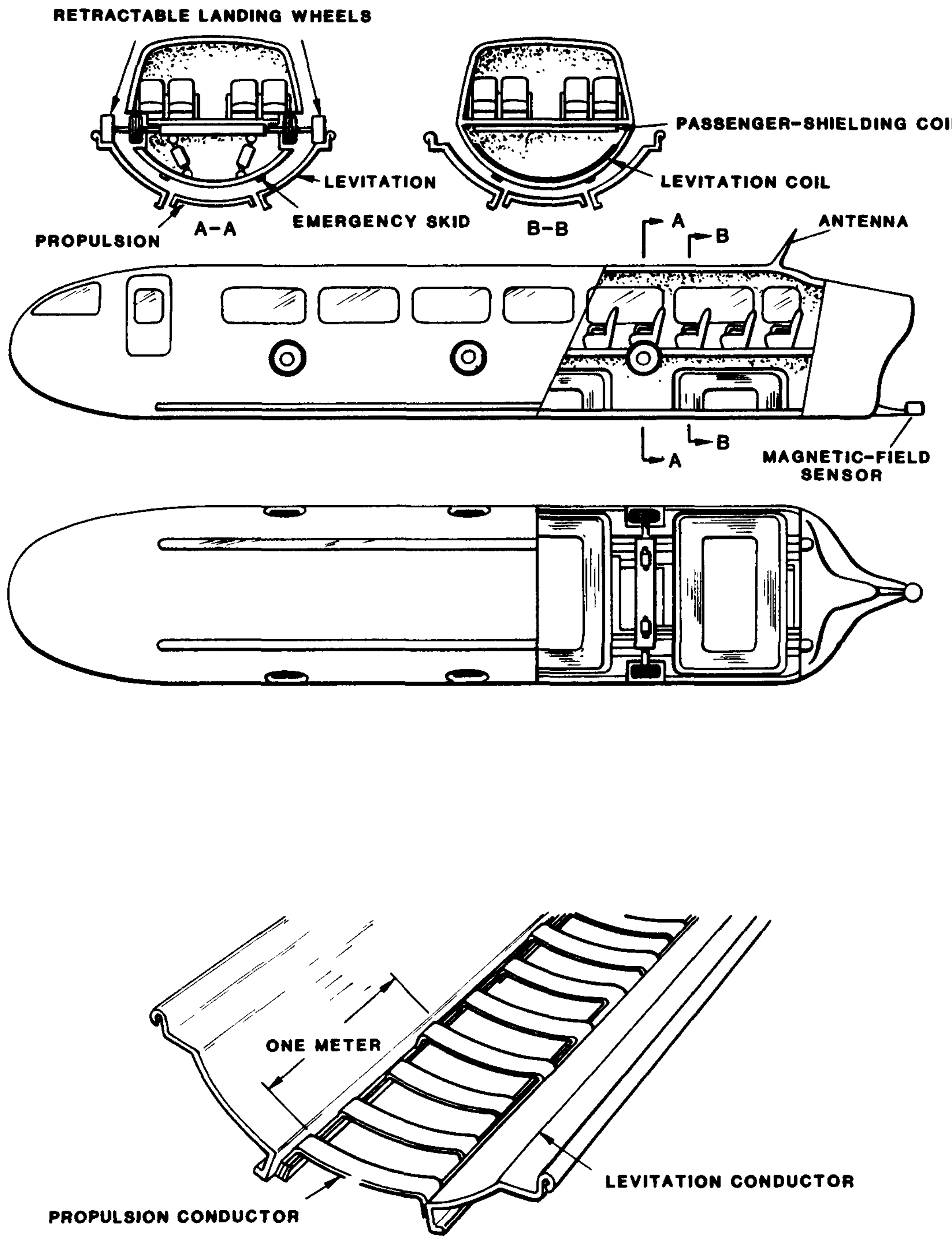


FIGURE B.4 Magneplane Vehicle and Guideway (Source: adapted from Kolm and Thornton 1973) the 1-ft gap, the inventors referred to the motion of the magneplane vehicle in the semicircular trough as "guided flight."

Retractable wheels or landing gear provide support and guidance during low-speed operation when the repulsive forces are insufficient for levitation. Special coils provide magnetic shielding for the passengers because the levitation coils cover the entire lower surface of the vehicle. The system sustains slow oscillations with a period of about 1 s. Because of the circular geometry and nonlinear nature of the repulsive levitation force, vehicle heave motions are coupled to other motions, including pitch, sway, roll, and yaw. The inventors claim that the propulsion system, which controls vehicle heave, can also effectively control the other motions.

The original system concept was designed to accommodate 6,000 passengers/h at vehicle speeds of 200-300 mi/h and at automatically controlled vehicle separation times of 1 min. A 1/25th-scale model (using LTSC magnets) was demonstrated on a 400-ft guideway.

Maglev Development at Rohr Industries and Boeing Aerospace Company. Rohr Industries began work on maglev systems in 1970. It developed the "ROMAG" system, which was tested in a top-suspended vehicle designed to carry six passengers and in a bottom-supported vehicle for 20 passengers (see Fig. B.5). Both vehicles were suspended from dual rails by attractive magnetic forces. The bottom-supported model, which was demonstrated at Transpo 72 (held at Dulles International Airport near Washington, D.C.), used a 0.4-in. air gap and reached a speed of 30 mi/h -- the limit for the 1,200-ft-long track. Rohr's top-suspended vehicle used a 0.5-in. air gap, was tested on a track that included a 10% grade, a 400-ft-radius turn, and a low-speed switching section. Each vehicle used four LIMs for propulsion, levitation, and guidance, with each motor individually driven and with variable voltage and frequency power to control lift, pitch, roll, and yaw. Air gaps were sensed with sliding-shoe contacts, and emergency braking was provided by passive skid pads.

In 1974, UMTA began the Advanced Group Rapid Transit (AGRT) project, awarding contracts to three firms to develop competitive systems. Boeing, Rohr, and Otis were selected to develop rubber-tire, maglev, and air-cushion candidate suspension systems, respectively. Rohr in 1977 presented test results from a high-speed, top-switch design for its top-suspended AGRT entry. The switch operated within a monorail guideway structure, as shown in Fig. B.6. According to Gilliland (1989), the primary reason for modifying the earlier design was to reduce the moment arm from the thrust plane of the motor to the vehicle's center of gravity. During acceleration, lift forces in the forward and aft halves of the motor are unbalanced, but reducing the moment arm decreases this unbalance. Either design requires an upper guide rail to prevent overturning.

Boeing acquired the rights to the Rohr maglev technology in 1978 and was awarded an UMTA contract to further develop the Romag (short-stator LIM) concept. Design goals were to improve the motor, power conditioning units, and levitation controls. The results were increased energy efficiency, reduced size and weight of the power conditioning unit (PCU), and development of a noncontacting gap sensor that eliminated the noise and wear problems associated with the original Rohr design.

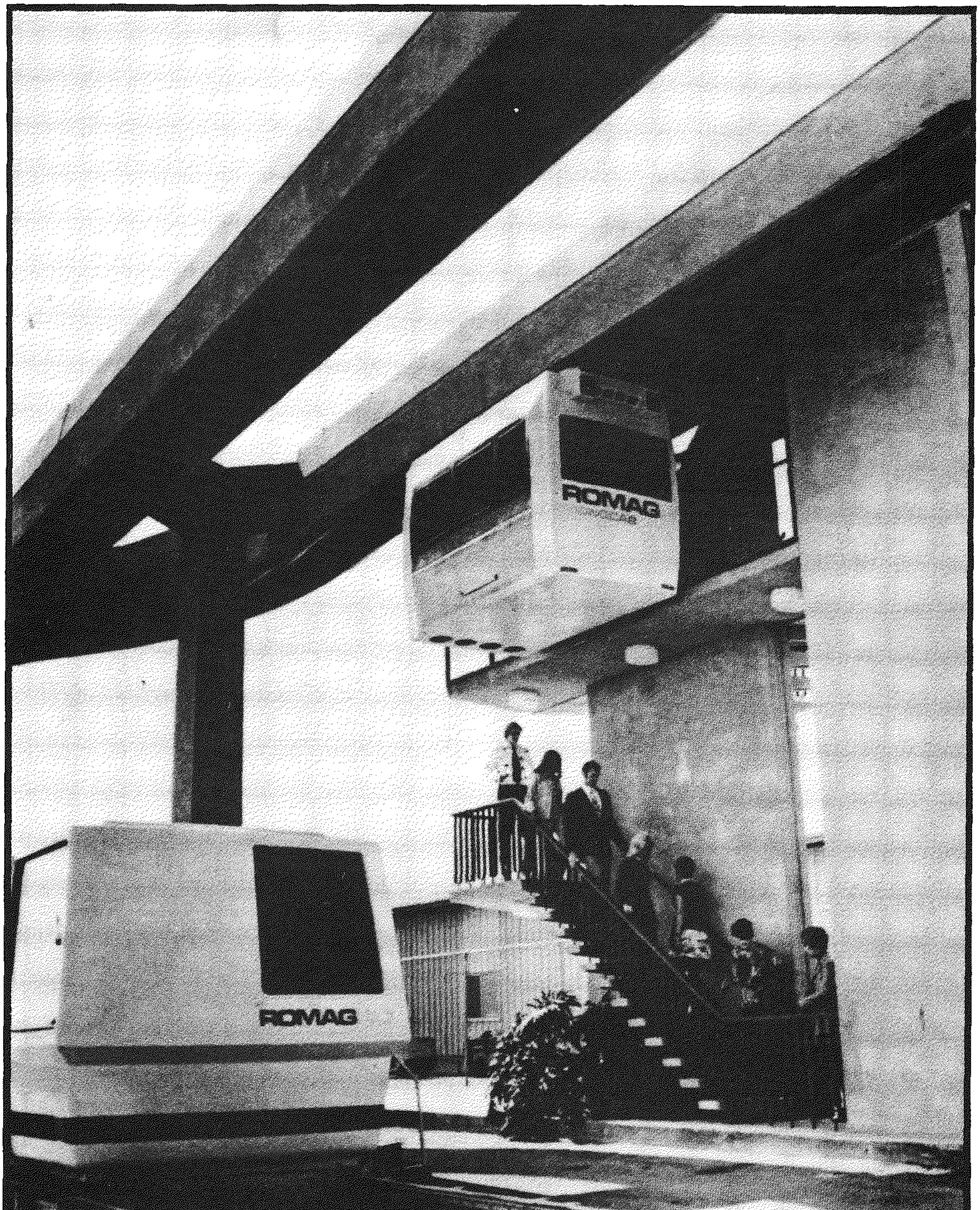


FIGURE B.5 Top-Suspended and Bottom-Supported ROMAG Vehicles at the Rohr Plant in Chula Vista, California (Source: Gilliland, Lyttle, and Pearson 1986)

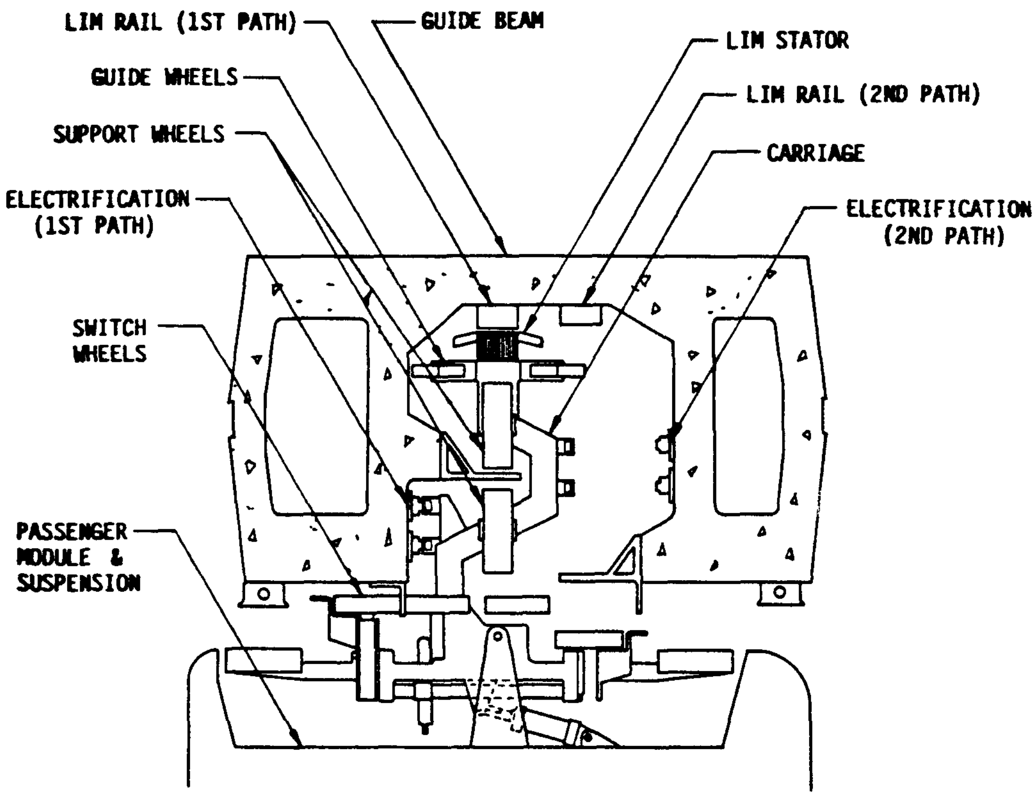


FIGURE B.6 Switch Used on the Top-Suspended ROMAG Vehicle. Vehicle Is Following Left Guide Surface (1st path). To Follow the Right (2nd path), the Right Guide Wheel Would Be Raised and the Left Lowered; This Occurs at an Earlier or Later Position, Depending on Direction of Travel, when Guide Surfaces Are Spaced for Simultaneous Capture (Source: Gilliland, Lyttle, and Pearson 1986)

In 1984, following the successful development and test of the LIM concept, Boeing's contract was modified to allow development of a short-stator LSM with permanent magnet bias. At the same time, it became obvious that the original performance requirements imposed by the AGRT program were not cost-effective for a maglev system. Performance requirements were therefore modified to allow for a higher-speed system with lower acceleration/deceleration characteristics than required for an AGRT (i.e., a short-headway, small vehicle) system. The technology favored a line-haul, longer-station-spacing application, and the result was the linear synchronous unipolar motor (LSUM), which replaced the LIM and also provided levitation, propulsion, guidance, and braking in a single unit (Fig. B.7). It also corrected three disadvantages of the LIM: its low power factor (<0.5), which requires an oversized power conditioning unit; its energy consumption for hovering, due to resistance losses; and its lift-off requirement for a current surge from the power conditioning unit that can exceed current levels for maximum thrust operation (Gilliland and Pearson 1986).

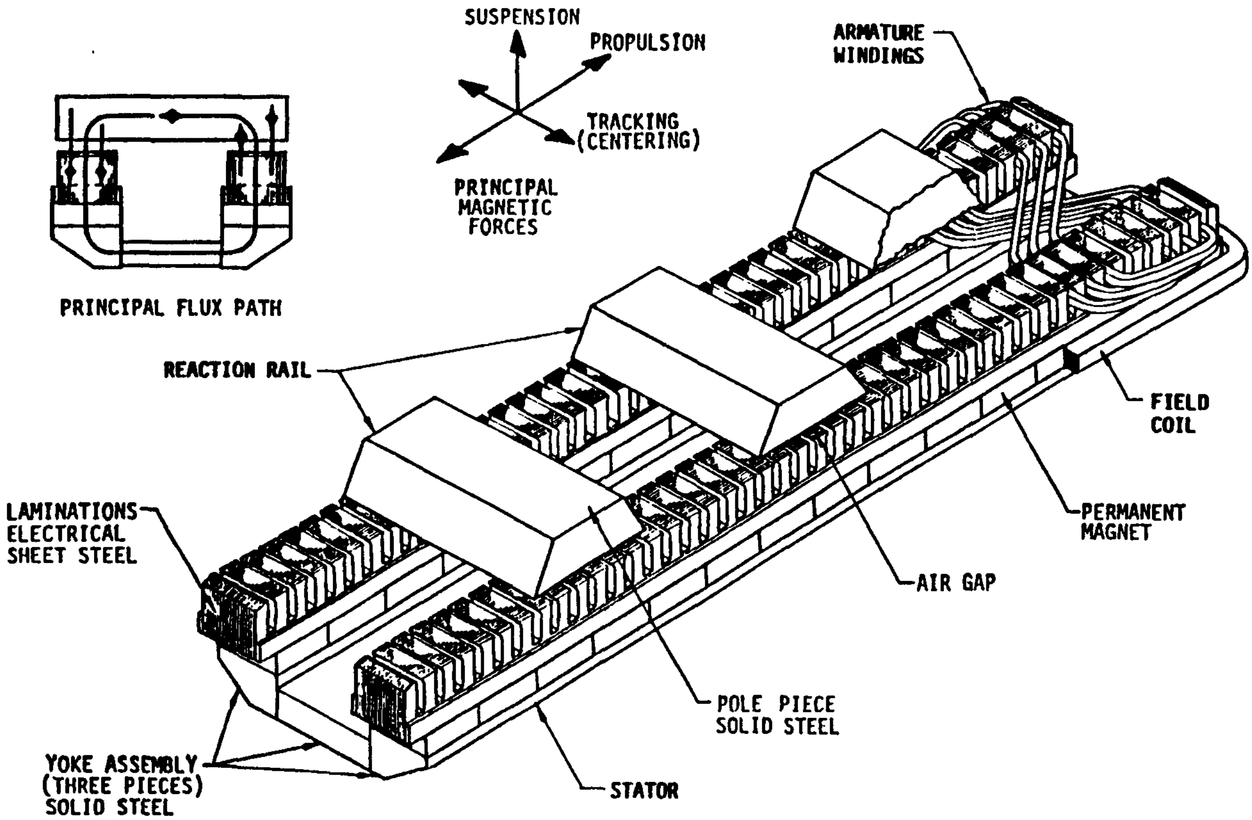


FIGURE B.7 Linear Synchronous Unipolar Motor Developed at Boeing Aerospace (Source: Gilliland, Lyttle, and Pearson 1986)

A first-generation LSUM was designed, built, and tested at Boeing. Although only static testing was performed, the results proved that the motor was more efficient than the LIM and that the use of rare earth magnets could provide additional lift without difficulty. Comparisons between the two motor designs are summarized in Table B.1. Boeing was interested in continuing the R&D program, pursuing a bottom-supported vehicle design, with additional federal funding from UMTA; however, decreased federal R&D funds -- as well as policy redirection on research -- forced UMTA to discontinue the program.

Because Boeing was unwilling to continue the work with its own funds at the completion of the program in 1986, the technology was licensed to the High-Speed Ground Transportation Center at Carnegie-Mellon. To assist in the transfer, UMTA provided nominal funding to Carnegie-Mellon through the Commonwealth of Pennsylvania; the federally purchased equipment at Boeing was also transferred to Carnegie-Mellon. Initial efforts will focus on the LSUM system, and there are plans to investigate the application of new superconducting technologies to maglev systems. Within the next four years, a 2,000-ft test track is planned. A likely application will be a moderate-speed line-haul people mover for Pittsburgh. The applicable speed range for this short-stator LSUM, relative to that of a long-stator LSM, deserves further attention. Moreover, the question of whether the short-stator technology could benefit from HTSC technology remains to be addressed.

TABLE B.1 Summary of Comparisons between Linear Induction Motor and Linear Synchronous Unipolar Motor

Criterion	Linear Induction Motor	Linear Synchronous Unipolar Motor
Energy consumption to hover	---	Significantly lower
Energy consumption at all speeds	---	Efficiency as good or better
Use of power-conditioning unit	High-thrust systems better; requires large current surge to lift off, which controls the power conditioning unit's size	Higher power factor at maximum power-conditioning-unit voltage and current; smaller power-conditioning unit; lift-off current from DC power supply
Capital investment	---	Lower net cost
Motor weight and cross-sectional size	Better; can lift 10 times its weight	Heavier and wider; can lift six times its weight
Lateral forces	Claimed to be adequate in some applications	Not adequate for guidance unless supplied with costly pole shapes
Anomaly reactions	Favored	May fail in up or down position; stator may snag permanent magnets

Source: Adapted from Gilliland, Lyttle, and Pearson (1986).

Alternating-Gradient Concept for Maglev Application. Although the use of magnetic levitation for high-speed ground transport has focused mainly on the two general methods of electrodynamic and electromagnetic suspension, relatively little attention has been given to the use of superconducting magnets with the latter system. The alternating-gradient concept (first proposed in Hull 1985) uses on-board superconducting magnets below the rails in positions similar to those of conventional electromagnets in an attractive maglev system. However, the iron rails are composed of alternating segments that are offset both vertically and horizontally (Fig. B.8).

This concept has the advantage of a large gap (approaching that of EDS systems), low magnetic drag, DC current in the vehicular coils, dynamic stability (achieved with alternating gradients established by the periodic changes in the rail configuration), and

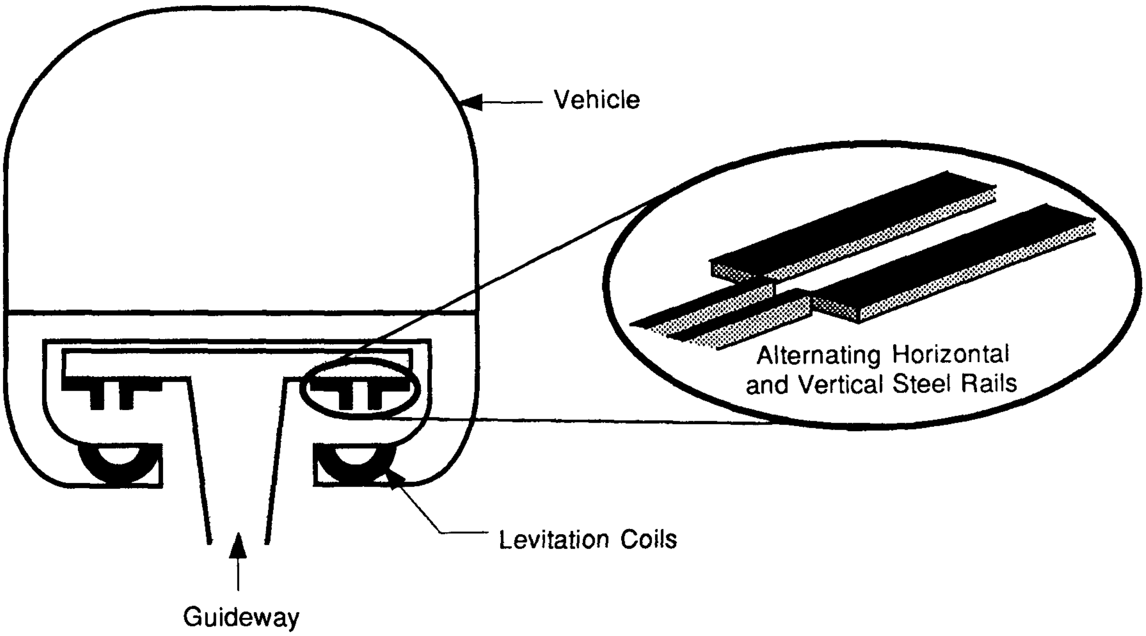


FIGURE B.8 Alternating-Gradient Concept

the use of laminated iron rails rather than passive coils or aluminum strips, which may permit a less expensive guideway. Placing the magnets below the iron rails should also result in little magnetic-field intrusion into the passenger compartment. The dynamic stabilization method is analogous to that used in strong-focusing synchrotron particle accelerators.

The alternating-gradient concept for use in high-speed maglev systems is still in the early stages of development. Some geometries have been analyzed for stability (Hull 1989), but factors such as trade-offs in ride quality vs. degree of track alignment have yet to be examined.

B.3.5 Maglev Development in West Germany

West German maglev development started in 1970; see Menden and Hartmann (1987) and Raschbichler and Wackers (1987) for historical accounts and Rhodes and Mulhall (1981) for a discussion of early work with EDS suspension systems. The West German government sponsored two maglev transportation research and development programs (Rhodes and Mulhall 1981). One was carried out by the Federal Department of Research and Technology, together with Krauss-Maffei and Messerschmitt-Bölkow-Blohm, and focused on EMS levitation. The second program was conducted by AEG-Telefunken, Brown Boveri, Siemens, and Linde and focused on EDS levitation. The EDS group developed a test facility at the Siemens Research Laboratories at Erlangen, West Germany (Rhodes and Mulhall 1981). Figure B.9 is a cross section of the Erlangen test track. The test vehicle, referred to as the "EET," used a double-sided LIM and

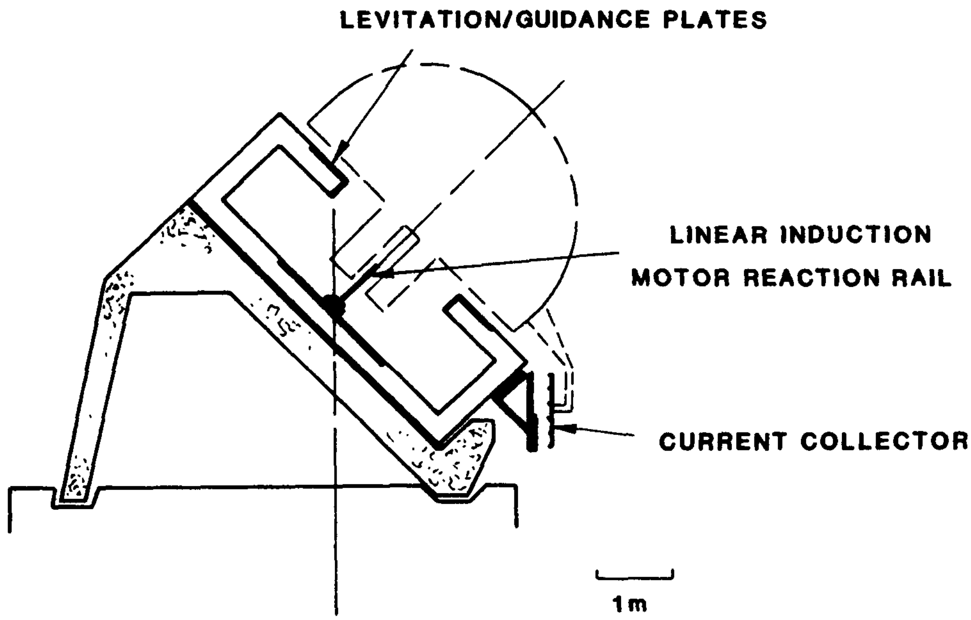


FIGURE B.9 Cross Section of Test Track at Erlangen, West Germany (Source: Adapted from Rhodes and Mulhall 1981)

carried eight superconducting magnets for lift and guidance, as well as a cryogenic cooling system. This configuration was abandoned in favor of the more efficient long-stator LSM, and the Erlangen test track was converted to allow testing of this concept. The new test vehicle, EET (02), ran on wheels and carried two superconducting field windings to test the propulsion system. In 1977, the West German government decided to terminate support for the EDS system. The technical reasons for this critical decision were not clear, but were almost certainly based on a determination that EMS was closer to commercialization than EDS because of the additional R&D required for the superconducting components.

West German Transrapid System. The EMS system development work in West Germany that led to the Transrapid system is described in Menden and Hartmann (1987) and Raschbichler and Wackers (1987). Early highlights include the first proof of feasibility with the Transrapid 01 test vehicle in 1970. Using a single-sided LIM for propulsion and an EMS suspension system, it attained a speed of 55 mi/h in 1970. Subsequently, using a double-sided LIM, the Transrapid 04 test vehicle reached 157 mi/h in 1973. In 1979, Transrapid 05 became the first test vehicle to carry public passengers. With the EMS suspension technology and an iron-core LIM, it attained 46 mi/h.

Development of the Transrapid Test Facility at Emsland (TVE) began in 1978 (see Fig. B.10). This facility is operated jointly by the German National Railway, Lufthansa Airlines, and IABG. Using the Transrapid 06 test vehicle, trial runs up to 250 mi/h were conducted in 1987. According to Meins, Miller, and Mayer (1988), empty vehicle weight is 112 tons and the payload is 22 tons. On-board power requirement is 450 kW. At

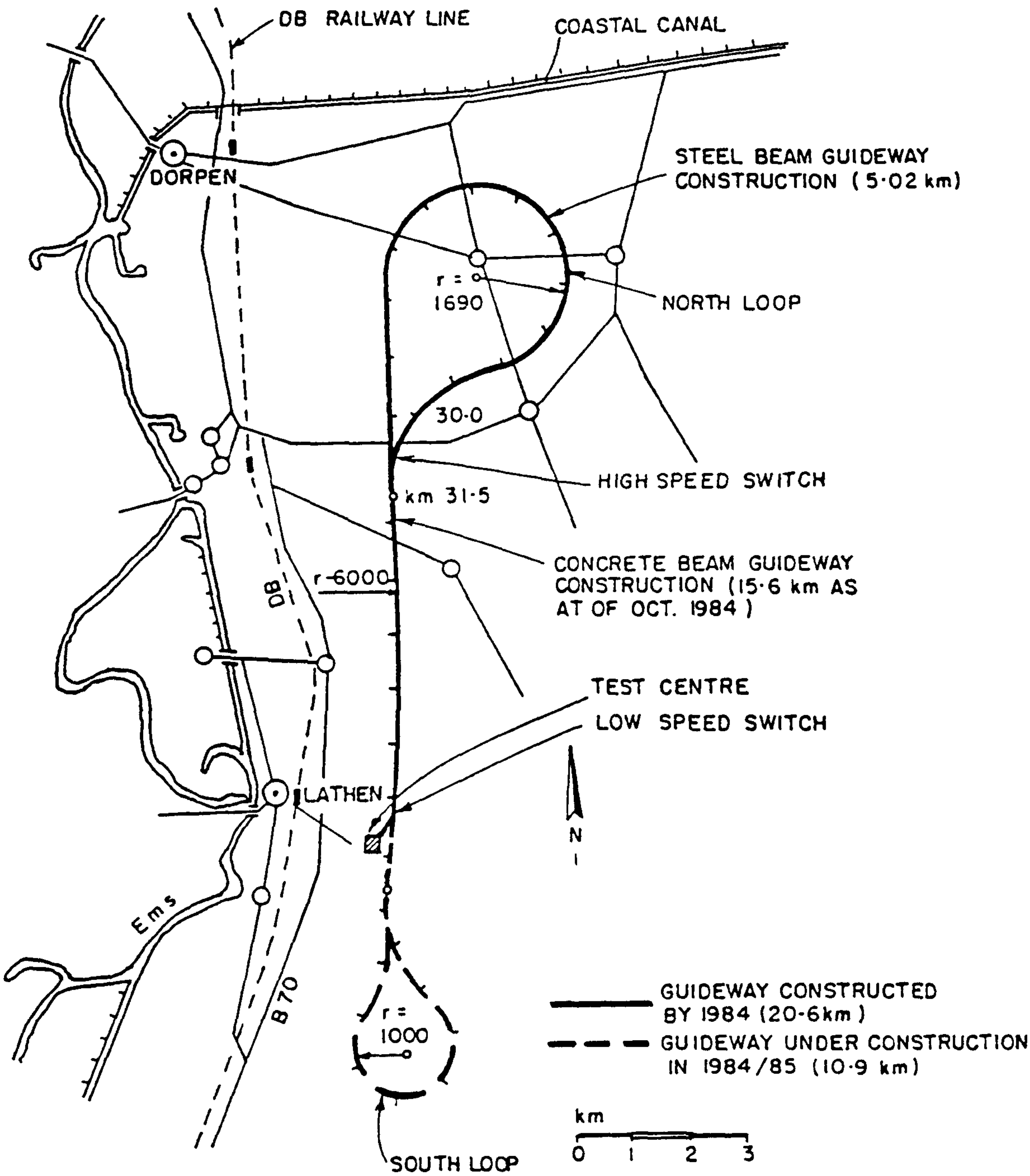


FIGURE B.10 Layout of Transrapid Maglev Test Track at Emsland, West Germany (Source: MVP 1985)

250 mi/h, tractive resistance is about 5 tons, which implies a 4.9-MW rate of energy expenditure for propulsion. Maximum thrust of the LSM is about 10 tons. If all this thrust were available for acceleration (i.e., no drag forces), maximum possible acceleration would be 0.07 g. The Transrapid TR06 test vehicle uses EMS suspension with an iron-core long-stator LSM propulsion system (Figs. B.11, B.12).

Testing of a new and lighter test vehicle, Transrapid 06-II (the prototype of the Transrapid 07 revenue vehicle), began in 1988. This vehicle is intended to (1) incorporate improvements in the electromagnetic levitation and guidance units that reduce dynamic loading on the vehicle batteries, (2) increase the safety and reliability of the levitation and guidance systems, and (3) eliminate the "touching of a levitation magnet" to the guideway rails. In addition, the guideway has been simplified and automated production techniques devised. This vehicle is expected to attain speeds in excess of 250 mi/h on the extended Emsland test track.

Some details of the Transrapid 06-II vehicle have been reported in Miller (1987). Important features include (1) the on-board power supply, which consists of four electrically separated battery and condensor-buffered networks per vehicle section, with decentralized supply via linear generators and boost converters for the electrical components; (2) magnetic control circuits with fail-safe monitoring to ensure noncontacting levitation in case of component failure; (3) fail-safe eddy-current brakes; and (4) skids for vehicle support if the magnets are deactivated. The empty vehicle weighs about 88 tons and has a 22-ton payload. It can reach about 280 mi/h (and higher, with some component changes). Primary braking is furnished by the LSM acting as a dynamic brake; backup braking is provided by a separate set of magnetic braking units.

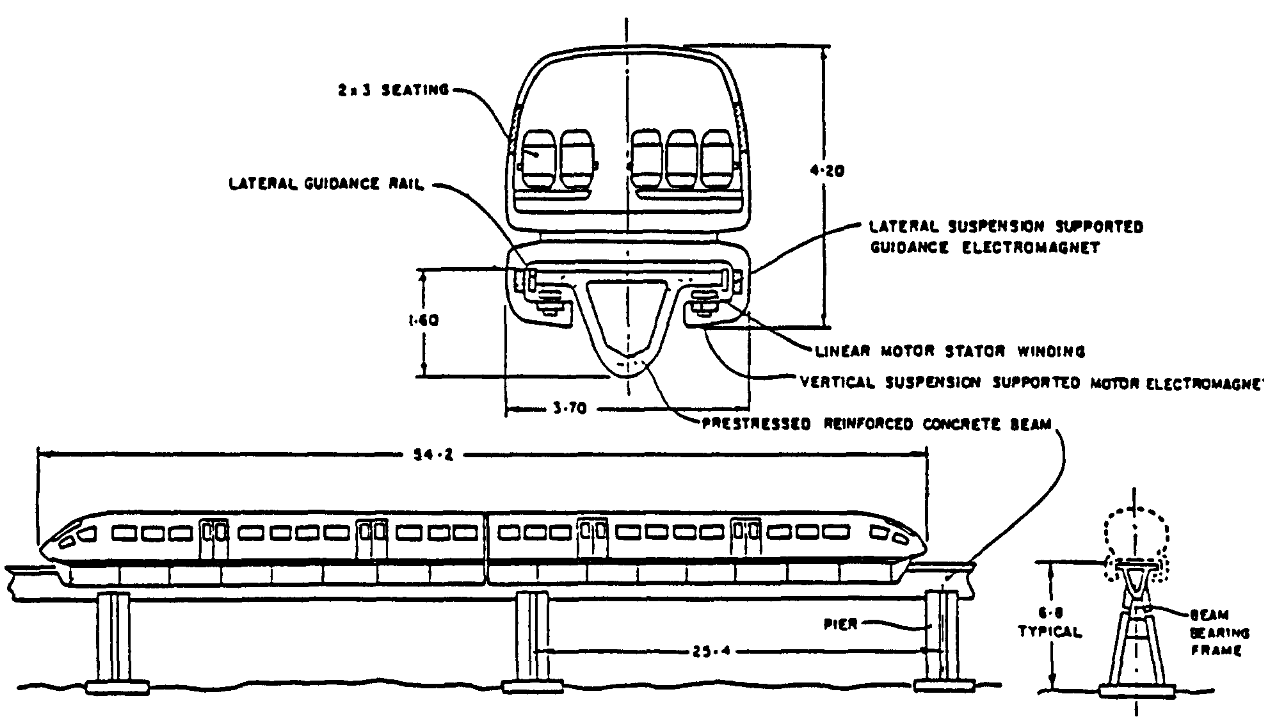


FIGURE B.11 Transrapid TR-06 Maglev Train Set (Source: Boon et al. 1987, ©1987-IEEE)

Separate on-board magnets are used for guidance and support on both Transrapid 06 and 06-II. Propulsion is achieved through interaction between iron-core stator windings mounted on the guideway and levitation coils mounted on the vehicle. Levitation is provided by attraction of the levitation coils to the iron cores placed between the stator windings on the guideway. For illustrations, see Merklinghaus and Mnich (1987), Stockl and Schwindt (1987), and Raschbichler and Wackers (1987). A similar configuration is evidently planned for a future revenue vehicle designated as Transrapid 07 (see figures in Boon et al. 1987).

M-Bahn. The West German M-Bahn is a fully automated, short-distance maglev rapid transit system. Its operation is not completely free of contact. Vehicle-borne permanent magnets provide levitation in the attractive mode (see Fig. B.13), and propulsion is by LSM. Stator windings in the guideway interact with the on-board permanent levitation magnets to produce forward thrust. At the same time, vehicle-borne permanent magnets attract the laminated iron cores of the stator windings to produce the attractive levitation force for primary vehicle suspension. The attractive force is matched to the loaded vehicle weight by a spring and lever system and vertically mounted mechanical rollers that adjust the air gap. Horizontally mounted mechanical rollers provide lateral guidance. According to Dreimann (1987), the vertical rollers carry no load except for "small nonlinear residual forces and dynamic forces due to guideway misalignments." Vehicle speed is controlled by the frequency of the stator winding excitation current.

Only one section of the stator winding is energized at a time (in the vicinity of the train), to minimize energy losses. Switching from one section to the next is current-free because the inverter supplying the power is interrupted for 20 ms during the switch. Propulsion power is supplied via constant-voltage DC links to the substations, and inverters in each substation supply power (controlled variable voltage and variable frequency) to the corresponding guideway sections via feeder cables. The tractive force produced by the LSM is 4 tons per vehicle up to 25 mi/h and 2 tons thereafter, up to a maximum of 50 mi/h.

Component endurance testing with one vehicle and a 1,970-ft-long test-track section was completed in the fall of 1984, and operational testing of subsystems commenced thereafter. In 1986, approximately 43,000 mi were covered during automatic train operation with empty and loaded vehicles. All subsystems were shown to be ready for revenue service. Running noise was found not to exceed 65 dbA, and the only audible noise was generated by the linear motor.

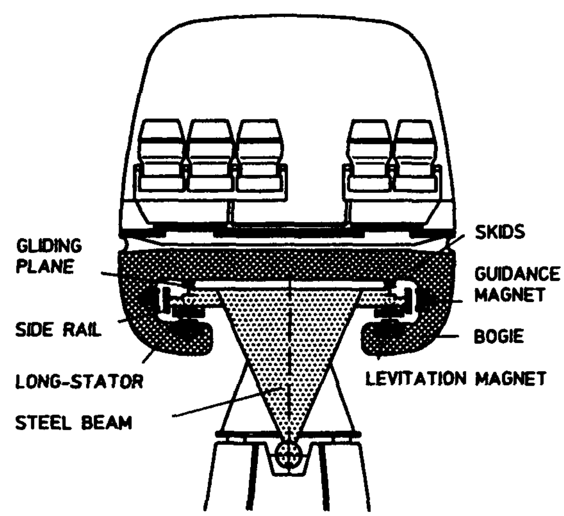
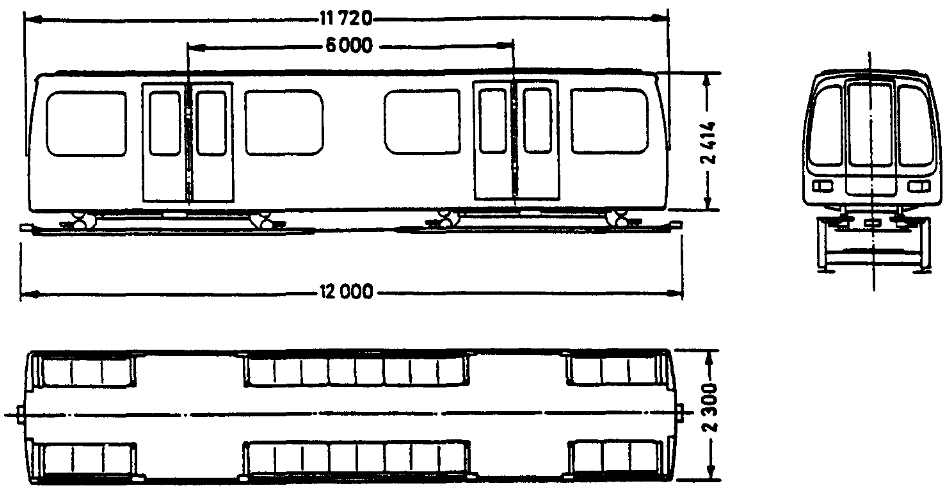
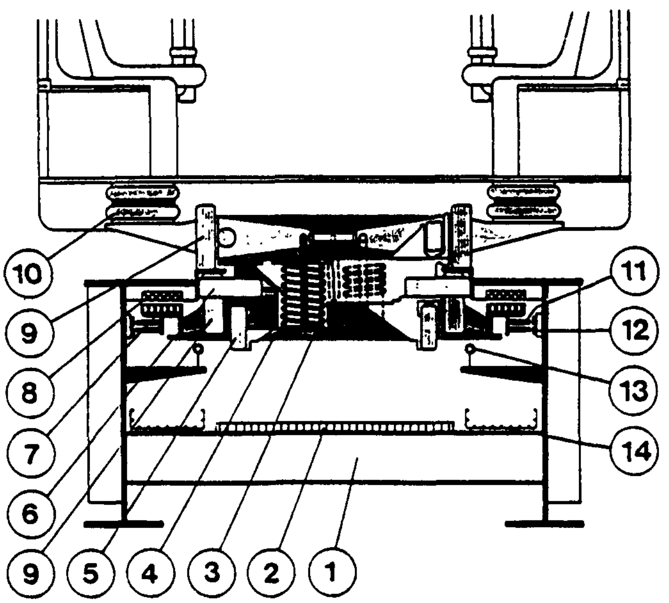


FIGURE B.12 Wraparound Structure of Undercarriage Used in Transrapid Attractive-Force Levitation Suspension System (Source: Hessler and Wackers 1986, ©1986-IEEE)





1	Guideway Cross Section
2	Emergency Escape Path
3	Primary Suspension/Air Gap Control
4	Bogie
5	Switch Guidance Rollers
6	Horizontal Guide Rollers
7	Permanent Magnets
8	Travelling Field Stator
9	Vertical Guide Rollers
10	Secondary Suspension/Air Spring
11	Collector
12	Auxiliary Power Rail
13	Line Conductor
14	Cable Duct

FIGURE B.13 M-Bahn Vehicle Type M80/2 Used on the Berlin Reference System, and Cross Section of M-Bahn Attractive-Force Suspension System (Source: Dreimann 1987, ©1987-IEEE)

Energy consumption was found to be lower than that for conventional railway cars because of the vehicle's light weight. The absence of weight-carrying wheels, heavy bogies, traction motors, and power-conditioning equipment on board reduces the empty weight of the vehicles by more than 50%. Because of this reduction and because of the relatively low vehicle height, some construction costs can be saved on rights-of-way. Maximum vehicle speed range is 25-50 mi/h, depending on station separation. Its most economic configuration is a train consisting of two 7.5- x 39-ft cars, each with a capacity of 130 passengers. Each car is carried on two bogies with an air-spring secondary suspension system, while lateral and longitudinal forces are transmitted to the car body through rubber springs. Power is delivered to the car by sliding contacts and power rails.

Operation of the complete M-Bahn system began on a "reference line" in Berlin in May 1987 (Eck 1987). Public service is provided by single- or double-coach trains with a normal separation of 3.5 min, which corresponds to a maximum capacity of 7,000 passengers/h. Overall track length is 8,200 ft, of which 3,200 ft is dual track.

The M-Bahn rapid transit system appears to be an attractive alternative to conventional systems in other locations as well. In Las Vegas, for example, construction of an M-Bahn system is reported to have begun in the fall of 1987 (Huss and Sulkin 1987). In fact, construction actually began in late 1988 (Welch 1989). The project is being undertaken jointly by the City of Las Vegas, Magnetic Transit of America, Inc. (MTA), and Daniel, Mann, Johnson, and Mendenhall (DMJM). MTA has the exclusive license for M-Bahn in the United States, Canada, and Taiwan. The line will consist of an elevated dual-track guideway 1.3 mi long. Initially, this people-mover system will have six vehicles that can operate singly or in two-car train sets. Each vehicle has 26 seats and room for 64 standees. Empty and fully loaded weights are 10 and 20 tons, respectively. Public service operation is scheduled to begin about three years from the start of construction (Welch 1989).

B.3.6 Maglev Development in Japan

Studies of ways to eliminate reliance on frictional adhesion between wheels and rails began in the early 1960s in Japan (JNR 1983). Several large-scale test facilities were constructed to investigate EMS and EDS suspension concepts and various propulsion systems. An LSM test vehicle and a magnetic levitation demonstration vehicle (ML-100) were both levitated by Japanese National Railway (JNR) in 1972 (Oshima and Kyotani 1974). Both vehicles used mechanical guidance. Work began on a 2.9-mi-long linear test track at Miyazaki on Kyushu Island (in southern Japan) in 1974; the track was later extended to 4.3 mi. Running tests began in 1977 with the ML-500 vehicle. This 11-ton vehicle employed an EDS levitation system and had retractable rubber wheels for support and guidance at low speeds. Straddling an inverted T-shaped guideway, the vehicle used both electrodynamic braking (via the LSM used for propulsion) and a backup mechanical braking system that pressed a brake shoe onto an I-beam mounted atop the vertical stem of the inverted T (JNR 1980).

The vehicle carried four helium cryostats, each enclosing two superconducting coils mounted horizontally for levitation and two coils mounted vertically for guidance and propulsion. There were 16 magnets in all. The vehicle-borne levitation coils interacted with two rows of aluminum coils set in the guideway to produce the repulsive levitation force. Cryostats were operated as sealed systems and had a duration of about two hours before recharging was necessary. A powered stator winding in the guideway interacted with the vehicle-borne, vertically mounted superconducting coils to produce vehicle propulsion and a null-flux type of lateral guidance.

Designed for stable operation, the ML-500 used an air gap of 3.9-4.7 in. A world speed record for an unmanned vehicle was set at 517 km/h (323 mi/h) in 1979 and still holds (Ozeki 1987). This early work was largely supported by JNR. Later, the Japanese

Ministry of Transportation supported the maglev technology development work and extended it considerably. The inverted T-shaped guideway at Miyazaki was replaced in 1980 by a U-shaped guideway, and testing began on the MLU series of maglev vehicles, starting with MLU001 in 1981 (JNR 1983).

A parallel development was undertaken using the EMS suspension concept in the HSST vehicle series. This work, originally supported by Japan Air Lines Co., Ltd. (JAL), was taken over recently by the HSST Corp., which has acquired all rights and technology from JAL.

Development and testing of the MLU vehicle series, which uses the EDS levitation concept, and the HSST vehicle series, which uses the EMS levitation concept, continue today. Both are further described below.

Japan Railway Technical Research Institute. In early 1987, the government-owned JNR was dissolved. Responsibility for maglev research and development at the Miyazaki test track was transferred to the Railway Transportation Research Institute, which is funded jointly by the government and several railway companies created by the JNR privatization. Institute president M. Ozeki (1987) has stated that maglev technology research will accelerate after the divestiture.

The MLU001, described in some detail in Tanaka (1985), consists of a three-car train 94 ft long and with a mass of about 33 tons. Space in each car is divided equally between passenger seating and equipment (e.g., inverter, battery, and instrument control unit). Each car has eight vertically mounted superconducting coils distributed in two rows along its body and providing all three functions (i.e., suspension, guidance, and propulsion). Rubber wheels are used for suspension and guidance at low speeds when the repulsive magnetic force is insufficient for levitation. Following tests of various configurations, the optimal arrangement was found to be individualized refrigeration systems for each magnet or pair of magnets and a single compressor for each car.

Manned test runs began in September 1982; speeds of 138 mi/h were reached with a three-car set, 189 mi/h with a two-car set, and 249 mi/h with a single car. Speeds were limited by substation power supply and length of the test guideway (Japan Rolling Stock Exporters' Assn. 1986). In tests at speeds up to 185 mi/h with irregularities built into the guideway, performance was satisfactory over irregularities that would have derailed a conventional train (Tanaka 1985).

The U-shaped Miyazaki guideway contains coils for propulsion and guidance in the sidewalls and coils in the bottom for suspension (see Fig. B.14). Maximum feasible thrust is 5.7 tons (Mitsui 1984), and maximum electrodynamic drag -- encountered at about 30 mi/h -- is about 2 tons. Aerodynamic drag increases with speed to a value of about 2 tons at 310 mi/h. The levitation force increases with speed and equals the vehicle weight (lift-off condition) at about 60 mi/h, while the lateral guidance force also increases with speed and reaches a maximum of about 4 tons at 125 mi/h. In tests conducted in late 1986 and early 1987 -- after installation of a new substation -- the MLU001 vehicle in a three-car configuration reached speeds of 218 mi/h, while a manned, two-car set attained about 250 mi/h (Tanaka 1987).

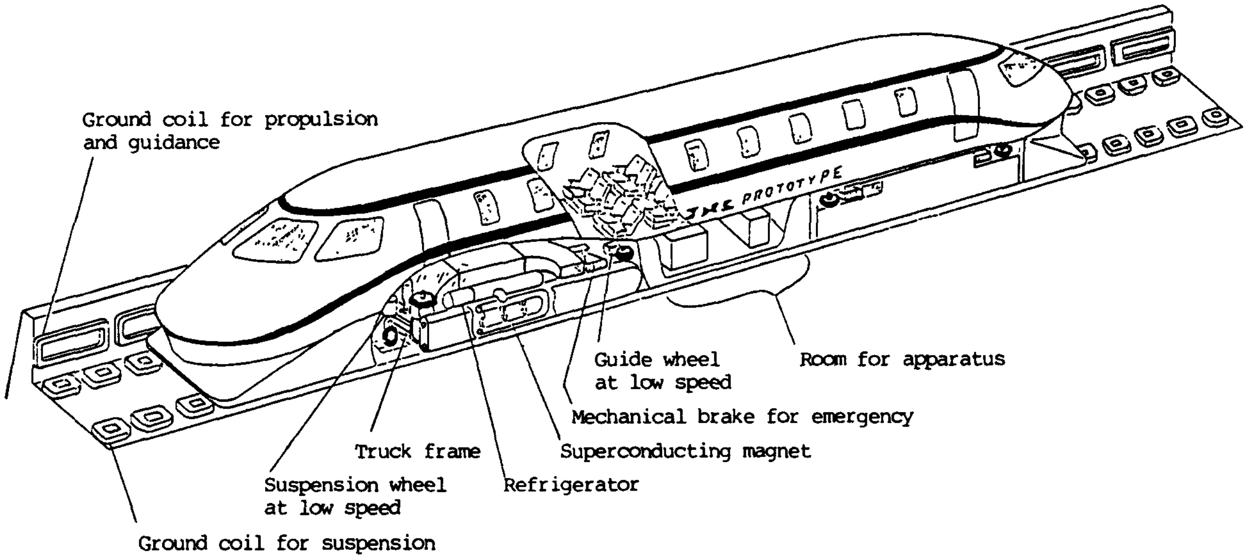


FIGURE B.14 Japanese MLU002 Maglev Vehicle and Guideway, Showing Discrete Horizontal Suspension Coils and Vertical Coils Used for Propulsion and Guidance (Source: Kyotani and Tanaka 1986, © 1986 IEEE)

Tests of a new version, MLU002, began in 1987 (Kyotani 1988). Unlike its predecessor, this 19-ton, 44-passenger version has six superconducting coils per side and concentrates them at bogies. Design work on the first revenue vehicle has also begun. It will consist of a train of up to 14 cars with bogies at the articulation points; each bogie will have two magnets per side. This configuration yields a lower center of gravity for a more stable ride and reduces the magnetic field intensity in the passenger compartment. This revenue vehicle is planned for fabrication after two years of testing the MLU002 vehicle.

Each vehicle-borne superconducting coil in the MLU002 vehicle serves all three functions (see Fig. B.15). The propulsion system draws a maximum current of 900 A at 5,800 V, and the range of operating frequency is 0-28 Hz. Guideway design is the same as that used for the MLU001 vehicle. Maximum design speed is 260 mi/h and peak thrust is 9 tons. The suspension and guidance air gaps are 4.3 in. and more than 5.9 in., respectively.

Further information on substation design at Miyazaki and the MLU002 test vehicle, as well as design specifications for a commercial vehicle, is given in Japan Rolling Stock Exporters' Association (1988).

Japanese HSST Maglev System. The HSST Corp. has taken over development of the HSST maglev system, which was started by JAL. The HSST-03 system operated for 184 days in 1985 at Expo 85 in Tsukubu, Japan, carrying a total of some 600,000 passengers. Normal-conducting electromagnets are used for combined levitation, lateral

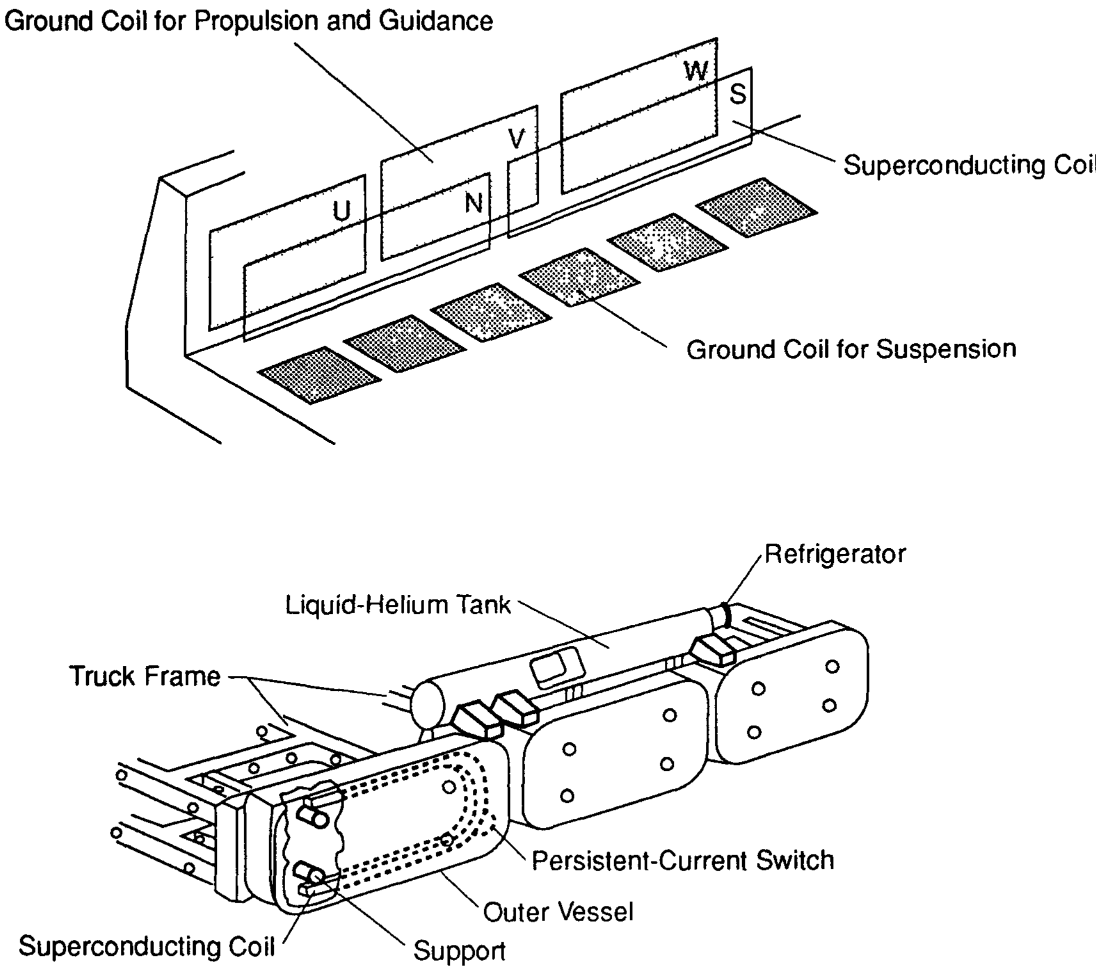


FIGURE B.15 Japanese MLU002 Maglev Vehicle: *top*, Guideway Coils and Single, Vertically Mounted, On-Board Superconducting Coil for Suspension Guidance, and Propulsion; *bottom*, Superconducting Coil and Refrigeration Module (Source: Adapted from Tanaka 1987)

guidance, and propulsion. Empty and loaded weights are 13 and 16 tons, respectively. The vehicle holds 40 fixed and eight retractable seats. At its normal operating speed of about 20 mi/h on its 1,150-ft track, the HSST-03 operated remarkably trouble-free. Only 49 min were lost because of system problems.

The HSST-03 vehicle also operated at Expo 86 in Vancouver, British Columbia. With two curved portions, the track was 1,480 ft long, allowing operating speed to increase to 25 mi/h. After Expo 86 ended, the system was moved to Okazaki, Japan. Both DC and three-phase variable voltage, variable frequency power are fed to the vehicle for levitation and propulsion, respectively, by brush contact with energized cables.

The HSST-04 vehicle, which uses the EMS levitation concept and operates at 25 mi/h with a 0.4-in. air gap, was demonstrated from March to May 1988 at the Saitama Exposition in Japan. With some component changes, its operating speed could be increased to 185 mi/h for commercial use, according to the authors (Suzuki, Murai, and Kawashima 1987). This vehicle is 64 ft long, 10 ft wide, and 12 ft high; in its 70-seat configuration, empty and loaded weights are 20 and 26 tons, respectively. Power is fed to the vehicle by dual 750-V DC power rails, while propulsion is provided by eight LIMs that are fed three-phase AC power by an on-board inverter. An on-board chopper provides regulated DC power for the levitation magnets.

A modified version called the HSST-200 will be operated in a two-car train set as a licensed transportation system at the Yokohama exposition from March to October 1989. With a route length of about 1,900 ft, the HSST-200 will reach a cruising speed of 37 mi/h (Takatsuka 1988).

B.3.7 Canadian Maglev Development

Development of maglev technology in Canada began in the early 1970s under the auspices of the Transportation Development Center of Transport Canada; for a review and status report, see Fife et al. (1986). Present system design has evolved from contracts with several Canadian university groups (i.e., Queens, Toronto, and McGill), the National Research Council, and industry (CTF Systems, Inc.). The impetus for the work has been the desire to develop a high-speed ground link for the 600-mi Toronto-Ottawa-Montreal corridor.

The original system design called for a 100-passenger vehicle that cruises at speeds up to 300 mi/h (Atherton et al. 1977). The vehicle is supported by an EDS levitation system atop a flat guideway. Separate superconducting coils on the vehicle, which provide lift and guidance, are assisted by retractable wheel sets for low-speed support and guidance. An LSM provides vehicle propulsion and braking. The track consists of two parallel aluminum strips carrying the eddy currents that give rise to the levitation force, an air-core stator winding for the LSM, and two null-flux windings that provide lateral guidance with minimal magnetic drag. Design of the parallel aluminum eddy current strips is intended to minimize magnetic drag forces and cost (i.e., they are thickest in low-speed regions).

The present design differs from the original in several respects (Hayes and Tucker 1984; Campbell et al. 1986; Fife et al. 1986). Of major importance is the box-type guideway structure (see Fig. B.16) with aluminum strips on its top surface for levitation and the null-flux guidance coils and LSM stator winding on its sides. This design was estimated to save 5-35% on construction costs while improving safety. Another change is the use of two-car, bidirectional train sets designed to cruise at up to 280 mi/h. The vehicle-borne levitation and combined propulsion/guidance magnets are mounted horizontally and vertically, respectively, as shown in Fig. B.17. Superconducting coils of NbTi, isothermally cooled by on-board cryocoolers, are used in lieu of the Nb_3Sn superconducting coils cooled isochorically on the original design. Each car has nine LSM solenoids per side, grouped in sets of three. Each triplet, together with its

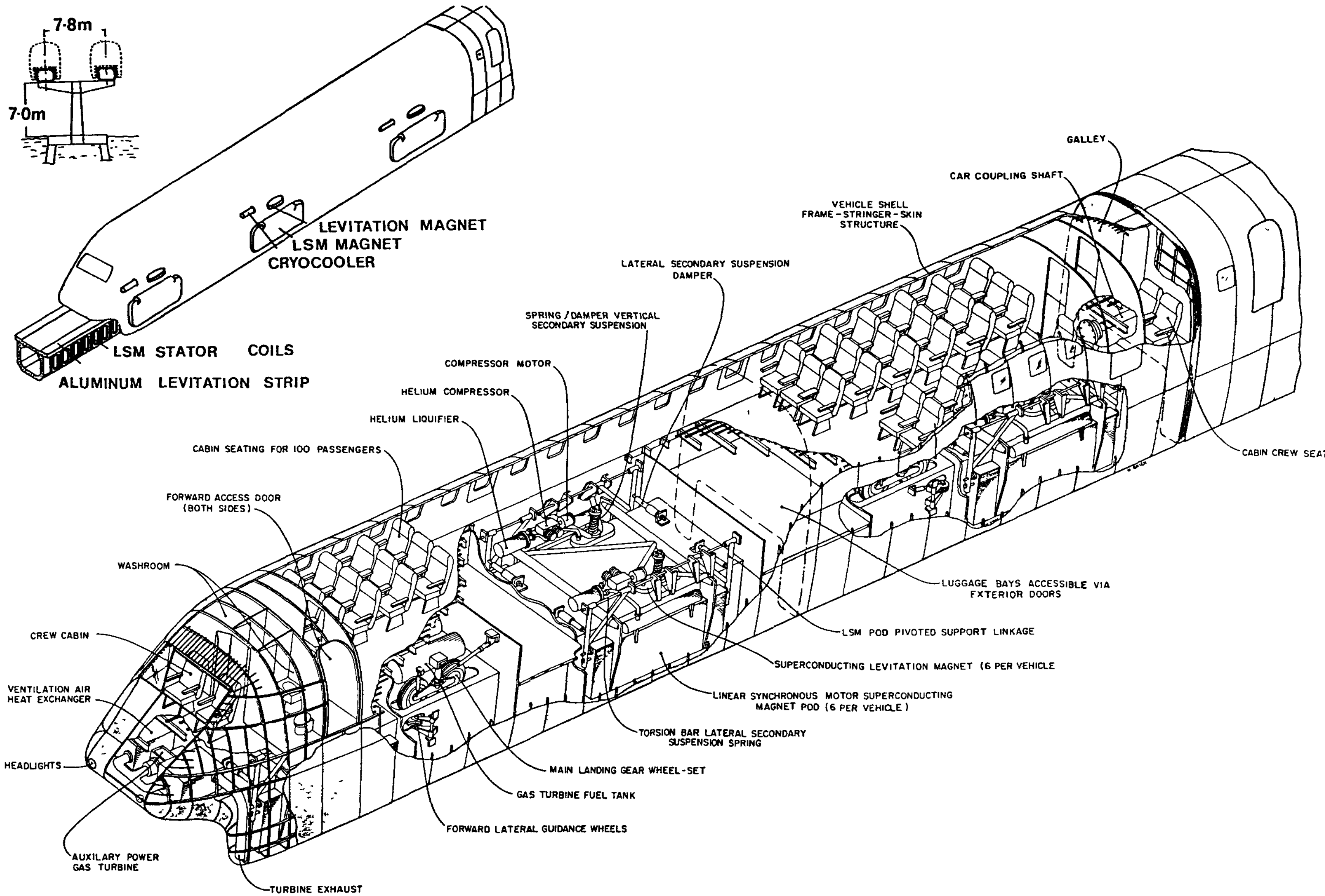


FIGURE B.16 New Canadian Maglev Design (Source: Fife et al. 1986, ©1986-IEEE)

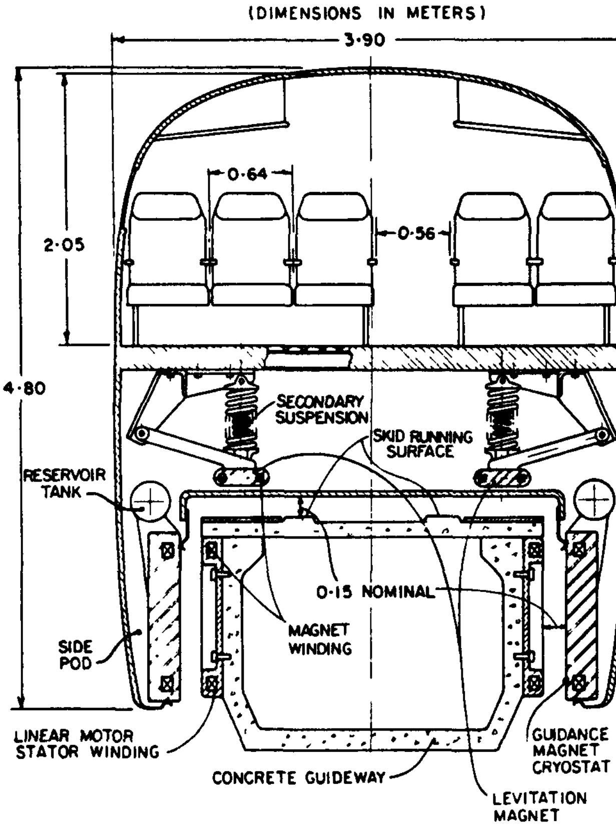


FIGURE B.17 Magnet and Coil Arrrangement in New Canadian Maglev Design, Showing On-Board Levitation Magnets and Combined, Vertically Mounted Guidance and Propulsion Coils (Source: Hayes and Tucker 1986, ©1986-IEEE)

cryocooler and a set of levitation coils, forms an integrated module that is removable for servicing. A design development under consideration is elimination of the separate levitation coils and use of a single system for propulsion and levitation.

In addition to these design changes, recent efforts have focused on improvements in magnet and dewar design. Recent findings include the following (Fife et al. 1986):

- Conductor weight can be minimized for a given fill factor at the expense of increased current density and peak stresses.

- Variation in the coil section from square to rectangular (aspect ratio 2) decreases the conductor weight and increases the stress levels by roughly 10%.

- Coils with pancake shapes are preferred, but lead to greater stresses, reduced stiffness, and greater cooling difficulties.

Based on these findings, rectangular LSM coils with an aspect ratio of 2 and square levitation coils were selected. Relatively large-diameter wire is preferred to meet the requirements of a large coil fill factor and a stiff coil structure. NbTi wire with a copper ratio of 2 has been selected for the first prototype coils. Progress has also been reported in designing coil frames and cryostats and in developing techniques for fabricating epoxy-impregnated coils.

B.3.8 Romanian "Magnibus"

Magnetic levitation studies began in 1976 at Romania's Polytechnic Institute in Timisoara (Boldea et al. 1984). Following theoretical and laboratory studies in 1976-79, a test vehicle (Magnibus 01) and a 93-ft-long test track were built. The 3-ton vehicle, which is 13 ft long, used on-board integrated attractive-force levitation and an LSM system for primary suspension and propulsion, together with a separate set of electromagnets for guidance. A secondary mechanical suspension system couples the vehicle body to an undercarriage, which is wrapped around the underlying guideway; this allows vehicle weight to be suspended below the horizontal guideway rails by the attractive magnetic force (see Fig. B.18). An entirely passive guideway structure is

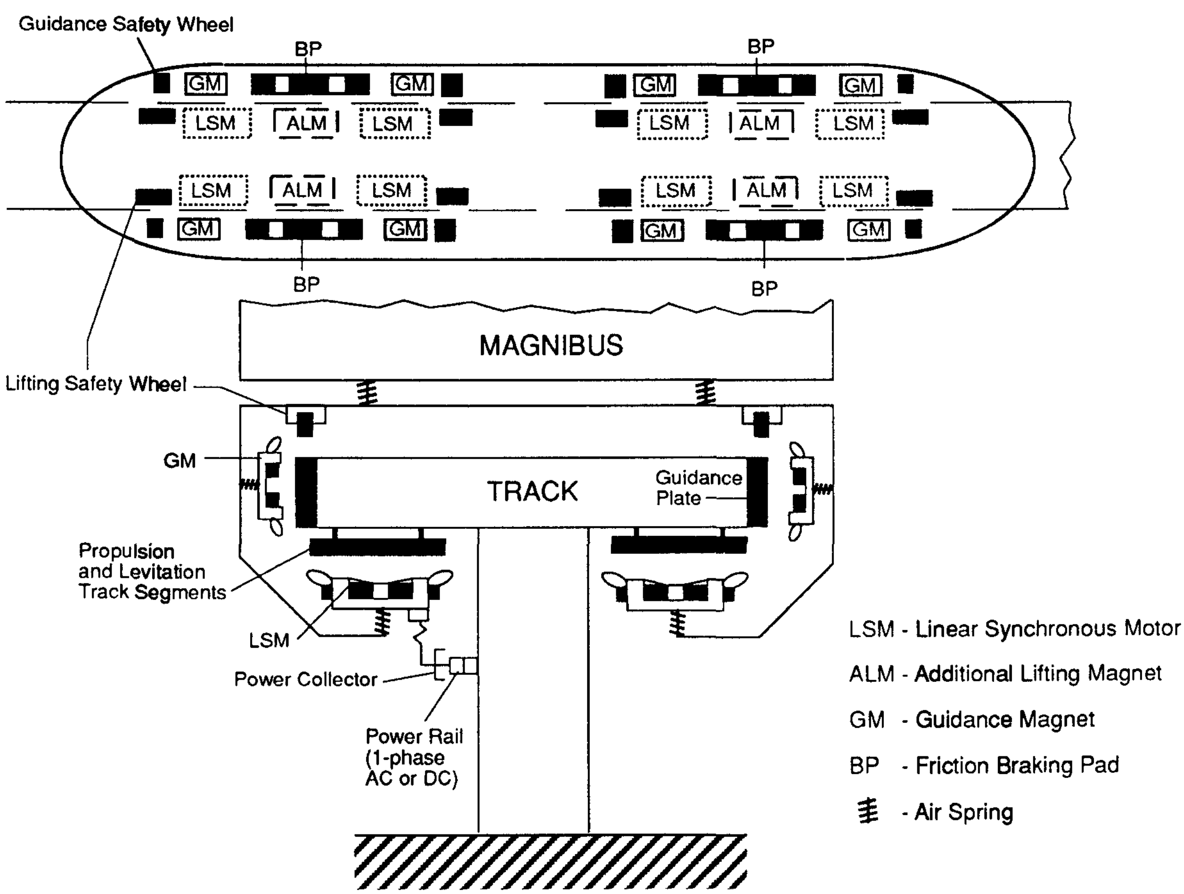


FIGURE B.18 Typical Structure of Romanian Magnibus (Source: Adapted from Boldea et al. 1984)

used, and power is supplied to the vehicle by cast-iron brush-type contactors sliding on three-phase and DC power rails.

Both urban and high-speed applications were considered. For urban applications, the LSM provided adequate thrust and lift. For high-speed applications up to 250 mi/h, additional iron-core electromagnets were required to provide the necessary lift. The LSM and the additional lift magnets were placed in alternating sequence along each side of the vehicle undercarriage. Solid iron segments were placed along the guideway's undersides for propulsion and levitation, and solid iron plates were used along the guideway sides for guidance. Four LSMs each developed 0.07 ton of thrust and 0.8 ton of lift. On-board equipment included a power conditioner consisting of a controlled rectifier and current inverter for the four LSMs, together with eight thyristor choppers to drive the levitation and guidance coils. Regenerative braking is used above 3 m/s (7 mi/h). Emergency friction brakes were also installed.

At the time the cited article was written (1984), the Magnibus 01 had been tested only statically. Track testing was scheduled to begin soon. In parallel with the Magnibus 01 testing program, a high-speed prototype vehicle (Magnibus 02) was being designed. It was expected to weigh 39 tons and carry 64 seated passengers at speeds up to 185 mi/h. A new single-phase power feed was being considered for this vehicle. Its construction, together with a 0.6-mi test track, was planned for the 1984-85 time frame. A subsequent 5-mi test track was planned for 1986-88. According to Eastham (1989), neither of these test tracks have been built.

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