

**Report to Congress:
Costs and Benefits
of Magnetic Levitation**



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



September 2005





U.S. Department
of Transportation

**Federal Railroad
Administration**

Administrator

**1120 Vermont Ave., NW.
Washington, DC 20590**

SEP 13 2005

The Honorable Thad Cochran
Chairman
Committee on Appropriations
United States Senate
Washington, DC 20510

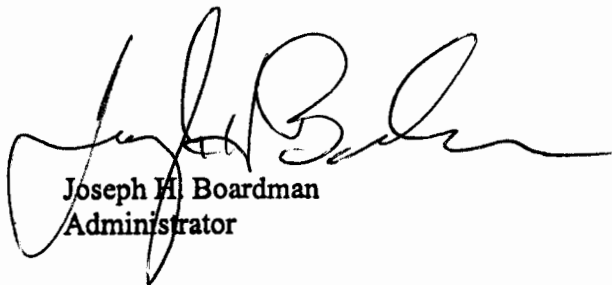
Dear Mr. Chairman:

House Report 108-401, the Conference Report to Accompany P.L. 108-199 (the Consolidated Appropriations Act, 2004, Division F: Departments of Transportation and Treasury, and Independent Agencies Appropriations Act, 2004), dated November 25, 2003, requested the Federal Railroad Administration to provide to the House and Senate Committees on Appropriations a report comparing the costs and benefits of magnetic levitation to other modes of travel.

I am pleased to submit the report as requested.

Identical letters have been sent to the Ranking Member of the Senate Committee on Appropriations, and to the Chairman and Ranking Member of the House Committee on Appropriations.

Sincerely,

A handwritten signature in black ink, appearing to read "Joseph H. Boardman".

Joseph H. Boardman
Administrator



U.S. Department
of Transportation

**Federal Railroad
Administration**

Administrator

**1120 Vermont Ave., NW.
Washington, DC 20590**

SEP 13 2005

The Honorable Jerry Lewis
Chairman
Committee on Appropriations
United States House of Representatives
Washington, DC 20515

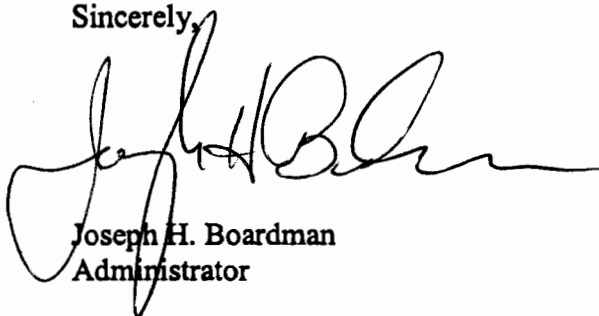
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Joseph H. Boardman
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COVER PHOTO ACKNOWLEDGEMENT: Ronald A. Mauri of the Volpe National Transportation Systems Center, Cambridge, Massachusetts, took and contributed the cover photos of the Yamanashi Maglev test facility and vehicle in Japan (top and bottom) and of the Transrapid vehicle operating in Shanghai, China (center).

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Executive Summary:

COSTS AND BENEFITS OF MAGNETIC LEVITATION

In response to a Congressional request to compare the costs and benefits of magnetic levitation (Maglev) with those of other modes, this report provides technical background on this new form of transportation, identifies the types of travel markets that it could optimally serve, estimates its likely capital costs, and assesses the likely return—in terms of transportation service and economics—on the commitment of resources that Maglev investments would require.

What Is Maglev?

Maglev is an advanced transport technology in which magnetic forces lift, propel, and guide a vehicle over a specially designed guideway. Utilizing state-of-the-art electric power and control systems, this configuration can reduce or eliminate the need for wheels and many other parts, thereby minimizing mechanical friction and permitting excellent acceleration, with cruising speeds on the order of 300 mph or more. Thus Maglev, if built on alignments that support its highest capabilities, would provide:

- Passenger comfort and convenience;
- Matchless center-to-center travel times for city-pairs in the 200-300 mile distance range—for example, about one hour between midtown Manhattan and downtown Boston; and
- Air-competitive trip times at longer trip distances than other high-speed ground transportation systems.

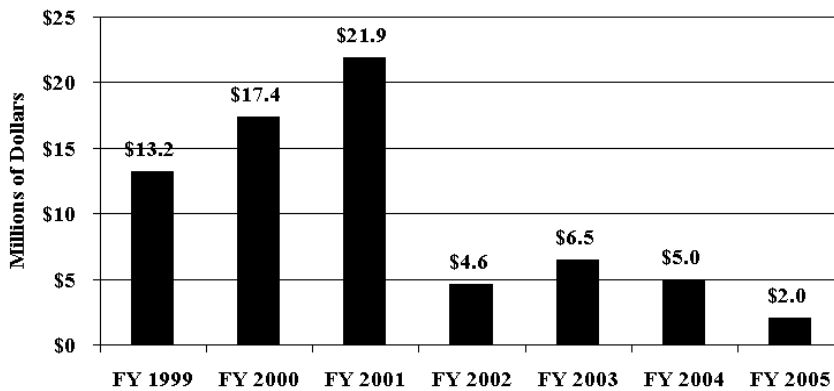
Transrapid, a German company, has developed a Maglev technology that is in revenue service in Shanghai, China, where it links the city with its airport. Japan has developed a technologically different system that has reached the point where decisions on its deployment can be made.

The United States has authorized, but not funded for construction, a Magnetic Levitation Transportation Technology Deployment Program (“Maglev Deployment Program”) that would demonstrate a relatively short (30-50 mile) Maglev system in commercial service. Projects are currently being planned in four locations: Baltimore/Washington (MD-DC); Pittsburgh (PA); Las Vegas (NV)–Anaheim (CA); and Los Angeles International Airport (LAX)–Riverside (CA).

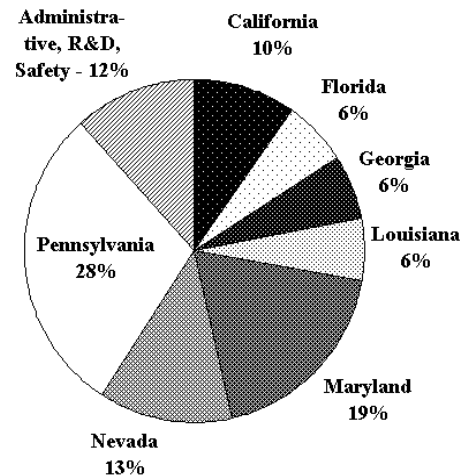
While the President’s FY 2006 Budget (like those for each year since the program’s 1998 enactment) does not request funding for the Maglev Deployment Program, Congress has made a total of \$70.6 available for Fiscal Years 1999 through 2005. The flow and uses of these funds have been as follows:

Maglev Deployment Program—Funding Summary

Annual Program Funding for All Projects



Distribution of Total Funds, FY 1999–FY 2005



Comparable Modes

Maglev most aptly comes into comparison with the other modes of high-speed ground transportation (HSGT): incremental and new high-speed rail (HSR).¹ Incremental HSR (IHSR) makes use of existing railways, upgraded for enhanced capacities and top speeds in the range of 90 to 150 mph.² New HSR, if implemented,³ would provide service at speeds reaching 175 to 200 mph on new alignments and trackage over most of its distance, while accessing city centers over improved legacy railroads where appropriate. (Maglev's top speed, as mentioned above, would be on the order of 300 mph.)

Capital Costs

For the currently available Maglev technologies, the initial capital cost—averaging some \$40 to \$100 million per mile for the most recently-estimated projects—exceeds that of IHSR by a factor ranging from four-fold to nine-fold. Maglev's unit capital costs surpass those of New HSR by lesser, but still significant, amounts, ranging from \$11 to \$19 million per mile in recent studies. Thus, the Maglev technologies of today are the most expensive form of HSGT in terms of up-front investment.

¹ This report also compares HSGT modes with air and highway transportation under specific rubrics, such as travel times.

² The prime example of Incremental HSR is Amtrak's Northeast Corridor between Boston, New York, and Washington. Other corridors that exceed the normative 79 mph railway speed limit are New York–Albany, Los Angeles–San Diego, and short segments of trackage in the Midwest that have benefited from ongoing train control development projects.

³ There is no New HSR operation in the United States. The most notable examples overseas are the Japanese Shinkansen, French TGV, and German ICE.

Line-Haul Travel Times

Conversely, Maglev could provide the highest average speeds and quickest station-to-station trip times available by any public mode of land transportation. A potential one-hour line-haul trip time between Boston and New York would be almost as fast as today's best scheduled airline times.⁴

Benefit/Cost Analysis

To appraise Maglev's value, the Federal Railroad Administration (FRA) has adopted two approaches. First, since very high speeds on the ground are Maglev's chief claim to superiority, the "transportation approach" asks whether the travel time impact of Maglev on the markets it can serve would suffice to justify its cost. This approach is discussed on pages 19 to 25 of the Main Report and summarized in Box ES - 1, below. Second, the "economic approach" (addressed on pages 26 to 35 of the Main Report and summarized in Box ES - 2) inquires whether the total benefits to society of having Maglev in place counterbalance the associated costs.

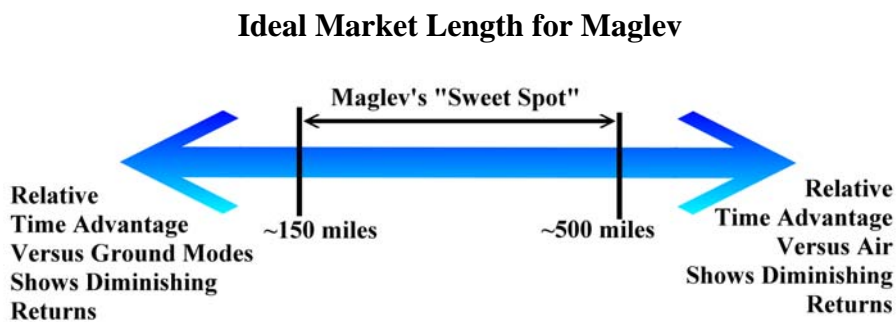
Transportation Effects

As trips grow shorter, users of public transport spend an ever-higher portion of the total travel time in getting to and from stations, as opposed to the line-haul journey itself. Thus, no matter how much faster Maglev can speed between terminals, there is nothing unique about Maglev that can expedite the passenger's access to the originating station, and his or her egress from the arriving station to the ultimate destination. The shorter the trip, the less Maglev can influence the passenger's total travel time.

At the other end of the distance spectrum, at the 400-500 mile plateau, air travel begins to catch up with Maglev on a door-to-door travel time basis, as the superior cruising speed of air overcomes its disadvantages with respect to terminal locations, access/egress, and time

consumed in taxiing.

In combination, these factors suggest that Maglev's optimal range of travel lengths would be between approximately 150 and 500 miles. Furthermore, these same factors heavily



⁴ Federal Railroad Administration, *High-Speed Ground Transportation for America*, September 1997, p. O-34 and Statistical Supplement, p. 19.

influence the comparisons of Maglev projections with those for other modes, as summarized in Box ES - 1.

Box ES - 1—Summary of Results⁵:

TRANSPORTATION APPROACH TO BENEFITS/COSTS

- The primary justification for Maglev's high initial cost must be its promised reductions in travel times. Essential, therefore, to an evaluation of Maglev is its cost per unit of time saved versus the cost of time savings in comparable modes.
- In most corridors, Maglev shows increased costs and reduced benefits in comparison with incremental high-speed rail (IHSR 110) on the measures used in this report:
 - The cost per unit of time savings for Maglev is double or triple that of IHSR;
 - Maglev's transportation production per investment dollar is well below that available through IHSR; and
 - The value of transportation provided to system users (fare revenues plus consumer surplus) per investment dollar is more favorable for IHSR than for Maglev.
- As the difference between New HSR and Maglev is much less pronounced on these measures, no generalizations can be made of the basis of the available projections.

Economic Effects

FRA's Commercial Feasibility Study (CFS) of HSGT, completed in 1997, compared the social benefits and costs of Maglev with those of comparable modes. The benefits included congestion relief on parallel air and highway systems, emissions reductions from passenger diversions to cleaner modes, and benefits to HSGT users. The CFS results (summarized in Box ES - 2) clearly differentiated the benefit/cost ratios of Maglev from those of IHSR, while the differences between Maglev and New HSR were less pronounced.

Box ES - 2—Summary of Results⁶:

ECONOMIC APPROACH TO BENEFITS/COSTS

- Maglev's projected benefits exceeded its costs in only two heavily populated, relatively long corridors—the Northeast Corridor (441 miles, plus extensions to the Southeast and in New York State) and California (527 miles);
- In most of the corridors studied, either IHSR or New HSR produced higher benefit/cost ratios than Maglev.
- Under the Commercial Feasibility Study assumptions, IHSR emerged as the most cost-effective approach (among HSGT options) to reducing highway traffic congestion in most intercity corridors.

Maglev, with its expected ability to attract passengers from airlines, might assist in reducing the growth of local highway congestion generated by airport access and egress. The potential for such assistance at a specific air terminal would depend on the market reach of

⁵ Based on Federal Railroad Administration, *High-Speed Ground Transportation for America*, September 1997.

⁶ Ibid.

available, air-competitive Maglev service; the origin/destination mix of the air passengers using the terminal; and their habitual modes of ground travel to and from the airport.

Some direct shifting of intercity automobile trips to Maglev would also be anticipated. The extent of such diversions, and their potential impacts on congestion in affected highways, would depend largely on each corridor's characteristics (for example, on comparative total travel times by Maglev and by auto in the constituent city-pairs), on prevailing gasoline prices, and on the fare policy adopted for Maglev. By emphasizing maximization of operating surpluses rather than that of gross revenues or ridership, the CFS tended to gear its Maglev fare levels toward air rather than toward auto diversions. Other fare assumptions might have yielded proportionately higher projected diversions of auto travelers to Maglev—but to the likely detriment of each Maglev corridor's commercial feasibility as foreseen by the CFS.

Of the two corridors in which Maglev showed favorable benefit/cost ratios, California—acting through the California High-Speed Rail Authority—is proposing to develop New HSR due primarily to the latter's connectivity, environmental friendliness, and ability to make flexible use of existing rail rights-of-way in sensitive, densely-settled areas.⁷ The Northeast Corridor (NEC) presents formidable institutional, engineering, and environmental obstacles to the introduction of Maglev along much of its length, as well as other investment needs centering on the high-volume commuter and intercity rail passenger services that depend on the existing, aging fixed plant. Even if a parallel New HSR or Maglev system were constructed, many of the investment requirements of today's NEC main line would remain, as it would undoubtedly continue to provide for important commuter and intercity feeder operations. In any event, proposals for building a new HSGT system throughout the NEC are not presently under consideration by responsible authorities.

Uncertainties

Maglev is a new mode currently under development in a number of countries, with a sole revenue installation in regular service in Shanghai only since April 2004.⁸ As with any embryonic transport mode, there exist numerous uncertainties, such as:

- The long-term capital, operating, and maintenance costs of currently available technologies;
- The long-term performance characteristics of these technologies—for instance, their all-weather reliability under American conditions, in comparison with currently-available modes;
- The opportunities for technological breakthroughs that might substantially reduce the life-cycle costs of installing, operating, and maintaining a Maglev system;
- Innovative performance upgrades and unforeseen safety drawbacks that might manifest themselves in the decades to come;

⁷ See Annex B.

⁸ CNN/Reuters, "China to Cut Costs on New Maglev Link," December 7, 2004, at: <http://www.cnn.com/2004/TRAVEL/12/07/bt.china.maglev.cost.reut/index.html>

- Public reaction to various types of Maglev systems, in terms of demand and revenue over a range of stage lengths; and, more generally—
- The long-term effects of September 11, 2001; ensuing changes in travel demand, the security environment, total travel times, and competitive positions of the air and—potentially—other modes; and structural changes in the airline, rail passenger, and other transportation industries.

The present report necessarily bases its analysis and conclusions on currently available Maglev systems and extant projections of those and other HSGT systems' performance. However, neither the spectrum of Maglev technologies nor the American transportation environment will likely remain static throughout the 21st Century.

Conclusions

Although each region conducting planning under the Maglev Deployment Program is best able to evaluate the benefits and costs of the proposed projects **within its own region**, the Federal Government must view Maglev in the context of national needs and priorities. From a local perspective, a particular project may promise overwhelming benefits in relation to its costs. Nothing in this study should suggest that a State or metropolitan area not act accordingly, within its own financing capabilities and those of its potential partners, and subject to such applicable Federal laws as those bearing on safety and the environment. However, from a strictly Federal viewpoint, this report reaches the following conclusions:

- Intercity systems based on currently available Maglev technologies are expensive, with high per-mile costs.
- Conversely, if implemented, Maglev might provide line-haul travel times that improve on those of any other mode of ground transportation. The following noteworthy factors place Maglev travel times in their broader context:
 - Maglev's line-haul speed advantage can only result in substantial total travel time improvements in markets in which line-haul travel times are a significant proportion of total travel times—i.e., in markets more than approximately 150 miles in length.
 - Beyond trip distances of about 500 miles, air's superior cruising speeds would begin to detract from Maglev's advantages of station location and access.
 - Therefore, Maglev's most appropriate transportation niche is in corridors of extremely high travel density that include strong city-pair markets in the 150-to-500-mile range.
- In the densely populated corridors where Maglev has the greatest potential for yielding significant transportation benefits to recompense its costs, existing development, environmental concerns, and other practical constraints would make it very challenging to acquire and develop an alignment that permits current Maglev technologies to fully achieve their trip time improvement capabilities.
- In comparison with today's available Maglev systems, other contemporary HSGT technologies (IHSR and, in some cases, New HSR) typically show higher projected transportation and economic benefits, including highway traffic congestion relief,

relative to their costs, and could bring many of the advantages of HSGT to many more markets at much less cost.

- The proposed short-distance demonstrations under the Maglev Deployment Program, if any are constructed, could ultimately produce operational, engineering, and financial data on Maglev under American conditions, at a lower level of outlay and risk than would pertain to a lengthier and costlier installation. Such data might augment information gathered in other countries that have already invested significant resources in Maglev technology, in the event that private and public entities in the United States should someday contemplate longer-distance Maglev systems in corridors of the highest density. In and of themselves, however, the short corridors under consideration in the Maglev Deployment Program would not fully demonstrate Maglev's transportation potential, which is best perceived in systems serving intercity corridors over some 150 miles long.
- As a form of transportation based on new technologies, Maglev is subject to a high degree of uncertainty. Consequently, whatever policy the Federal Government adopts toward Maglev in the short term, the American transportation community—including the private sector—might profitably monitor the Maglev industry for noteworthy changes in its prospective costs, benefits, performance, and applicability to the evolving transportation environment in the United States.
- As Maglev's capabilities, challenges, and cost-effectiveness in a particular region must remain speculative until they undergo examination on a site-specific basis, public officials may wish to weigh the desirability of including Maglev, in light of its evolving characteristics through the years, as a technological alternative in future studies of high-density corridors.

Main Report:

COSTS AND BENEFITS OF MAGNETIC LEVITATION

Introduction

This report responds to a request contained in House Report 108-401, the Conference Report to Accompany H.R. 2673 (the Consolidated Appropriations Act, 2004):

In order to assist in the evaluation of the potential of magnetic levitation to achieve traffic congestion relief and determine its appropriate role in our nation's transportation system, the conferees direct FRA to provide the House and Senate Committees on Appropriations a report comparing the costs and benefits of magnetic levitation to other modes of travel. This report should be undertaken while moving forward on submitted projects.⁹

To fulfill this request, the report describes today's technological approaches to magnetic levitation (Maglev); analyzes Maglev's transportation-related and economic benefits and costs, with reference to comparable modes of travel; and discusses Maglev's advantages, disadvantages, and uncertainties.

It is not the purpose of this report to critique the individual projects receiving planning funds under FRA's Magnetic Levitation Transportation Technology Deployment Program ("Maglev Deployment Program"). Individual project characteristics are mentioned only for the purpose of illustrating Maglev's "appropriate role in our nation's transportation system," in keeping with the Congressional report language.

Background on Maglev

As a backdrop to Maglev's benefits and costs, this section discusses the most prominent Maglev technologies and the Maglev Deployment Program. Further information appears in Annex A.

Maglev Technology Options

This section describes the most prominent Maglev systems currently available or under intensive development.

All Maglev technologies share the basic principle of substituting magnetic forces for the direct physical contact between vehicle and fixed infrastructure that characterizes other ground transportation modes. These magnetic forces may be either repulsive (as when the north poles of two magnets are brought face-to-face) or attractive (as when opposite poles of two magnets are brought near each other).

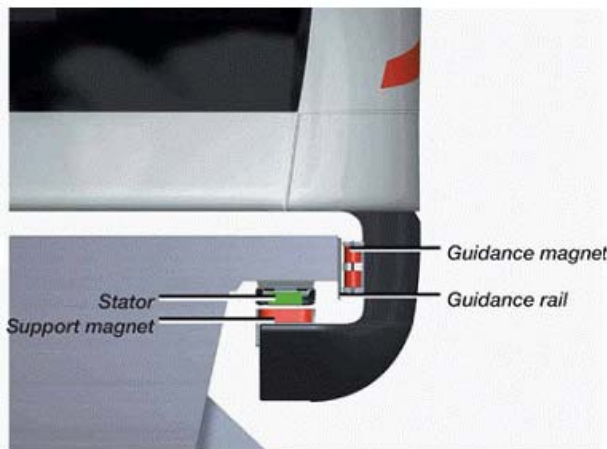
⁹ House Report 108-401, the Conference Report to Accompany H.R. 2673 (the Consolidated Appropriations Act, 2004, Division F—Departments of Transportation and Treasury, and Independent Agencies Appropriations Act, 2004), dated November 25, 2003, p. 976.

The German Technology

The Germans have undertaken development of a variety of high-speed ground transportation (HSGT) technologies. In the early 70's, repulsive and attractive Maglev and air cushion technologies were brought to a half-scale demonstration stage. Repulsion was eliminated largely because of the perceived complexity of the superconducting subsystem, while air cushion was eliminated for reasons of noise and energy consumption. Subsequent development has focused on attractive Maglev. The initial systems employed linear induction motors, but as speeds increased these were abandoned in favor of the linear synchronous motor (LSM),¹⁰ as a measure to reduce on-board weight.

The current German Transrapid Maglev design uses a vehicle about 82 feet in length and

Figure 1: Levitation/Guidance Magnet Arrangements—Transrapid



12.2 feet wide, with seats for about 100 in coach class. Trains generally consist of three to ten sections. The guideway is “T”-shaped; it is generally elevated, and can be fabricated from steel, concrete or a hybrid design. Levitation is accomplished by conventional electromagnets attached to the vehicle (see Figure 1), which pull the vehicle upward toward iron stator packs mounted on the guideway. As the magnet approaches the rail, the attractive force gets stronger; thus, it is necessary to employ feedback to rapidly decrease the current in the magnet as the gap closes. Transrapid states that “a highly reliable, redundant electronic control system

insures that the vehicle levitates at a constant distance of [3/8 of an inch] to its guideway.”¹¹

Propulsion of the Transrapid vehicle is by means of an LSM whose primary windings (or stator) are embedded in the guideway while the secondary (or rotor) consists of the levitation magnets on board the vehicle. The frequency of the alternating current feeding the stator must be synchronized to the speed of the vehicle. The LSM is also used for braking by reversing the phasing of the primary current. There are separate controlled electromagnets, which provide

¹⁰ The linear synchronous motor uses the same electrical principle that which causes an electrical motor to spin. Electricity is introduced into the windings of the motor causing the interior of the motor to spin. Instead of the rotating magnetic field in the motor, Maglev places the electric motor's components horizontally to produce a traveling magnetic field along the guideway (hence the term “linear”). Unlike conventional rail systems, the vehicle's propulsion is provided in the guideway. For Maglev propulsion, the center part of the motor is stretched horizontally in the bottom of the vehicle's carriage while the outer wire wrappings of the motor are placed horizontally on the underside of the guideway. As an electrical current is placed over the wires an electromagnetic field is produced and the resulting horizontal force pulls the vehicle along the guideway. Adjusting the frequency of the three-phase current can alter the speed of the vehicle (hence the term “synchronous”). Adapted from Federal Railroad Administration, *Draft Environmental Impact Statement—Maglev Deployment Program*, June 2000 (prepared by Volpe National Transportation Systems Center), pp. 2-7 and 2-8.

¹¹ Thyssen Henschel America, Inc., “Magnetic Levitation Technology—Super Speed Maglev System Transrapid,” undated brochure.

vehicle guidance. The vehicle chassis wraps around the guideway, so that in the event of delevitation the vehicle safely drops onto skids and coasts to rest.

The German Transrapid technology has been brought to a high state of readiness. Almost 600,000 train-miles (or 25 times around the equator) of operation have been accumulated at a test track at Emsland, Germany, and 555,000 passengers have safely been carried. This system has demonstrated several of the claimed advantages of Maglev, including high speed (279 mph), safety, low noise, and reduced maintenance. However, acceleration/deceleration is no better than that of rail systems (3.3 feet/s^2), and vehicles are in fact no lighter than modern electric rail cars, due mainly to the amount of iron required in the conventional electromagnets. The system has been certified for application by German authorities, and Transrapid has entered into agreements with Lockheed-Martin and other U.S. groups to jointly market the technology in the U.S.

The 19-mile system recently built in Shanghai has demonstrated high reliability and availability.¹² On July 3, 2004, it welcomed its one millionth paying passenger. In a record run (without passengers) in November 2003, the train reached 311 mph. At this writing, operations are still in “ramp-up” mode and do not include evening service.

Japanese High-Speed Maglev

The Japanese have developed both low- and high-speed Maglev systems, and have a 62 mph system in operation near Nagoya to serve the 2005 Aichi Prefecture EXPO. Central Japan Railway Company (JR Central) has developed a high-speed system, the MLX01, which is undergoing testing and demonstration on an 11.4-mile test track¹³ in Yamanashi Prefecture (Figure 2). The technology for this system was derived from the superconducting, null-flux concept of Powell and Danby. Superconducting magnets on the moving vehicle induce currents in short-circuited coils mounted on the sides of the “U” shaped guideway constructed of concrete. The magnetic interaction serves to levitate and guide the vehicle. A certain amount of forward motion is required to induce enough current to lift the vehicle, just like an airplane. Although it could levitate at lower speed, the Japanese do not retract the “landing wheels” until speed reaches about 160 km/h (100 mi/h), so this technology would not be applicable to mostly low- speed operation. The MLX01 test vehicle has already operated some 250,000 train-miles (over 10 times the distance around the earth’s equator) and carried over 80,000 passengers. The one-day record for test runs is 1,800 train-miles or the distance from Chicago to Los Angeles, including 180 reversals of direction.¹⁴ The Japanese Maglev technology has attained a peak speed of 361 mph for a single train, and a peak relative speed of 638 mph for two trains passing each other in opposing directions.

Unlike the German Transrapid system, the Japanese high-speed “Superconducting Maglev” technology has not been deployed in revenue service. Present development centers on enhancing performance (for example, with respect to passenger comfort) and reducing capital cost. The Japanese authorities plan to decide on whether to deploy Maglev on the new Chuo route within the next 3 years. If a new line is to be built, the alternative is conventional bullet-

¹² See Walter Antlauf et. al., “Fast Track,” *Civil Engineering*, November 2004, pp. 37 ff.

¹³ The plan for the line is 26.6 miles, but only the 11.4-mile “Priority Section” has been built.

¹⁴ http://www.rtri.or.jp/rd/maglev/html/english/maglev_frame_E.html

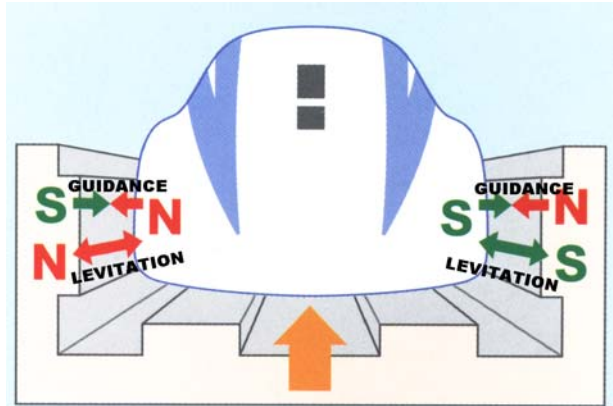
train technology, which is estimated to cost 20 percent less at present. However, Maglev system improvements under development may favorably impact this differential.

The use of superconducting magnets allows a vertical clearance between the guideway and the vehicle of 3.9 inches or more, which would be valuable in Japan because of the prevalence of seismic activity that occasionally produces misalignments of this magnitude. Also the speeds attained are not limiting as they may be with the attractive system, which must

Figure 2:
Japanese MLX 01¹⁵



Figure 3:
Levitation Principle in Japanese System¹⁶



Letters “N” and “S” indicate poles of magnets on board the vehicle and in the guideway. At left, the north pole of the on-board vehicle magnet repels the north pole of the lower guideway magnet to levitate the vehicle (the converse occurs at right). Feedback-controlled attractive forces between the upper guideway magnets and the on-board magnets create proper lateral guidance of the vehicle within the guideway.

contend with a tight gap (about 0.4 inches), eddy current¹⁷ and hysteresis.¹⁸ Aside from the fact that operation in the atmosphere at speeds above 310 mph results in enormous aerodynamic drag, there is no intrinsic reason why much higher speeds could not be attained. Although the use of superconductors on a transportation system seems novel, they have proven their reliability in

¹⁵ Photo by, and courtesy of, Ronald A. Mauri, Volpe National Transportation Systems Center.

¹⁶ From undated brochure produced by JR Central (sometime in 2004-05), “Superconducting Maglev—The Review.”

¹⁷ According to *Wikipedia*, “an eddy current is a phenomenon caused by a moving magnetic field intersecting a conductor or vice-versa. The relative motion causes a circulating flow of electrons or current within the conductor. These circulating eddies of current create electromagnets with magnetic fields that oppose the external magnetic field . . . An analogous eddy current is seen in water when dragging an oar, localized areas of turbulence give rise to vortices, which persist for a while then dissipate.”— http://en.wikipedia.org/wiki/Eddy_current.

¹⁸ Hysteresis is “a lag of effect when the forces acting on a body are changed, as a lag in magnetization of a ferromagnetic substance when the magnetizing force is changed.”—*Webster’s New World Dictionary, Third College Edition*, p. 666. Further information may be found at <http://en.wikipedia.org/wiki/Hysteresis> and at <http://www.lassp.cornell.edu/sethna/hysteresis/WhatIsHysteresis.html>.

daily use on traveling medical nuclear magnetic resonance imaging devices all over the world. They also result in reduced vehicle mass relative to modern electric rail cars.

The Japanese technology for this configuration is expensive. It is estimated that a 311-mile-long system between Tokyo and Osaka via the Chuo route would cost \$69-83 billion, or \$222 to \$267 million per route-mile.¹⁹ However this route would be mostly in tunnel, which accounts for the majority of the cost. For comparison in terms of construction costs alone, in the Northeast Corridor (NEC) of the United States, with its gentler alignment, the cost of the Japanese technology is estimated at about \$80 million per mile,²⁰ or not significantly different from that foreseen for the Transrapid version of Maglev.

U.S. Maglev Technology

In addition to the German and Japanese Maglev systems, there are many other Maglev approaches. Of these, some are being actively pursued in the United States. Many of these American approaches, if brought to fruition, would probably be suitable for low speed application only. These concepts, which are in varying stages of development, include the American Maglev Technology system at Old Dominion University in Norfolk, Virginia; CHSST Colorado (a proposal to install Japanese low-speed technology between Denver International Airport and Eagle Airport in the Rocky Mountains); MagneMotion Maglev M³ (a concept for using permanent magnets in attraction, developed by Professor Emeritus Richard Thornton of the Massachusetts Institute of Technology); LevX (using permanent magnets in repulsion); and others.

With approximately \$13 million in combined funding from the State of Florida and the U.S. Department of Transportation, Maglev 2000 of Florida (James Powell and Gordon Danby's company) is pursuing a low speed application and maintains that its technology is suitable for very high speed. At this writing, much progress remains to be accomplished toward the development of Maglev 2000's technology, including verification of its operating characteristics and its costs. One unique feature of the system is that it would allow electronic switching to shift the vehicle to another track, rather than movement of a section of guideway.

An "Inductrack" system devised by the Lawrence Livermore National Laboratory and General Atomics uses permanent magnets in a Halbach array²¹ for repulsive levitation. Although this system was designed for low speed, it has possibilities for speeds of about 155 mph. This system is at a very early stage of development; the levitation concept has only been demonstrated on a rotating wheel, although testing of a half-length vehicle on a quarter-mile track is planned.²²

¹⁹ "Chuo Maglev Shinkansen To Cost up to \$U.S. 82.5 Billion," *International Railway Journal*, May 2003.

²⁰ At a meeting with FRA on November 19, 2004, Central Japan Railway Company presented a preliminary estimate of \$17 billion (excluding right-of-way acquisition) for a 219-mile project with 3 stations, which works out to \$77.6 million per mile.

²¹ According to *Wikipedia*, "a Halbach array is a special arrangement of permanent magnets (or electromagnets) which augments the magnetic field on one side of the device while canceling the field to near zero on the other side." Further technical details, including a diagram, may be found at http://en.wikipedia.org/wiki/Halbach_array.

²² Information on the Lawrence Livermore/General Atomics Maglev system comes, in part, from the General Atomics web site (<http://www.ga.com/atg/urbanmaglev.php>) and that of Lawrence Livermore National Laboratories (<http://www.llnl.gov/str/>).

In common with other induction repulsion systems, levitation can only be achieved with motion of the vehicle; a novel feature of this system is that it levitates at a speed of just a few meters per second.

Congressional earmarks (disbursed by various operating administrations of the U. S. Department of Transportation) have supported many of these efforts to develop American Maglev technology. Since 1998, the total Federal funding obligated to American maglev technology development for transportation purposes²³ has amounted to approximately \$30 million.²⁴

Maglev Deployment Program

Authorized by the Transportation Equity Act for the 21st Century in 1998,²⁵ the “Maglev Deployment Program” sought to modify an existing Maglev system, German or Japanese, and demonstrate it in revenue service in the U.S. Although invited to participate, the Japanese declined, stating their technology required additional testing before deployment. Seven proposed projects conducted system studies. After evaluating the projects, the Secretary of Transportation in January 2001 narrowed the field to a 39-mile project between Baltimore, Maryland, and Washington, D.C., and a 54-mile project in Pittsburgh, Pennsylvania. By means of earmarked appropriations, Congress has also elected to fund continued planning for a 269-mile project between Las Vegas, Nevada, and Anaheim, California, and a 55-mile project in Los Angeles, California.

The President’s FY 2006 Budget (like those for each year since the program’s 1998 enactment) does not request funding for the Maglev Deployment Program, for which Congress has made a total of \$70.6 available since 1998 (see Table 1).

Maglev Compared with Other Modes

This section weighs the costs and benefits of Maglev against those of the comparable modes of transportation—incremental and new high-speed rail.²⁶ Factors considered include: the initial capital costs for construction; the transportation payback of Maglev’s relatively high initial investment requirement; and comprehensive economic costs and benefits.

²³ The use of Maglev for other possible purposes, such as rocket launching, is beyond the scope of this report. See, for example, <http://liftoff.msfc.nasa.gov/News/1999/News-MagLev.asp>.

²⁴ Obligations through Federal Highway Administration (FHWA) have totaled \$1.8 million; through Federal Transit Administration (FTA), \$26.7 million; and the earmark for Old Dominion University, disbursed through FRA, was \$2 million. In addition, \$8.1 million remains to be obligated by FTA under the TEA-21 extension. Source: Table prepared by FTA, Office of Research, Development, and Innovation, “Urban Maglev Program: Status of Funds as of July 19, 2005.”

²⁵ The Transportation Equity Act for the 21st Century (TEA-21) was enacted June 9, 1998 as Public Law 105-178 and was amended in the TEA-21 Restoration Act, Title IX of Public Law 105-206. The Maglev Deployment Program, established under Section 1218(a) of TEA-21, is codified at 23 U.S.C. 322.

²⁶ Other intercity modes—automobile, bus, air, and existing rail—are brought into the comparison as warranted by specific topics, e.g., the discussion of travel times.

Table 1
Sources and Distribution of Federal Funding Under the Maglev Deployment Program²⁷
(Millions of Dollars)

	FY 1999	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004	FY 2005	TOTAL
SOURCES OF FUNDING								
<i>Funding as Enacted</i> ²⁸ :								
Contract Authority	\$ 15.0	\$ 20.0	\$ 25.0					\$ 60.0
Authorizations		\$ 200.0	\$ 200.0	\$ 250.0	\$ 300.0			\$ 950.0
<i>Total Funding as Enacted:</i>	\$ 15.0	\$ 220.0	\$ 225.0	\$ 250.0	\$ 300.0			\$1,010.0
<i>Funding Actually Made Available:</i>								
Contract Authority Available for Obligation ²⁹	\$ 13.2	\$ 17.4	\$ 21.9					\$ 52.5
Appropriations ³⁰				\$ 4.6	\$ 6.5	\$ 5.0	\$ 2.0	\$ 18.1
<i>Total Funding Actually Made Available:</i>	\$ 13.2	\$ 17.4	\$ 21.9	\$ 4.6	\$ 6.5	\$ 5.0	\$ 2.0	\$ 70.6
DISTRIBUTION OF AVAILABLE FUNDING ³¹								
(Dollar amounts in bold are "earmarks.")								
California	\$ 1.4	\$ 2.0	\$ 0.9	\$ 1.0	\$ 0.5	\$ 1.0		\$ 6.8
Florida	\$ 1.4	\$ 2.0	\$ 0.9					\$ 4.3
Georgia	\$ 1.4	\$ 2.0	\$ 0.9					\$ 4.3
Louisiana	\$ 1.4	\$ 2.0	\$ 0.9					\$ 4.3
Maryland	\$ 1.3	\$ 2.0	\$ 7.1	\$ 1.2	\$ 0.5	\$ 1.0		\$ 13.1
Nevada	\$ 1.4	\$ 2.0	\$ 0.9	\$ 1.2	\$ 1.5	\$ 1.0	\$ 1.0	\$ 9.0
Pennsylvania	\$ 4.4	\$ 3.0	\$ 7.1	\$ 1.2	\$ 2.0	\$ 1.9	\$ 1.0	\$ 20.6
FRA Administration, Research & Development, and Safety	\$ 0.5	\$ 2.4	\$ 3.2		\$ 2.0	\$ 0.1		\$ 8.2
<i>Total Funding Distributed</i>	\$ 13.2	\$ 17.4	\$ 21.9	\$ 4.6	\$ 6.5	\$ 5.0	\$ 2.0	\$ 70.6

²⁷ Federal funds only; does not include \$17.8 million in state and local matching shares.

²⁸ Section 1218, PL 107-178.

²⁹ Remaining budget authority after adjusting for annual obligation limitations on the Highway Trust Fund and rescissions.

³⁰ Earmarked annual appropriations to the Next Generation High-Speed Rail Program. The sole exception is \$2 million in FY 2003 that was earmarked in Section 330 of the Appropriations Bill to Old Dominion University for an R&D project, as shown in the next-to-last line in the table under FRA Administration, R&D, and Safety.

³¹ Includes \$1.0 million of FY 2004 funds, and \$2.0 million of FY 2005 funds, that are earmarked but not yet obligated as this report goes to press.

Capital Costs

The current state-of-the-art Maglev systems entail initial capital expenditures that materially exceed those of comparable modes on a per-mile basis.³² This is the fundamental fact about Maglev, against which its positive qualities must be weighed.

Costs of Maglev Systems

Although the capital costs of any new transportation system can vary widely on a unit basis (with such site-specific factors as topography, land use, real estate values, and environmental issues), a typical range of Maglev capital costs can emerge from many estimates that engineers have developed for proposed systems.

The initial capital cost-per-route-mile of a number of recently estimated Maglev systems appears in Figure 4; costs include infrastructure, vehicles, and all appurtenances, and have been escalated to Year 2004 constant dollars. As shown in the chart, the routes planned as single-track facilities (with passing sidings) show lower per-mile costs than those which would be double-tracked; however, the proportion of savings is less than one-half because of the fixed costs of installing any right-of-way and appurtenances, regardless of width. The more urbanized or topographically challenging areas show the highest per-mile costs of all. The more recently estimated projects form part of FRA's Maglev Deployment Program and, with their short length in built-up areas, naturally promise to cost more on a per-mile basis.

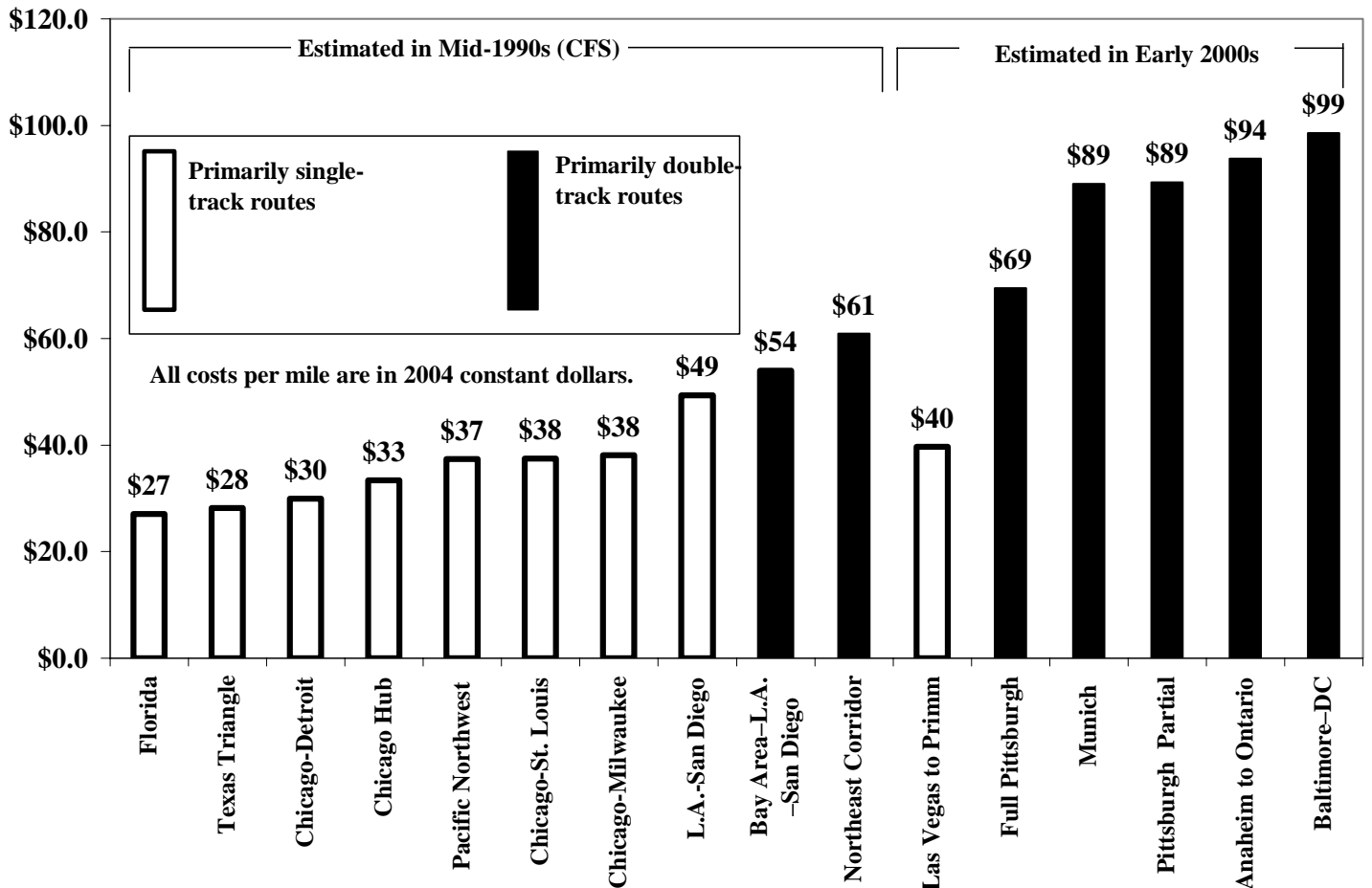
The current \$99 million-per-mile forecast for the Baltimore-Washington project is the most recent estimate of Maglev construction costs in the NEC megalopolis. The NEC, however, comprises diverse environments and engineering requirements—including urban/suburban development like that between Baltimore and Washington, rural areas in northeastern Maryland and eastern Connecticut, challenging crossings of the Susquehanna, Hudson, East, and numerous other rivers, a station underneath Manhattan, and some method of traversing Baltimore. Accordingly, it would require additional, more detailed investigations at some future time to determine whether the \$61 million-per-mile estimate in FRA's commercial feasibility study (CFS) of HSGT,³³ the \$99 million from the Baltimore-Washington project, or some other number, is the most accurate per-mile cost projection for Maglev in the NEC taken as a whole. In general, the unit costs reported in Figure 4 for double-track Maglev systems in heavily populated and urbanized areas range from \$50 to \$100 million per mile.³⁴

³² This report focuses on Maglev technologies currently available for deployment or likely to be available in the near future. While there may eventually be opportunities to significantly alter the initial capital cost of deployment, it is presently unclear when, how, and to what extent such opportunities may be realized.

³³ FRA reported on the commercial feasibility study (CFS) at length in its 1997 report, *High-Speed Ground Transportation for America*, available at <http://www.fra.dot.gov/us/content/5150> and referred to as the "CFS report." All CFS costs have been updated to 2004 constant dollars.

³⁴ Reportedly, the total capital cost of the Shanghai system was \$1.2 billion, or \$64 million per mile (Antlauf et. al., op. cit., p. 43). Since accounting methods, environmental requirements and procedures, and labor costs in the People's Republic of China would differ markedly from those of the United States, and since the project was built on a fast-track schedule, any such estimate must be regarded with great caution.

Figure 4: Per-Route-Mile Costs of Recently Estimated Maglev Systems³⁵ (Dollars in Millions)



Whether in the NEC, California (see Box 1), or other intercity corridors, the accuracy of cost projections depends on the level of detail and the resources underlying them. Furthermore, the possibility exists that technological advances in Maglev design and in civil engineering (tunneling techniques, for example) could alter Maglev’s cost equations for the better. Any future analyses of Maglev, both in this country and abroad, should take such unit cost reductions—or countervailing increases—fully into account. For this reason among others, the private and public sectors of the American transportation community should monitor worldwide trends in this as in other contemporary modes of transport.

Another useful means of portraying the initial capital costs of Maglev systems is to display their total capital costs against the distances involved (Figure 5). Projecting an average Maglev investment requirement of almost \$40 million per mile in 2004 dollars, this display shows a clear relationship between distances and costs, conditioned by the many local factors and design decisions that differentiate these potential Maglev corridors.

³⁵ Source: CFS report—Statistical Supplement and Annex A to this report.

Box 1: California's Evaluation of Maglev

The State of California has been conducting intensive planning and environmental studies for a proposed HSGT system linking its important population centers. Although the California High-Speed Rail Authority has proposed settling on a New HSR approach to HSGT, it devoted considerable resources to an evaluation of Maglev, and developed capital cost and demand estimates for both options.

Table 2: Comparative Capital Cost, Trip Time, and Traffic Estimates for Maglev and New HSR in California

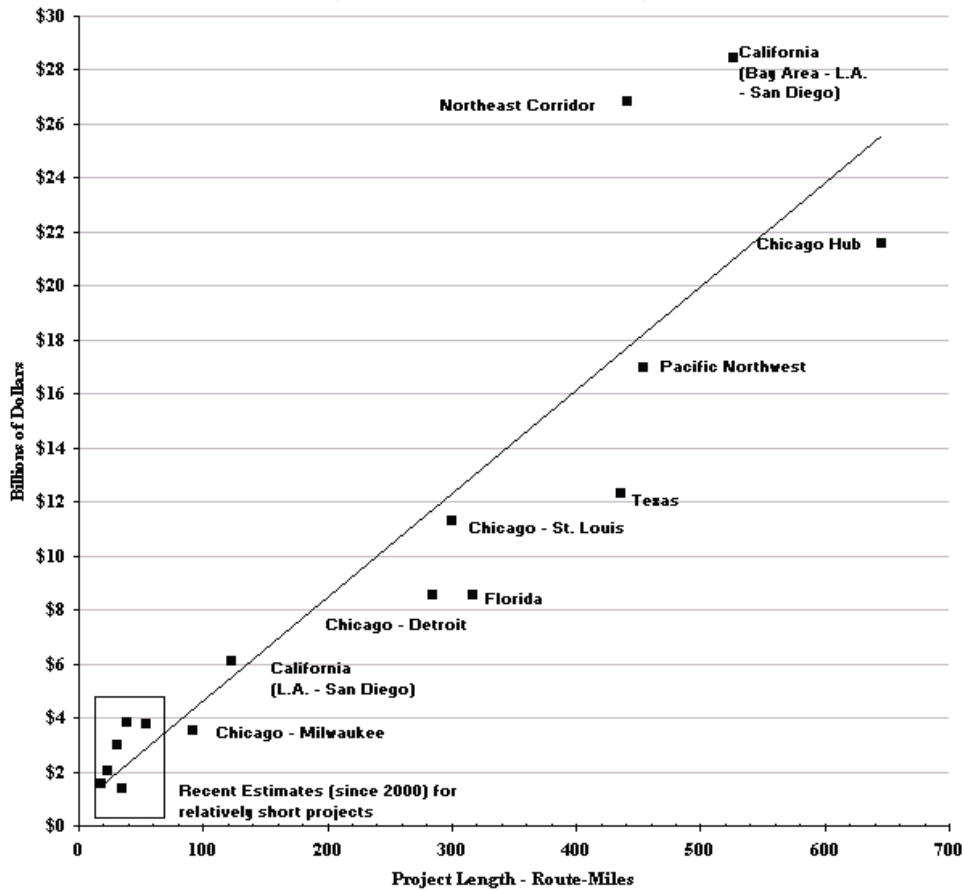
Sources: <i>Most data: California HSR Authority, California HSR Corridor Evaluation, December 30, 1999; Independent Ridership and Passenger Revenue Projections, January 2000. Costs have been escalated to 2004 dollars. Where noted: CFS data is from CFS report.</i>	Dollars are in Millions			Maglev as Percent of New HSR
	New HSR	Maglev	Difference, Maglev Higher (Lower) than New HSR	
Capital cost per mile for typical environments:				
In least-developed regions	\$14.2	\$27.4	\$13.1	192%
In average suburban areas	\$49.2	\$60.2	\$10.9	122%
In mountainous terrain	\$54.7	\$65.6	\$10.9	120%
In dense urban areas	\$87.5	\$98.5	\$10.9	113%
Average cost per mile overall (baseline systems)	\$37.7	\$51.1	\$13.4	136%
Average cost per mile overall (Authority-developed systems)	\$35.3	\$50.2	\$15.0	142%
Average cost per mile overall (CFS - California North/South System)	\$35.1	\$54.0	\$18.9	154%
Line-haul travel time, San Francisco–Los Angeles (hours)³⁶	2.75	2.25	(0.5)	82%
Passenger-trips, 2020 (millions)	31.1	39.1	8.0	126%
Passenger-miles, 2020, per CFS (millions)	4,742	5,888	1,146	124%

The table above summarizes salient cost and traffic information from the California feasibility studies that predate the 2004 Draft Program EIR/EIS. In those studies, the State's average per-mile capital cost estimates for the two technologies are similar to those earlier developed in the CFS (shown toward the bottom of the table); the CFS estimate for Maglev is about \$4 million higher per route-mile than that developed by the Authority. The table also shows the California High-Speed Rail Authority's travel time and ridership estimates for the two technologies. It is unsurprising that Maglev's line-haul speed advantage should contribute to a noticeable traffic differential over New HSR. The passenger-mile projections of the CFS, although predicated on a different system from that developed by the Authority, show an analogous traffic differential for Maglev over New HSR. Further engineering for the EIR/EIS has indicated increased capital costs, which would apply to the use of both New HSR and Maglev technologies.

Annex B excerpts the California High-Speed Rail Authority's conclusions regarding Maglev in that State's major intercity corridor.

³⁶ Simple average of major alternatives analyzed by the California High-Speed Rail Authority.

Figure 5: Maglev Corridors: Total Capital Cost Versus Length (2004 Constant Dollars)



Cost Comparison with Other Modes of Transportation

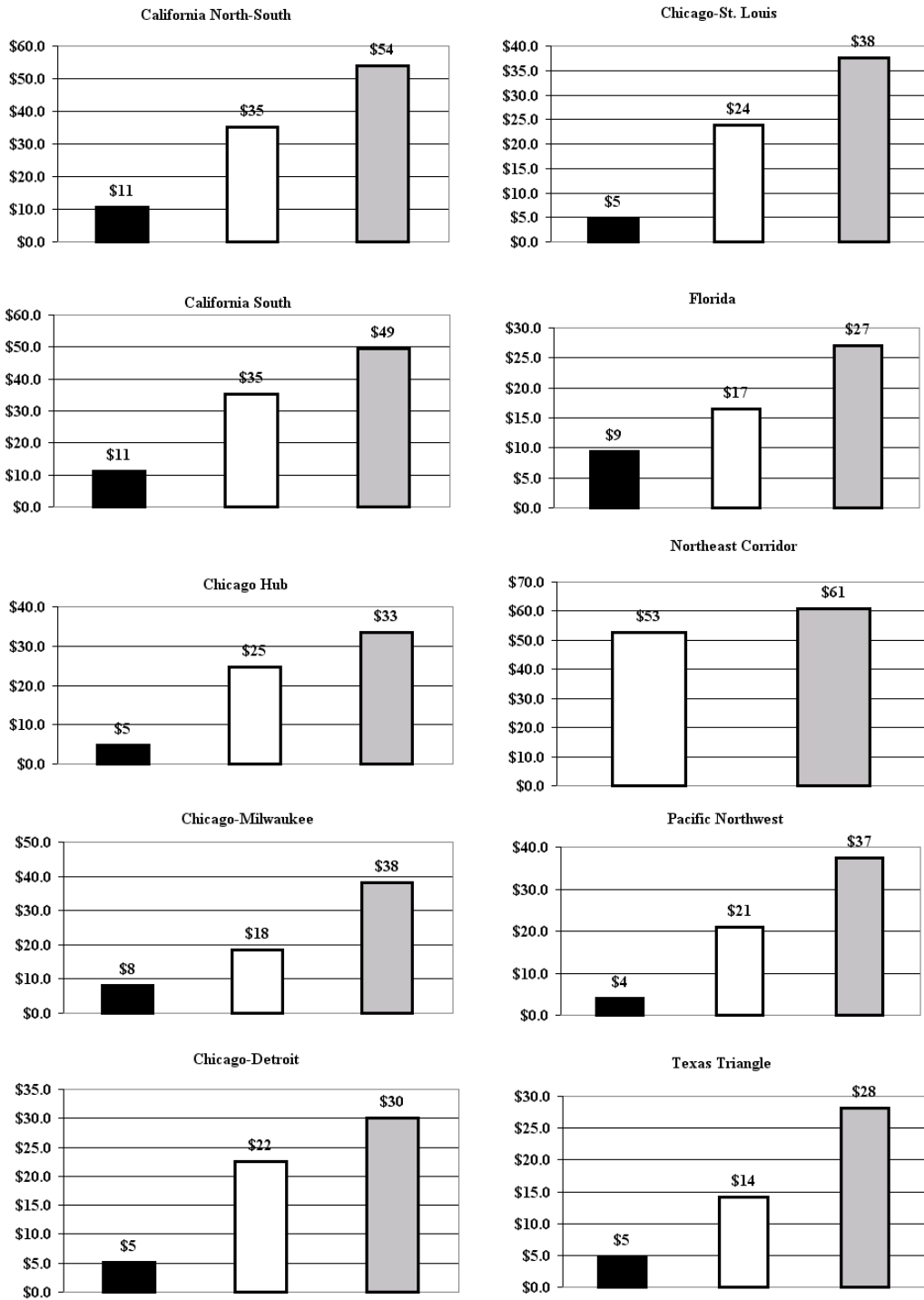
The CFS developed comparable initial capital cost estimates for several technologies: Maglev, New HSR, and IHSR.³⁷ (See Figure 6.) For use in the present report, the CFS costs have been updated to 2004 dollars.³⁸ Aside from the inflation adjustment, Maglev and New HSR costs remain exactly as estimated in the CFS. However, the IHSR estimates in Figure 6 reflect not only inflation but also recent transportation plans of FRA and Amtrak that analyzed the capital requirements of improved corridors. Technical monographs by FRA and Amtrak on the

³⁷ The incremental high-speed rail option selected for comparison is the “Accelerail 110” described in the CFS report.

³⁸ All inflation estimates in this report are taken from the Gross Domestic Product Deflator Inflation Calculator developed by NASA at the Johnson Space Center and publicly available at NASA’s Cost Estimating Web Site: <http://www.jsc.nasa.gov/bu2/inflateGDP.html>

Figure 6: Per-Mile Costs of HSGT Options
(Millions of 2004 Dollars per Route-Mile. IHSR Costs are updated from CFS based on subsequent transportation plans. IHSR 110 does not apply in NEC.)

■ IHSR 110 □ New HSR ▒ Maglev



Southeast Corridor (segments between Washington, Richmond, and Charlotte)³⁹ covered a broad and typical range of upgrading situations (HSR superimposed on both single- and double-track, and on low-, medium-, and high-density freight railroads) and as such, could be expected to be indicative of the range of costs in the Nation as a whole.⁴⁰ The per-route-mile capital cost of Southeast Corridor IHSR, when compared with that predicted in the CFS and adjusted for inflation, amounts to approximately 180 percent of the CFS estimates. This factor has been applied to IHSR cost estimates across-the-board, thus leading to reported IHSR investment requirements that are about double those reported in the CFS, and various benefit/cost measures for IHSR that are less promising than in the CFS.⁴¹ The effect of boosting the real per-mile costs of IHSR while keeping constant those of New HSR and Maglev is to improve the performance of the last two relative to the first option.

Since all cost-estimation must, in the end, be site-specific, actual cost estimates for a specific corridor may differ significantly from the parametric numbers in this report. A single major bridge or tunnel requirement can affect per-mile costs dramatically for any given corridor, for example. Thus, while the CFS estimates are useful because they were consistently applied in all illustrative corridors, site-specific estimates are necessary for a fully informed evaluation of the benefits and costs of the different approaches to HSGT in a particular corridor.

As depicted in Figure 6, Maglev’s per-mile cost is fractionally higher than that of New HSR, but many times that of IHSR in every applicable⁴² case—even though IHSR’s cost reflects a substantial upward adjustment in real terms, while Maglev’s does not. The index values for each corridor appear in Table 3.

Table 3: Costs Per Route-Mile—Maglev Times IHSR; New HSR Times IHSR

Illustrative CFS Corridors	Index Values (IHSR 110 = 1.0 for each corridor)		
	IHSR 110	New HSR	Maglev
California North-South	1.0	3.3	5.0
California South	1.0	3.2	4.4
Chicago Hub	1.0	5.0	6.8
Chicago-Milwaukee	1.0	2.3	4.7
Chicago-Detroit	1.0	4.4	5.9
Chicago-St. Louis	1.0	4.9	7.8
Florida	1.0	1.8	2.9
Pacific Northwest	1.0	5.3	9.3
Texas Triangle	1.0	3.0	5.9

³⁹ National Railroad Passenger Corporation, *Report to Congress: Potential Improvements to the Washington–Richmond Railroad Corridor*, May 1999; FRA, *Technical Monograph: Transportation Planning for the Richmond–Charlotte Railroad Corridor*, January 2004. These and other similar reports and methodological aids are freely available on the Transportation Planning Bookshelf of FRA’s web site, of which the address at the time of this report’s publication is: <http://www.fra.dot.gov/us/content/1240>

⁴⁰ About 20 percent of the Washington–Charlotte corridor would involve reconstruction of an abandoned segment.

⁴¹ To the extent that more detailed engineering suggests feasible economies of construction in IHSR corridors, their benefit/cost ratios would improve over those shown in this report.

⁴² Since IHSR 125 already exists on the Northeast Corridor, it is omitted in the comparison.

The section entitled “Other Measures of Transportation Efficiency” (page 23) and Box 3 (page 25) present illustrative cost and capacity comparisons of Maglev with a broader spectrum of transportation modes.

Benefits Versus Costs

Beyond capital requirements alone, any comprehensive analysis of transportation systems requires consideration of the interactions among many factors, for example:

- Capital investments and travel times
- Capital investments and initial costs
- Travel times and demand;
- Demand and operating costs;
- Demand and vehicle requirements;
- Demand and external benefits and costs, such as congestion in other modes.

The CFS, excerpted and updated in the present report, constitutes just such a comprehensive analysis,⁴³ providing ample data with which to explore two fundamental questions:

- In what transportation applications might Maglev surpass existing modes in moving passengers; and
- Are Maglev’s prospective benefits likely to cover or exceed its costs?

The following sections address these basic questions in turn.

Transportation Perspective

Whether and to what degree Maglev could be expected to outperform existing modes in trips of different lengths, largely reflects some basic principles of transportation analysis.

Fundamental Premises

In seeking explanations of traveler behavior, intercity transportation systems analyses dating back to the 1960s discerned that modal choices rely primarily on relative trip times, frequencies, and perceived costs, as well as a host of service quality factors such as reliability, comfort, convenience, ease of use, and avoidance of “hassles.” Under the important category of

⁴³ See Chapter 3 of the CFS report for a full analytical framework.

trip time, travelers normally choose among modes on the basis of total, door-to-door trip times rather than line-haul trip times only.⁴⁴

Maglev’s distinguishing features are (a) its high line-haul speed and (b) its inherent ability, as an HSGT mode, to serve center-city, suburban, and more distant stations. Both these factors relate to trip times above all. Thus, Maglev’s ability to attract traffic at the most remunerative rates possible (the better to finance its high initial cost) will depend largely on the proportion of line-haul to total travel times in the city-pairs it serves. By simple algebra, it is apparent that:

- As trip distances decrease, the proportion of line-haul to total travel time diminishes.
- As trip distances decrease, a given percentage reduction in line-haul travel time has less impact on total travel times.

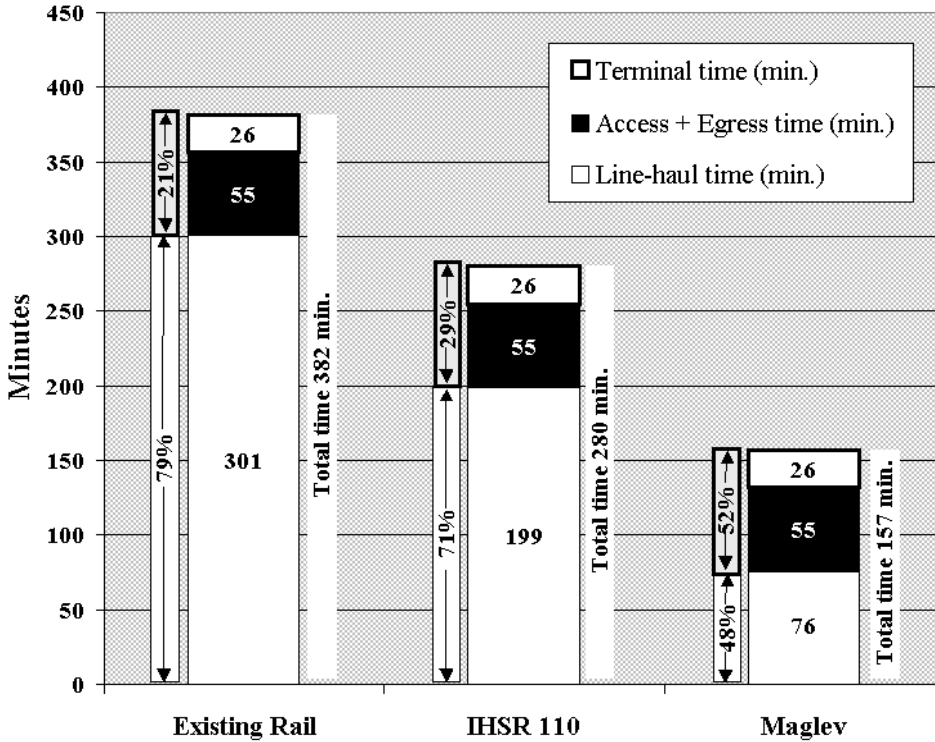
These principles are worked out in Table 4, which shows the impact on total travel time of a given combination of the line-haul proportion of total trip time, and the line-haul trip time reduction.

Table 4: Interaction of Line-Haul and Total Travel Times
(Example in text is highlighted in table.)

1. The percentage reductions in line-haul travel time shown below:	2. —When line-haul travel time consumes the following percentages of total travel time:								
	90%	80%	70%	60%	50%	40%	30%	20%	10%
	3. Yield the following approximate <i>net reductions in total travel time</i> :								
90%	81%	72%	63%	54%	45%	36%	27%	18%	9%
80%	72%	64%	56%	48%	40%	32%	24%	16%	8%
70%	63%	56%	49%	42%	35%	28%	21%	14%	7%
60%	54%	48%	42%	36%	30%	24%	18%	12%	6%
50%	45%	40%	35%	30%	25%	20%	15%	10%	5%
40%	36%	32%	28%	24%	20%	16%	12%	8%	4%
30%	27%	24%	21%	18%	15%	12%	9%	6%	3%
20%	18%	16%	14%	12%	10%	8%	6%	4%	2%
10%	9%	8%	7%	6%	5%	4%	3%	2%	1%

⁴⁴ FRA, Office of High-Speed Ground Transportation, *The Needs and Desires of Travelers in the Northeast Corridor: A Survey of the Dynamics of Mode Choice Decisions*, 1970.

Figure 7: Composition of Each Mode’s Total Travel Time, Chicago–Detroit City-Pair Example



Thus, according to Table 4, if Maglev introduces a 50 percent reduction in line-haul travel time over an existing mode (say, incremental high-speed rail), and if travel time via the existing mode consists of 60 percent line-haul time and 40 percent access/waiting time, then Maglev’s approximate⁴⁵ net effect on available total travel times is not 50 percent, but 30 percent (i.e., 50 percent times 60 percent).⁴⁶

An example from the FRA’s CFS report⁴⁷ illustrates this principle (Figure 7). For the

Chicago–Detroit city-pair, existing rail service (posited as a baseline) has a line-haul travel time of 301 minutes, or 79 percent of the total travel time for the average traveler. Maglev’s line-haul trip time, at 76 minutes, would represent a 75 percent saving over the line-haul time for existing rail. As described in Table 4, Maglev’s total time savings over existing rail would be 75 percent (the line-haul savings alone) times 79 percent (the relative importance of line-haul within the baseline time), or 59 percent.

Effect on Shorter Trips

This phenomenon detracts from Maglev’s claimed advantages in shorter-distance trips. Between Baltimore and Washington, for example, the line-haul travel time saving between IHSR (Amtrak’s Acela) at 35 minutes (with one stop) and the proposed Maglev line (also with one stop) at 18 minutes, is 49 percent. However, in an example prepared by the State of Maryland, line-haul travel time for IHSR is only 42 percent of its total time. Thus, the net saving effected by Maglev is approximately 20 percent.^{48,49}

⁴⁵ Site-specific conditions, such as the accessibility of the Maglev stations, will of course influence the precision of the comparison.

⁴⁶ Obviously, the principle exemplified in Table 3 also pertains to continuous values between the ten-percent increments chosen for use in the table.

⁴⁷ Adapted from *High-Speed Ground Transportation for America*, figures 7-4 and 7-5, pp. 7-4 and 7-5.

⁴⁸ State of Maryland, Mass Transit Administration, Office of Planning, “Baltimore-Washington Maglev Project: Cost Comparison: Maglev with Freeway, Light and Heavy Rail,” Technical Paper, September 2003, p. 14.

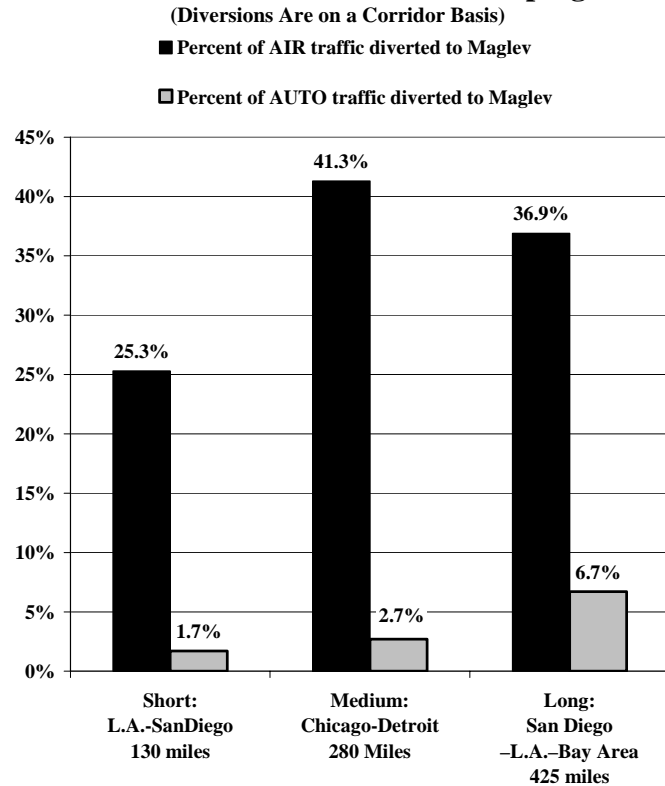
⁴⁹ This discussion does not incorporate the effects of frequency, which are discussed in Annex D.

Effect on Longer Trips

At the other end of this distance spectrum, at the 450-500 mile plateau, air travel begins to catch up with Maglev on a door-to-door travel time basis. This will engender no surprise, as the jet plane has a maximum cruising speed advantage over Maglev, which tops out at about 310 mph in all the recent projects described in Annex A. At the longer trip lengths, air—slow and cumbersome in its terminal operations, which are themselves located far from city centers—begins to overcome its inherent performance inefficiencies at airports, and in its passenger access to and from them, by means of its incomparable line-haul speeds. The total travel time benefit of Maglev over air thus becomes marginal in city-pairs at the 450-500 mile level, and further erodes at greater distances. Nevertheless, a single long Maglev line could still serve many overlapping or sequential city-pairs of lengths suitable for HSGT. Therefore, whether the net revenue potential of Maglev routes longer than 500 miles would overcome such systems’ need for an expensive line-haul right-of-way would depend on the constellation of city-pairs that would be served, among other factors.

Recap of Time/Distance Factors

Figure 8: Modal Diversions Reflect Competitive Characteristics of Distance Groupings



The CFS demonstrated how the competitive positions of Maglev, HSR at various levels, and other modes change with distance, as shown in Figure 8 and Figure 9.⁵⁰ In the shortest city-pair illustrated in the figures (Los Angeles–San Diego, about 130 miles in route-length but only 90 to 95 miles in average trip length), Maglev shows a marked total trip time improvement over the time-competitive auto mode (40 minutes or 24 percent for the typical trip),⁵¹ but effects minimal diversions from it (less than two percent). In this short corridor, such diversion patterns should come as no surprise: auto’s perceived cost per passenger-mile is half that of Maglev for business trips and one-quarter that of Maglev for personal travel⁵²; auto’s frequencies are infinite throughout the day, while common carriage always implies a waiting time, however small; and auto

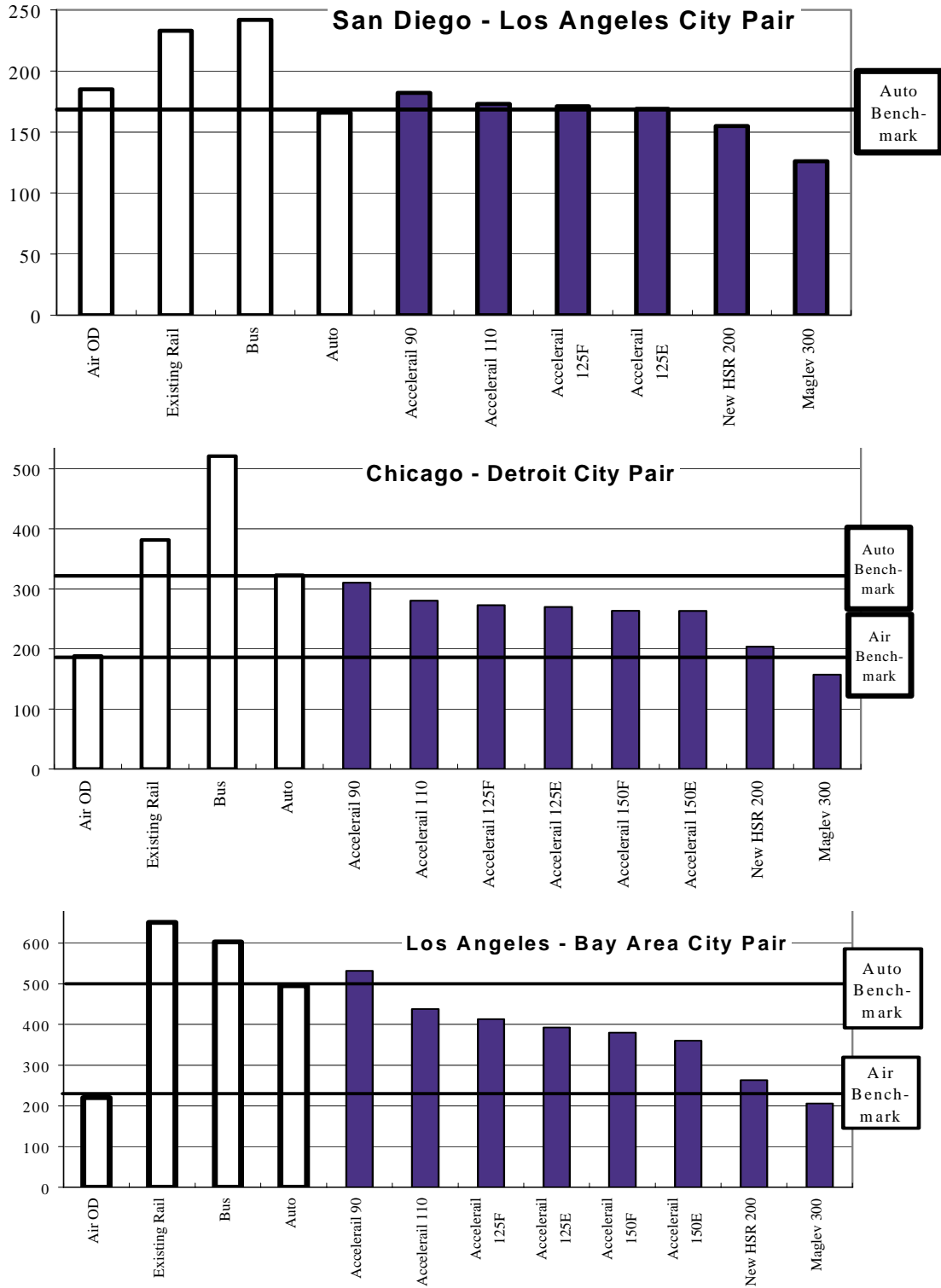
⁵⁰ Adapted from CFS report, figure 7-5, page 7-5.

⁵¹ Air—taking longer than auto in this city-pair on a total trip-time basis—is also relatively unimportant in San Diego–Los Angeles; it accounts for some 5 percent of trips, most of them transfers to and from other flights at Los Angeles.

⁵² CFS report, page 4-4 and Statistical Supplement, page 4.

provides a single ride to destination, as opposed to the transfers inherent in most public transport. For the medium-distance city-pair, Chicago–Detroit (280 miles), Maglev shows clear travel time superiority over all modes; and for the longer-distance route (Los Angeles–Bay Area, 425 miles),

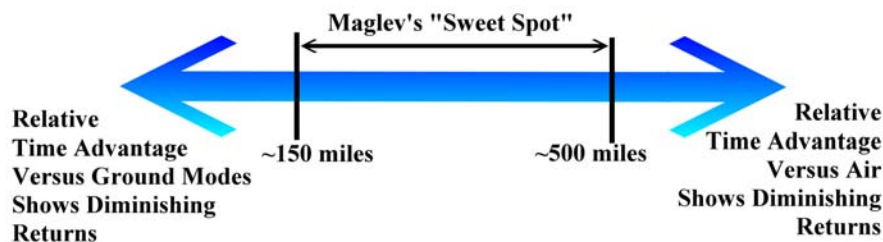
**Figure 9: Competitive Position of HSGT in Three Sample City Pairs—
Total Travel Time in Minutes**



Maglev increases its time-saving margin over all the ground modes, but begins to lose its clear supremacy over air. The CFS’s traffic projections for Maglev in 2020 appear to bear out these travel time relationships,⁵³ although many other factors are involved and would require study for specific corridors. Figure 8⁵⁴ would suggest that Maglev might maximize its diversion of air travelers in the middle of its “sweet spot” of market length.

Thus, from the point of view of city-pair market length, Maglev’s most opportune range appears to be as depicted in Figure 10. As mentioned above, city-pair and corridor route length are not the same thing; the projected performance of a particular Maglev (or other HSGT) corridor project will reflect the summarized traffic levels and revenues of the city-pairs that it would serve, as well as the capital cost of constructing the entire route and the operating and maintenance expenses of the services that would be tailored to satisfy the configuration of travel demand in a cost-effective manner.

Figure 10: Ideal Market Length for Maglev



Measures of Transportation Benefits and Costs

The primary justification for Maglev’s high cost must be its promised reduction in line-haul and, especially, total travel times. Certainly, Maglev’s proponents may adduce a host of additional factors, including enhanced ride quality through contactless suspension, but other modes can approach these comfort advantages. Acela, for example, already offers its riders a much-improved ride quality and sound insulation over its predecessor equipment. It is, however, the combination of these amenities with Maglev’s travel time potential—outstanding among the HSGT modes—that has generated interest in Maglev. It all comes down to trip time reduction, and its cost.

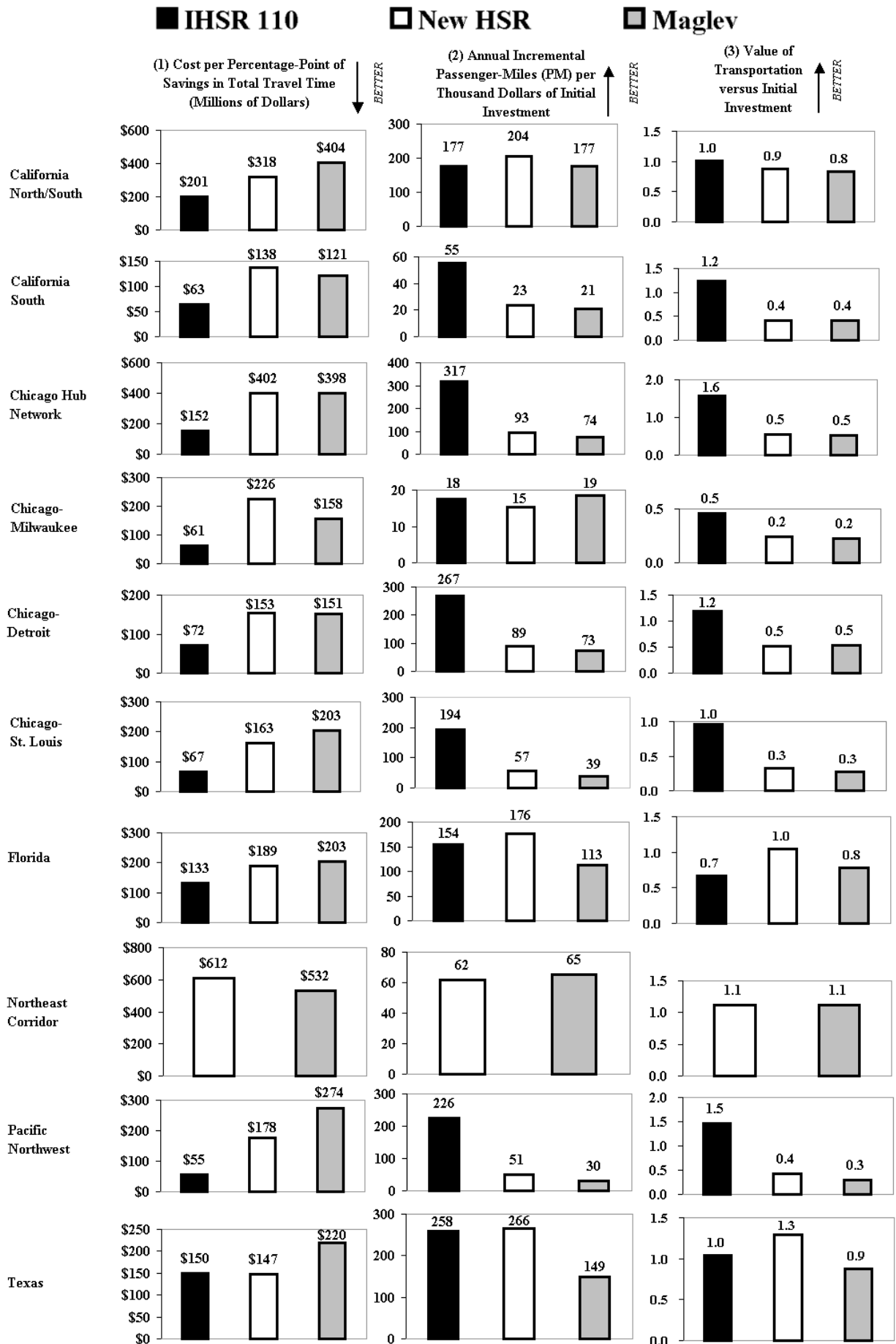
Three measures are useful in characterizing the efficiency and effectiveness of Maglev versus other HSGT modes in achieving trip time reductions. The results of these measures for typical CFS corridors appear in Figure 11⁵⁵:

⁵³ For a full description of the analysis, see the CFS report, particularly Chapters 4, 5, 6, and 7.

⁵⁴ Source for Figure 8: CFS report, Statistical Supplement. Diversion numbers are for the full corridors, of which the city-pairs in Figure 9 are only the most prominent markets. Air is relatively unimportant in San Diego–Los Angeles; it accounts for some 5 percent of trips, most of them transfers to and from other flights at Los Angeles.

⁵⁵ For the sources of these measures, see the Statistical Supplement at the end of the CFS report. All dollar amounts are present values in year 2004 constant dollars.

Figure 11: Measures of Transportation Benefits Versus Costs for Maglev, New HSR, and IHSR 110



1. **Cost per percentage-point of savings in total trip times.** For the bellwether city-pair in each CFS corridor, it is possible to estimate total travel times “after investments” via each of the modes under consideration. A baseline “before investments” travel time was also developed.⁵⁶ For each mode, the total travel time is compared with the baseline to derive the minutes saved and a percentage reduction in total time from the baseline. The “cost per percentage-point of savings,” then, results from dividing the total capital cost by the percentage point reduction. *Example:*
 - Baseline time is 120 minutes
 - New time by mode X is 108 minutes
 - Travel time reduction is 12 minutes, or 10 percent—i.e., 10 percentage points
 - Capital cost of mode X is one billion dollars
 - “Cost per percentage-point of savings in total trip times” equals one billion divided by 10, or \$100 million.
2. **Annual incremental passenger-miles per thousand dollars of initial investment.** If the rationale for public investment in transportation systems is deemed to be the total benefits to society that accrue from those systems’ use, then travel volume is a useful surrogate measure of benefits. The more service provided per dollar of initial investment, according to this rationale, the greater the justification for that initial investment. For each HSGT technology in the CFS, therefore, this measure divides the “incremental” passenger-miles projected for 2020, by the initial investment required. In this context, “incremental” passenger-miles are calculated as follows for each version of HSGT (Maglev, New HSR, and IHSR) in each illustrative corridor⁵⁷:

Total passenger-miles forecast for HSGT by CFS

Less

**Passenger-miles obtained by diverting traffic
from conventional rail**

Yields

“Incremental” passenger-miles.

⁵⁶ The baseline was prepared as part of the CFS, and reflects the best capabilities of a 79 mph system. Exceptions: The timing for the existing 90 mph system was used for California South (Los Angeles–San Diego). Existing Acela timings were used for the NEC. The existing 79 mph system performance was used for the Pacific Northwest baseline, as no fully capable 79 mph system was analyzed for that corridor. In calculating total travel times for purposes of this report, 45 minutes were added to the line-haul time for access/waiting, and 30 minutes for egress, for a total of 75 minutes. For the “bellwether” city-pair, see the Statistical Supplement of the CFS report, second line of data for each illustrative corridor, “Trip time, hours, [city-pair].”

⁵⁷ The rationale for this subtraction is that conventional rail is qualitatively the closest present-day mode to HSGT, the existing alternative to air and highway travel, and the source of benefits to society that most resemble those projected for HSGT. The “incremental” passenger miles—mainly representing traffic diverted from the air and highway modes—provide a surrogate measure of the incremental social benefits accruing from those diversions, rather than any potentially “recycled” benefits from a shift of conventional rail riders to HSGT.

The policies for fare-setting across modes are described in Chapters 4 and 5 of the CFS; basically, fares were set to maximize net revenues. Lower fares would have yielded many more projected auto diversions and passenger-miles, thus heightening this measure of use, but would have detracted from the commercial feasibility of any HSGT system as foreseen by the CFS.

3. **“Value of transportation” versus initial investment.** Correcting for the dampening effect of the CFS’s commercially-oriented fare policies on New HSR and Maglev ridership, this ratio uses as its numerator the value of transportation provided to users (as measured by system revenues plus users’ consumer surplus⁵⁸). The denominator is the total initial investment for each case.

More often than not on all three of these transport-related measures, Maglev displays increased costs and reduced benefits in comparison with IHSR 110 (see Table 5). The cost per unit of time savings for Maglev is two to three times that of IHSR in most of the corridors studied; Maglev’s transportation production per dollar of investment is generally a fraction of that available through IHSR. By incorporating consumer surplus, hence recognizing the total user value of the transportation rather than just the fare-impacted units of production, the third

**Table 5:
Measures of Transportation Benefits and Costs—
Index Values based on IHSR 110⁵⁹**

(1) Cost Per Percentage-Point of Total Time Savings (Lower is better.)				(2) Annual Incremental ⁶⁰ Passenger-Miles in 2020 Per Thousand Dollars Of Initial Investment (Higher is better.)			
INDEX VALUES, IHSR 110 = 1.0:	IHSR 110	New HSR	Maglev	INDEX VALUES, IHSR 110 = 1.0:	IHSR 110	New HSR	Maglev
California North-South	1.0	1.6	2.0	California North-South	1.0	1.2	1.0
California South	1.0	2.2	1.9	California South	1.0	0.4	0.4
Chicago Hub	1.0	2.6	2.6	Chicago Hub	1.0	0.3	0.2
Chicago-Milwaukee	1.0	3.7	2.6	Chicago-Milwaukee	1.0	0.9	1.1
Chicago-Detroit	1.0	2.1	2.1	Chicago-Detroit	1.0	0.3	0.3
Chicago-St. Louis	1.0	2.4	3.0	Chicago-St. Louis	1.0	0.3	0.2
Florida	1.0	1.4	1.5	Florida	1.0	1.1	0.7
Pacific Northwest	1.0	3.2	5.0	Pacific Northwest	1.0	0.2	0.1
Texas Triangle	1.0	1.0	1.5	Texas Triangle	1.0	1.0	0.6

[Table 5 continues on the next page.]

⁵⁸ The “value of transportation” thus equals the “benefits to HSGT users” described in Table 8 and under “User Benefits Versus Costs to Users” on page 32. For a definition of “consumer surplus,” see footnote 84, page 28.

⁵⁹ In this table, the NEC is omitted in the absence of IHSR 110 for that corridor. (IHSR 125 already exists in the NEC.)

⁶⁰ For the meaning of “incremental” in this table, see page 21.

Table 5:
Measures of Transportation Benefits and Costs—
Index Values based on IHSR 110

[Table continued from the previous page]

(3) Value of Transportation divided by Initial Investment (Higher is better.)			
INDEX VALUES, IHSR 110 = 1.0:	IHSR 110	New HSR	Maglev
California North-South	1.0	0.9	0.8
California South	1.0	0.3	0.3
Chicago Hub	1.0	0.3	0.3
Chicago-Milwaukee	1.0	0.5	0.5
Chicago-Detroit	1.0	0.4	0.4
Chicago-St. Louis	1.0	0.3	0.3
Florida	1.0	1.6	1.2
Pacific Northwest	1.0	0.3	0.2
Texas Triangle	1.0	1.2	0.8

measure yields, in some corridors, more promising results for Maglev in comparison with IHSR. For all measures, IHSR’s relatively inferior projections in Texas reflect the different route alignments envisioned for the higher-speed modes; IHSR was configured as a triangle, but New HSR and Maglev were assumed to adopt a star-like configuration necessitating fewer route-miles.

On the three transportation measures described above, the differential between Maglev and New HSR is much less pronounced than that between Maglev and IHSR. In many cases, the projections for Maglev and New HSR are identical, or only fractionally different. In California, the Maglev projections are inferior to those for New HSR in all three measures, while in the NEC, the forecasts for Maglev are better than or equal to those for the New HSR. Thus, as between Maglev and New HSR, no generalizations can be made on the basis of the CFS data. Local considerations, such as those which informed the California High-Speed Rail Authority’s proposal to opt for a steel-wheel system (see Annex B), would generally influence any analysis of the two new-construction modes. The kinds of considerations that would come into play are described elsewhere in this report.

Other Measures of Transportation Efficiency

The relative cost per mile of new construction for all modes, including highway and air, is a topic of some interest to transportation analysts and decision-makers, even though the intrinsic differences among the various modes⁶¹ may impose heavy caveats on any such comparison. Furthermore, the capacity, in terms of passenger throughput, of each lane of highway, railroad track, Maglev guideway, and airport runway commands a similar degree of interest. Unfortunately, the development of comparative costs and capacities must necessarily

⁶¹ For example, air relies on a natural, rather than a man-made, physical right-of-way between terminals.

Box 2: Comparison with the Metroliner Program

It is instructive to compare the transportation costs and benefits of the proposed Maglev Deployment Program with those of an analogous—but much less expensive—HSGT program of 35 years ago: the Metroliner.

The programs are comparable in their prime purpose—to demonstrate a technology. However, in any such comparison it is only fair to note that a short-distance Maglev project, whether or not it captures the mode’s full potential, would certainly leave behind a permanent system; whereas the Metroliner project was superimposed on a deteriorated facility needing significant rehabilitation.

Still, for the price, it is evident that in the 1960s the Federal Government obtained a successful⁶² demonstration for a pittance in comparison with the cost of demonstrating Maglev to the American public. The costs shown for the Metroliner demonstration are the total costs and include contributions of about \$260 million and \$50 million from the Penn Central Railroad and the Federal Government, respectively (2004 dollars).

Table 6: Comparison of Demonstration Programs—Metroliner and Maglev

	Maglev, Baltimore-Washington (proposed) (Baseline is Acela)	Metroliner, New York-Washington (implemented 1969) (Baseline is fast PRR schedule)
Total cost, millions of 2004 dollars	\$3,852	\$310
Total travel time before (minutes)	84	300
Total travel time after (minutes)	68	254
Percent decrease in total time	19%	15%
Cost per percentage point reduction in total travel time (millions of dollars)	\$202	\$20
Minutes' decrease in total travel time	17	46
Cost per minute saved (millions of dollars)	\$227	\$7

depend on an intricate latticework of assumptions about vehicle design, trackage configurations, station layouts, control system capabilities, and operating policies, many of which rely on detailed decisions by owners, operating managers, and suppliers whose identities cannot even be imagined and whose policies cannot now be foreseen. Thus, the box on other measures of transportation efficiency (next page) represents a compilation and initial sifting of reasonable assumptions regarding the capacity and cost of a broad spectrum of transportation modes. Detailed studies of particular corridors would, as a matter of course, explore these topics in much greater depth, and with much more searching attention to specifics, than is possible or appropriate in a nationwide overview such as the present report.

⁶² The “successful” evaluation is by Walter Shapiro, “The Seven Secrets of the Metroliner’s Success,” *The Washington Monthly*, March 1973.

Box 3: Other Measures of Transportation Efficiency

**Table 7: Illustrative Capacities and Costs
of Intercity Transportation Modes—Initial Approximations (Note A)**

Row	Line item	Air (See Note B)	Freeway		IHSR 110	New HSR	Maglev
			Urban	Rural			
A	Facility Assumptions	Runway: 8000 ft x 150 ft ⁶³ , unidirectional operation	1 lane	1 lane	110 mph top speed	200 mph top speed	300 mph
B	Hourly Capacity In One Direction	2,430 passengers per runway	3,588 passengers per lane	3,634 passengers per lane	2,640 passengers	5,600 passengers	7,728 passengers
C	Capital Cost	\$22 million per runway ⁶⁴	\$4.9-\$10.3 million per lane mile ^{65, 66}	\$3.9-\$6.6 million per lane mile ⁶⁷	\$2.9 million per track-mile ⁶⁸	\$17.6 million per track-mile ⁶⁹	\$25.1 million per single guideway-mile ⁷⁰
D = C/B	Unit Capital Cost (capital cost per hourly passenger in one direction)	\$6,349	\$2,090	\$1,376	\$1,098	\$3,143	\$3,248

Note A: Site-specific analysis would be required for comparisons of the capacities and costs of modal alternatives in real-world applications.

Note B: Air is not comparable with the ground modes as there is no permanent way construction cost (except control/communications systems) for use of the atmosphere. The figures for runways are included solely as a matter of interest, not of comparability.

Assumptions (See Discussion on Page 23)

1. Air –
 - a. Facility. This runway dimension handles regional jets and narrow-body aircraft, such as the Boeing 737. The California High-speed Train Program Environmental Impact Study (EIS) Alternatives Analysis specifies that these types of planes would be used to compete with Maglev service.
 - b. Hourly Capacity. The airplane used in these calculations was a Boeing 737. This is the type of aircraft specified in the California High-Speed Rail Environmental Impact Study (Appendix 4-B page 2) as that which would use an 8000 ft x 150ft runway. The capacity of a Boeing 737 ranges from 85 to 189⁷¹. The number of flights per day per gate was set at 8 because the California High-Speed Train Program EIS stated that a typical aircraft gate would serve between 6 mixed and 10 short flights a day.⁷² An average load factor of 75% and the ratio of gates to runways (30) also come from the California High-Speed Train Program EIS.⁷³ Actual runway capacities would be highly dependent on site-specific conditions, the sequence of aircraft types utilizing the runway, the sequence of landings and takeoffs, weather conditions, and related factors.
2. Freeway –
 - a. Hourly capacity. The 1994 Highway Capacity Manual⁷⁴ states that there is a lane capacity of 2300 passenger cars per hour per lane at a maximum service flow rate under ideal conditions for 6+ lane freeways. FHWA recommended using average vehicle occupancies for rural and urban residents as surrogates for average vehicle occupancies on rural and urban freeways. Referring to the 1995 Nationwide Personal Transportation Study (NPTS)⁷⁵, the average rural vehicle occupancy is 1.58 and the average urban vehicle occupancy is 1.56.
 - b. Capital costs are for the widening of existing freeways, which are deemed “high costs lanes”.
 - c. Unit Capital costs for urban and rural freeways are calculated using the midpoint of the capital cost range found in Row C.
3. IHSR 110 – Based on the CFS,⁷⁶ Table 4-5, with a seating capacity of 264 passengers per train. A six-minute headway was assumed in light of observed difficulties in Japan of running shorter headways.
4. New HSR – A ten-car train was assumed, 56 seats per car, with a seating capacity of 560 passengers per train. A six-minute headway was assumed in light of difficulties, observed by senior FRA staff, in Japan with running shorter headways.
5. Maglev – Hourly capacity was calculated using a seated capacity of 644⁷⁷. This is based on a 4 across seating layout, 10-section, Transrapid configuration. In addition, a five-minute headway was used which follows from studies done on Maglev corridors in the United States⁷⁸.

⁶³ California High-speed Train Program EIR/EIS, Appendix 4-b, page 2.

⁶⁴ Table 4-B-2, Airport Unit Costs, California HST Program EIR/EIS, Appendix 4-B.

⁶⁵ Personal communication, FHWA.

⁶⁶ California High-Speed Train Program EIR/EIS provided unit highway costs ranging from \$17 million to \$400 million.

⁶⁷ Personal communication, FHWA.

⁶⁸ Derived from *High-Speed Ground Transportation for America*, U.S. Department of Transportation, Federal Railroad Administration, September 1997; and transportation planning reports on Washington–Richmond and Richmond–Charlotte corridors, <http://www.fra.dot.gov/us/content/1240>.

Economic Perspective: Comprehensive Costs and Benefits

Travel time improvements and their relative costs are important indicators of the value of proposed transport system changes; but they do not tell the whole story. The CFS, in fact, devoted considerable research to the characterization of benefits to society beyond the purely operational and financial. Chapter 6 of the CFS report explores in detail the rationale for and means of treating the benefits and costs in the three ways shown in Table 8, which incorporate life-cycle costing techniques.

**Table 8:
CFS Approaches to Developing Benefit/Cost Measures for HSGT Systems**

Total Benefits Versus Total Costs	
<i>Types of Benefits and Costs</i>	
Total Benefits:	
Benefits to HSGT Users:	
Benefits for Which HSGT Users Pay Directly (Equates To System Revenues)	
Benefits for Which HSGT Users Do Not Pay Directly (Equates To Users' Consumer Surplus)	
Benefits to the Public at Large:	
Airport Congestion Delay Savings	
Highway Congestion Delay Savings	
Emissions Savings	
Total Costs:	
Initial Investment	
Continuing Investment (Equipment and Facility Expansion/Replacement)	
Operating and Maintenance Expense	
Benefits to HSGT Users Versus Costs Borne by Users	
<i>Types of Benefits and Costs</i>	
Benefits to HSGT Users:	
Benefits for Which HSGT Users Pay Directly (Equates To System Revenues)	
Benefits for Which HSGT Users Do Not Pay Directly (Equates To Users' Consumer Surplus)	
Costs Borne by Users (Equates To System Revenues)	
Benefits to the Public at Large Versus Publicly-Borne Costs	
<i>Types of Benefits and Costs</i>	
Benefits to the Public at Large:	
Airport Congestion Delay Savings	
Highway Congestion Delay Savings	
Emissions Savings	
Publicly-Borne Costs. Equates to Total Costs Less Costs Borne by Users (i.e., in practical terms, Total Costs Less System Revenues)	

⁶⁹ California HSR Authority, *California HSR Corridor Evaluation*, December 30, 1999. Costs have been escalated to 2004 dollars. CFS data for comparison is from CFS report.

⁷⁰ California HSR Authority, *California HSR Corridor Evaluation*, December 30, 1999. Costs have been escalated to 2004 dollars. CFS data for comparison is from CFS report.

⁷¹ http://en.wikipedia.org/wiki/Boeing_737

⁷² *California High-speed Train Program EIR/EIS*, Appendix 2-G.

⁷³ *California High-speed Train Program EIR/EIS*, Appendix 2-G.

⁷⁴ *Highway Capacity Manual*, Transportation Research Board, Washington D.C., 1994.

⁷⁵ <http://npts.orl.gov/npts/1995/doc/index.shtml>

⁷⁶ *High-Speed Ground Transportation for America*, U.S. Department of Transportation, Federal Railroad Administration, September 1997.

⁷⁷ Personal communication, Transrapid-USA.

⁷⁸ "Cost Comparison-Maglev with Freeway, Light and Heavy Rail," Baltimore-Washington Maglev Project, KCI/PB Joint Venture, July 21, 2003.

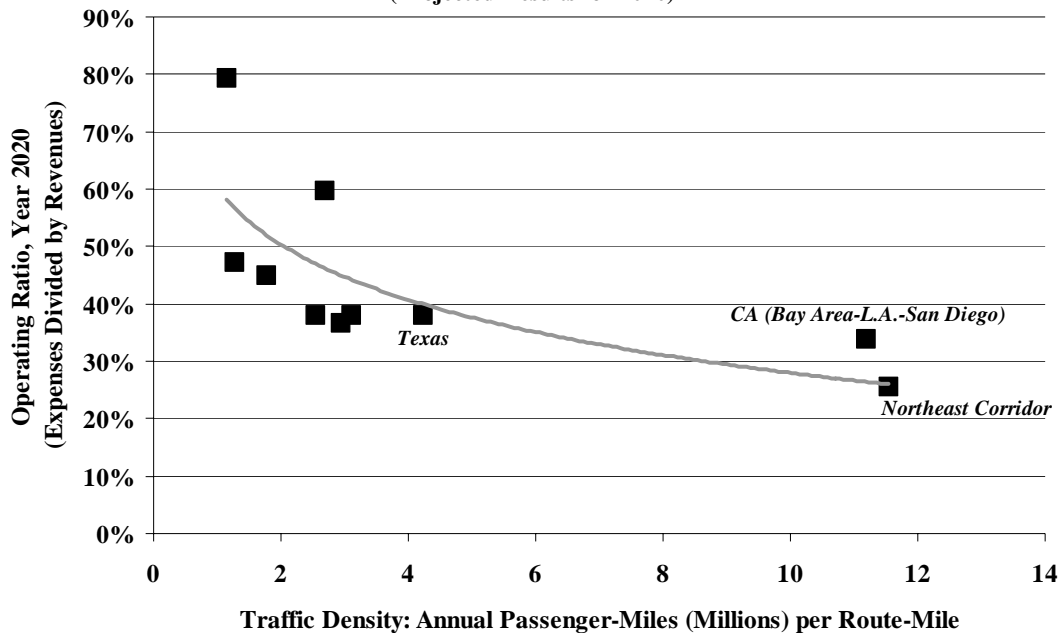
Importance of Density

As Table 8 demonstrates, both revenues and operating/maintenance (O&M) expenses heavily influence the projection of benefits and costs. Thus, Maglev’s revenues and expenses affect the numerator and denominator, respectively, of Total Benefits Versus Total Costs; and operating revenues and expenses are both part of the denominator of Benefits to the Public at Large Versus Publicly-Borne Costs. Thus the operating performance of a Maglev project will exert influence on its benefit/cost ratio. A prime determinant of operating performance in any HSGT system is the traffic density. In general, the higher the concentration of traffic on an HSGT route, the greater its expected surpluses and the more favorable its ratios.

To succeed in a simulation, a Maglev corridor must not only fall into a competitive distance range with respect to other available modes; it must also develop sufficient traffic density at remunerative fares to promise an operating subsidy-free service that can finance a significant portion of its initial costs from its own net revenues.⁷⁹

The CFS clearly indicates that higher traffic density correlates with greater operating surpluses and self-financing potential. The Maglev corridors in the CFS, when considered together, generate lower (i.e., better) operating ratios⁸¹ in proportion as their traffic densities, measured in passenger-miles per route mile, increase. This trend clearly emerges from Figure 12, where the lowest-density corridors generate the highest operating ratios, and vice versa.

Figure 12:
Relationship between Traffic Density and Operating Ratios in CFS Maglev Corridors⁸⁰
(Projected Results for 2020)



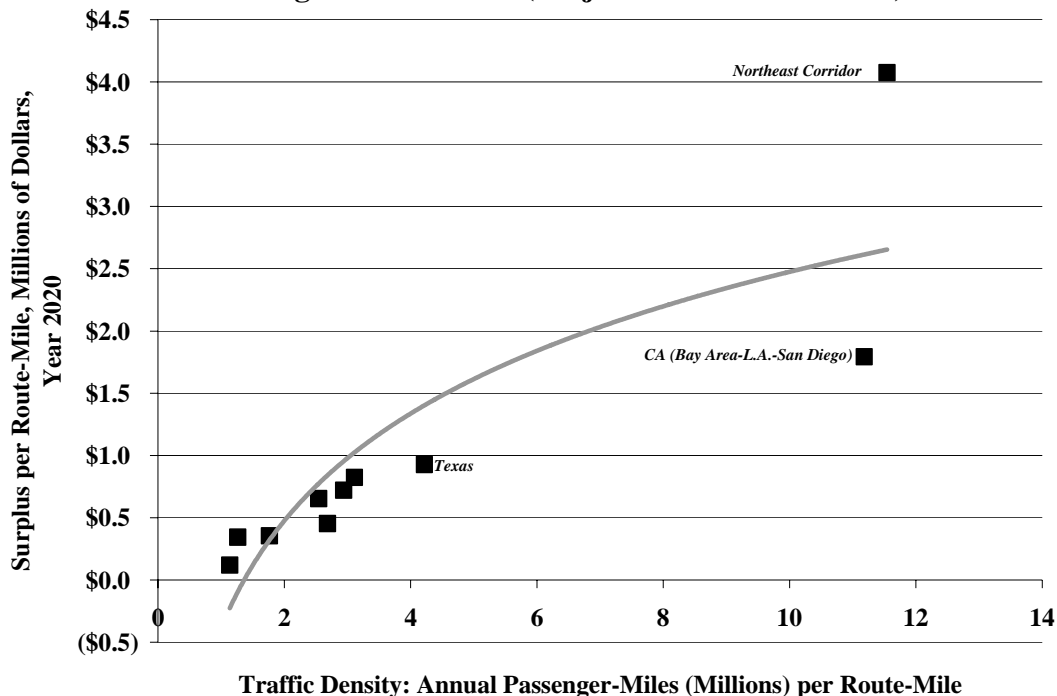
⁷⁹ This perspective is that of the CFS. For particulars, see FRA, *High-Speed Ground Transportation for America*, 1997, chapter 3.

⁸⁰ Source: CFS report, Statistical Supplement for all Maglev cases analyzed, except for the non-comparable Empire and Southeast corridors. HSGT Traffic Density per Route Mile versus Operating Ratio.

⁸¹ The operating ratio is the expenses divided by the revenues.

Of crucial importance to Maglev is the operating surplus that can be obtained on a per-route-mile basis, since investment requirements are so heavy. Again, it is the highest-density corridors that generate the highest surplus per mile, as revealed in Figure 13.

Figure 13: Relationship between Traffic Density and Surpluses per Route-Mile in CFS Maglev Corridors⁸² (Projected Results for 2020)



Finally, Figure 14 compares the traffic density with the percentage of initial capital costs that can be offset by the discounted future flow of surpluses. Following the pattern set in previous statistics, this percentage correlates quite well with traffic density.

Benefit/Cost Ratios

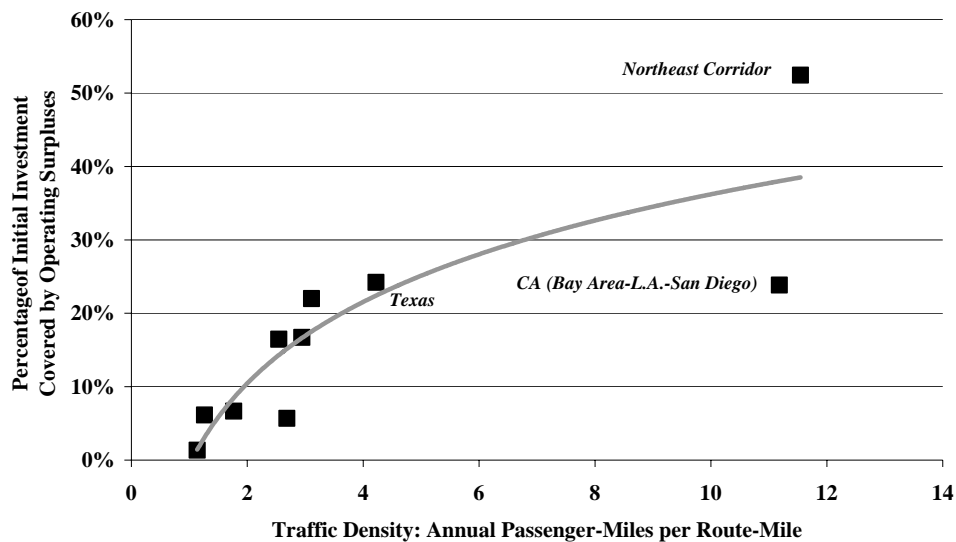
The CFS reported on a broad range of benefit/cost ratios: the total benefits and costs as measured in economic terms; those projected for system users only; and those projected for the general public only.⁸³ In accordance with OMB's guidelines,⁸⁴ the ratio of total benefits to total costs had primacy in the CFS and retains that position in this report.

⁸² Source: Derived from CFS report, Statistical Supplement (see Footnote 80). HSGT Traffic Density per Route Mile versus (Operating Surplus divided by Route-Miles).

⁸³ Table 8, above, defines the components of these three ratios.

⁸⁴ The Office of Management and Budget's (OMB's) Circular A-94, Section 6, states that "social net benefits, and not the benefits and costs to the Federal Government, should be the basis for evaluating government programs or policies that have effects on private citizens or other levels of government," and includes consumer surplus as one element of social benefits. In this context "consumer surplus" measures the difference between the value of the transportation service to the user (i.e., what he or she would have been willing to pay for a trip) and the value that is exacted by the carrier under the applicable fare structure.

Figure 14: Relationship between Traffic Density and Self-Financing in CFS Maglev Corridors⁸⁵
 (Projected Density for 2020; Investment Coverage based on 40-Year Discounted Cash Flows)



Total Benefits Versus Total Costs

As shown in Figure 15, the CFS projected that Maglev would produce total benefits equal to or greater than total costs only in the most densely traveled corridors: California North/South (ratio 1.1), the NEC (also 1.1), and two extensions of the latter—the Empire Corridor (1.0) and the Southeast Corridor (1.6). Both extensions, as explained in CFS Chapter 8, presuppose completion of Maglev in the NEC and take credit for the incremental net revenues they produce over the NEC. In all corridors with densities lower than those just mentioned, Maglev was projected to generate ratios of total benefits to total costs of 0.8 and below.

In most corridors, either IHSR or New HSR produced ratios of total benefits to costs that exceeded those of Maglev. The exceptions to this rule were:

- Chicago–Milwaukee, which suffers when considered by itself (i.e., not as part of a Chicago network with its traffic synergies) and yields no ratio beyond 0.5; and
- The NEC, where Maglev’s superior travel times in the especially lucrative and HSGT-oriented New York–Washington and New York–Boston markets would provide by far the fastest center-to-center travel time by any mode. Maglev’s ratio in the NEC (1.1) would slightly exceed that of New HSR (1.0), which would also entail much expensive new construction but which would not provide travel times as good as those of Maglev in these very profitable markets.

User and Public Benefits and Costs

Figure 16 presents all three measures of economic benefits and costs—total, user, and public—of which the last two are discussed below.

⁸⁵ Source: CFS report, Statistical Supplement. HSGT Traffic Density per Route Mile versus Percentage of Initial Investment Covered by Surplus After Continuing Investments.

Figure 15: Total Benefits Versus Total Costs for CFS Illustrative Corridors
 (Updated for Inflation. IHSR capital costs are revised upward by a factor of 1.8 to reflect intervening planning experience.)

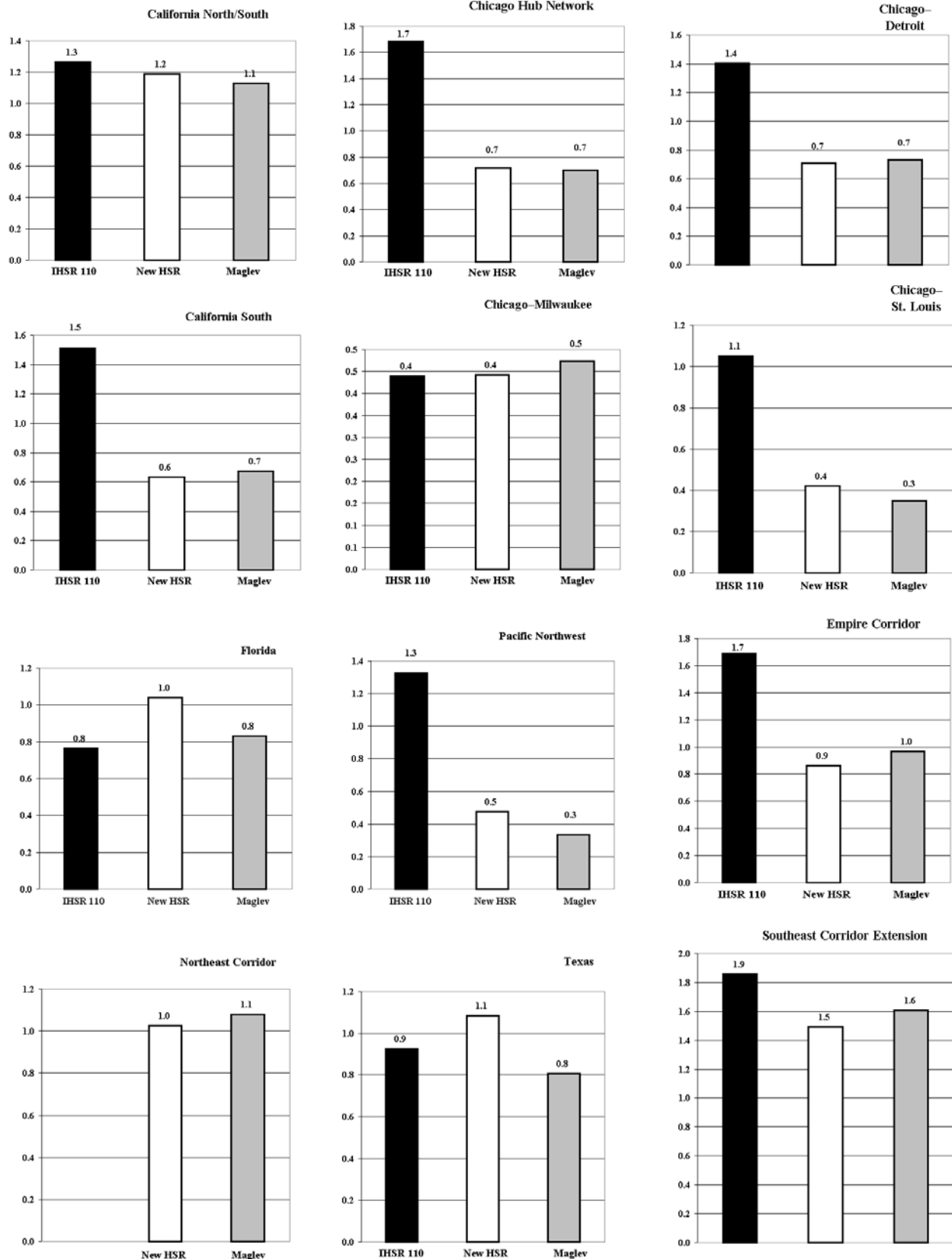
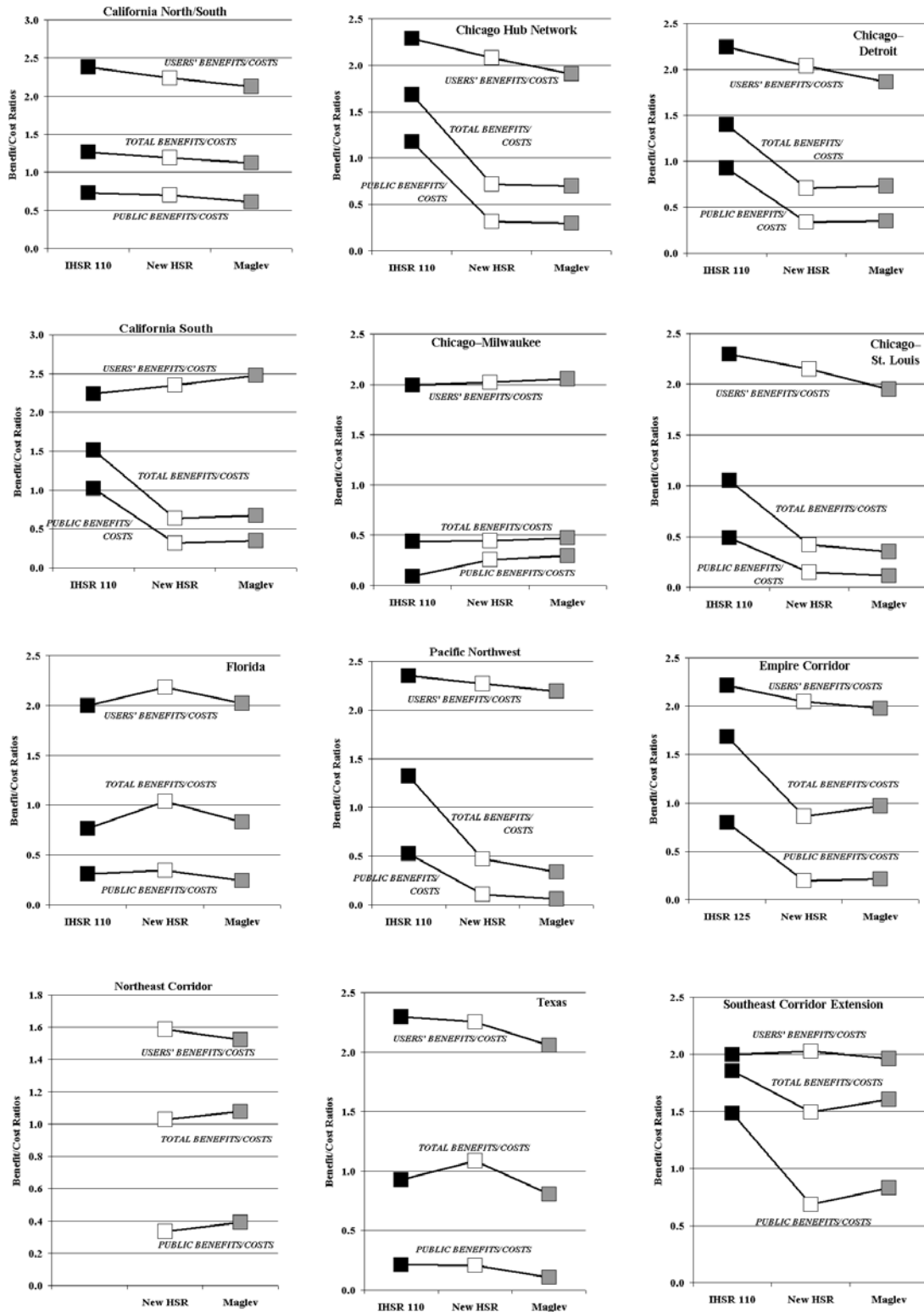


Figure 16: CFS Benefit/Cost Ratios—In Total; For Users; and For the General Public
 (Updated for Inflation. IHSR capital costs are revised upward by a factor of 1.8 to reflect intervening planning experience.)



User Benefits Versus Costs to Users

The ratio of the total value received by users to the fares they would have to pay produces a substantial net gain to passengers, on the order of two-to-one, for all HSGT technologies. As the CFS study team so set its simulated fares as to maximize projected net revenues,⁸⁶ any attempt to capture more of the value to users through higher fares would have actually harmed the operating and financial forecasts for each case. A typical system in revenue operation would, over time, try to modulate its prices to recapture a higher portion of the total value to users through a more sophisticated tariff-setting scheme (“revenue management”) than was available for the CFS analysis. If successful, such revenue management would expressly lower the users’ benefit/cost ratio.

Public Benefits Versus Publicly-Borne Costs

In only two cases does Maglev’s projected ratio of public benefits to public costs exceed 0.5: in California (0.6), where Maglev’s superior total trip times can better those of air in the lucrative Bay Area–Los Angeles market; and the Southeast Corridor extension of the NEC (0.8). All the other illustrative CFS Maglev cases yielded public benefit/cost ratios of significantly less than 0.5.

Owing to the definitions of all the economic benefit/cost ratios (in Table 8), all three of the HSGT technologies covered in this report promise lower ratios of public than of total benefits to costs. In most of the CFS corridors, Maglev’s ratios of public benefits to costs are less favorable than those of either IHSR 110 or New HSR, or both. The exceptions—Chicago–Milwaukee and the NEC—are the same as those for the total benefit/cost ratios, and reflect the same underlying factors.

Benefit/Cost Ratios from a Federal Perspective

All the ratios discussed above and depicted in Figure 16 are from a Federal perspective. Local conditions and site-specific factors may attribute to Maglev certain specialized benefits—for example, large increases in permanent employment, real estate development opportunities due to Maglev’s ability to transform spatial and temporal relationships, or diversion of air traffic from one airport to another—that would yield obvious and overwhelming advantages to a particular State, region, or locality. However, as explained in CFS Chapter 6, many of these locally-perceived benefits would be transfer effects from the Federal viewpoint: the Maglev project might simply be promoting economic growth in one locale at the expense of another. All such transfer effects were found to be inappropriate for inclusion in the Federally-sponsored CFS—nor can they be properly included here. However, individual States, regions, and localities may wish to consider these types of specialized benefits as they consider whether to undertake their own investments in possible HSGT projects, including Maglev options.

The ratios of benefits and costs from the CFS—a nationwide study that consistently analyzed a number of illustrative corridors—are useful mainly as they indicate the relative positions of the various modes in each corridor and among corridors. Clearly, more recent

⁸⁶ I.e., projected revenues less projected operating expenses.

specialized studies, such as the programmatic environmental review undertaken by the California High-Speed Rail Authority in cooperation with the FRA, must be generally regarded as more authoritative and up-to-date with respect to the individual corridors involved, except insofar as any such studies may reckon as part of total benefits the transfer effects discussed above.

Highway Traffic Congestion Relief

As a component of “total benefits,” reduced highway traffic enters into the calculation of the overall ratios described above. In requesting this report, however, the Congress singled out “[highway] traffic congestion relief” as a topic for discussion. This section therefore expands on that topic.

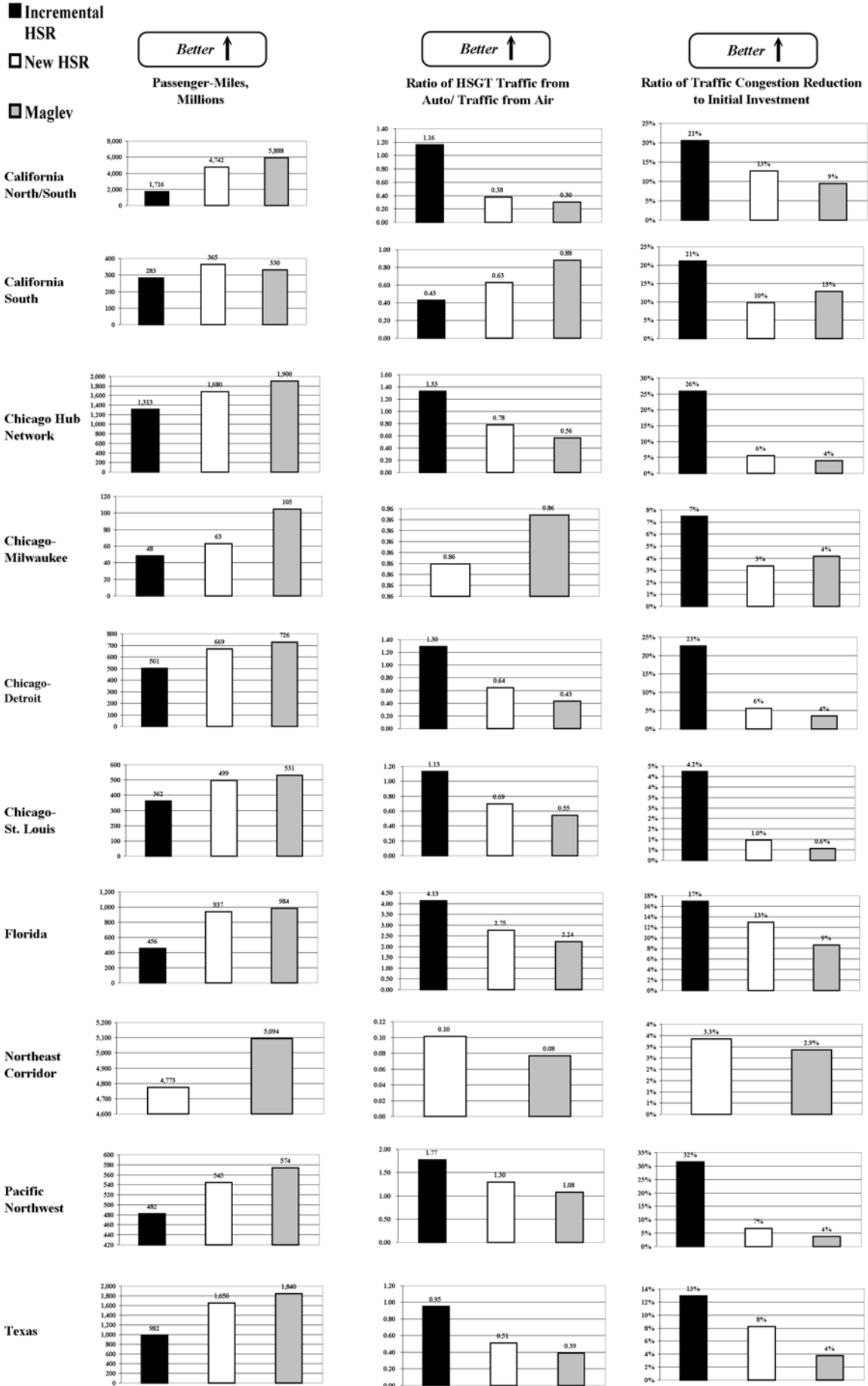
The CFS included an extensive examination of the benefits that would accrue if HSGT were to attract ambient automobile traffic from the congested highways in the illustrative corridors. For each corridor, specific locations—major metropolitan termini, intermediate urbanized areas, and typical places with lower population densities—underwent scrutiny, and the results were extrapolated to the corridor as a whole. The study team projected the increased highway speeds that would result from travel diversion to HSGT, and projected the resultant personal time savings for the remaining automobile users. Aggregate time savings estimates were multiplied by standard values of personal time to estimate the benefits from traffic congestion relief that would accrue for each HSGT technology in each illustrative corridor. A fuller explanation of the procedure, with references, appears in the excerpt from the CFS report that is included here as Annex C.

Closer examination and updating of the CFS results reveals and amplifies the same trend that characterizes the comprehensive benefit/cost ratios in the prior section. Per dollar of initial capital investment, the value of highway traffic congestion relief is significantly higher for the IHSR alternatives than for New HSR and Maglev in every corridor except the NEC, where IHSR already exists. On the other hand, the results for New HSR and Maglev are relatively similar.

The apparent cost-effectiveness of IHSR is consistent with other underlying trends in the CFS results. In brief, Maglev and New HSR produce more total HSGT traffic—in some cases, twice or three times more—than IHSR. However, the mix of traffic sources changes dramatically as the HSGT technologies advance from lower to higher speeds. In general, IHSR derives most of its traffic from ambient automobile, bus, and conventional rail passenger volumes; Maglev and New HSR, on the other hand, attract most of their customers from aviation, because they can compete forcefully with the airlines on total travel times. Thus, in the typical corridor, both the sources and the total volumes of passenger traffic shift markedly as the assumed technology becomes more capable. This general trend, coupled with the unit increases in capital cost from IHSR to New HSR and Maglev, inevitably tends to characterize IHSR as a more cost-effective tool for relieving traffic congestion than the new-construction forms of HSGT.⁸⁷ Figure 17 demonstrates the logic leading to this conclusion.

⁸⁷ It is interesting to note that a similar conclusion emerged from the all-encompassing Northeast Corridor Project studies of the 1960s, which set the tone for transportation systems analysis for decades to come. These multimillion-dollar studies led, in 1973, to a recommendation for Incremental HSR—rather than New HSR or an advanced technology—in the Northeast Corridor, which the Federal Government implemented over the next quarter-century.

Figure 17: Benefits from HSGT Highway Traffic Congestion Reduction



Some caution, however, must temper any such interpretation of the CFS data. The fare assumptions of the CFS referred to elsewhere in this report—especially the insistence on setting fares at the net-revenue maximizing point—inevitably depressed the ridership projections for New HSR and Maglev, as their traffic will bear a higher tariff due to the superior travel times they facilitate, and as their high initial costs necessitate a maximal payback from future users *from a commercial viewpoint*. Under a change of assumptions brought about by changes in the transportation environment, the projected ridership for New HSR and Maglev might sharply increase, and their prospective diversions from the highway mode could increase significantly, albeit at a price that the public would ultimately pay. Thus, in evaluating the trends highlighted in this section, readers should note that the inherent commercial orientation of the CFS drives many of the comparisons that underlie this overview of Maglev in its intermodal context.

Highway Traffic Congestion Relief in the Vicinity of Airports

Maglev, with its expected ability to divert passengers from air, might assist in reducing the growth of highway congestion in and around airports. The net extent of this prospective assistance at a specific air terminal would likely depend on at least four basic factors:

- The ambient mix of passenger access and egress modes (private vehicles versus mass transit) to and from the airport;
- The site-specific layout at the airport and the physical limitations on motor vehicle flows;
- Whether the Maglev line serves the airport directly, the volume of Maglev arrivals and departures at the airport station, and the means of access/egress of Maglev passengers; and
- The importance, within the particular airport's traffic base, of the city-pairs in which Maglev and the airlines compete. If the two modes overlap with respect to only a small percentage of the airport's traffic, then Maglev cannot exert much leverage on vehicular traffic tie-ups at the airport.

These site-specific factors would apply to other forms of HSGT as well, although with a diminishing effect in most cases due to the slower-speed options' reduced ability to divert air traffic (as revealed in Figure 17).

Maglev's Advantages, Disadvantages, and Uncertainties

In requesting this report, the Congress sought the assistance of the FRA in evaluating Maglev's potential to relieve traffic congestion and in ascertaining its appropriate role in the Nation's transportation system. The preceding sections systematically analyze Maglev's unit costs, its transportation payback, and its economic returns in comparison with those of comparable modes. The present section characterizes Maglev in terms of its salient pluses and minuses, as well as its inherent uncertainties.

Potential Advantages

The following advantages may pertain to Maglev systems:

Reduced maintenance cost. Inasmuch as there is no contact between the vehicle and guideway, there is no wheel or rail wear, which may lead to reduced equipment and maintenance-of-way costs from those of analogous steel-wheel systems. However, a Maglev vehicle still exerts physical forces on the guideway, and the precise extent of the maintenance cost advantage is unknown due to the lack of long-term operating experience in revenue service.

Environmental effects. At moderate speeds such as would be encountered in built-up areas, Maglev is significantly less noisy than wheeled systems like rail vehicles or buses. However, at high speed (greater than 155 mph), aerodynamic noise predominates and is quite loud (up to 90dbA at 100 feet). Although proponents claim the elevated guideway can be designed to be relatively attractive and non-intrusive, its prospective neighbors may not necessarily share that viewpoint. Electrically driven, the system produces no pollution along the guideway; however, the power produced at the electric utility plant does contribute to pollution or to such other environmental challenges as the disposal of spent nuclear waste.

Efficient Performance. Maglev may enable higher speed and reduced energy use compared to rail due to lighter vehicles, greater banking ability, lack of contact, and use of linear motors. Linear motor propulsion avoids wheel/rail adhesion problems and allows higher acceleration, braking, and steeper grades—up to ten percent. It has been claimed that Maglev offers a leap in performance relative to comparable high-speed rail on new right-of-way, where incremental improvements to high-speed rail technology may cost more and deliver less as the technology reaches a limiting plateau (currently on the order of 200 mph). With speed up to 310 mph, Maglev is envisioned as filling a niche, and making ground transportation fully competitive with highway and air travel in certain corridors for trips of about 150 to 500 miles.

High Capacity. Under the assumptions of Table 7, a single Maglev guideway could accommodate approximately the same number of unidirectional passengers-per-hour that three airport runways or two lanes of highway could handle.⁸⁸

Low Proportional Cost Increment Over New HSR. Although the cost of Maglev appears high, studies of recent high-speed rail systems in Germany envision that New HSR might approach, or even exceed, Maglev in cost. It seems clear that, in many, if not most cases, new HSGT systems cannot follow existing routes that were often designed for speeds below 79 mph. Only modest curvature in both horizontal and vertical alignment can be tolerated for ride comfort reasons. This may necessitate extensive elevated structures and occasional tunnels, depending on topography, for some high-speed rail systems, thereby narrowing the differential with Maglev costs. The costs for California, shown on page 10 above, indicate a per-mile differential between New HSR and Maglev on the order of \$11 to \$13 million, not a huge amount when the cost per mile reaches the \$50 to \$100 million level. Finally, engineers of the Central Japan Railway Company have recently estimated that Maglev on their proposed new,

⁸⁸ As noted in Table 7, capacity comparisons in real-world applications would depend heavily on site-specific conditions.

inland route between Tokyo and Osaka might cost 20 to 30 percent more than the New HSR alternative.

Passenger Service Quality. With its contactless suspension, Maglev offers the opportunity to provide a ride quality for its passengers that may exceed that obtainable on existing modes. Furthermore, as a ground mode, Maglev can penetrate to the heart of the cities it serves while also servicing airports and “beltway-type” suburban stations. Its projected, relatively low operating costs and quick turnarounds would also make a very high frequency of service feasible. Finally and most importantly, the high operating speeds would, in corridors with appropriate city-pair distances, allow Maglev to move passengers at least as quickly as any other mode, even air. For example, as projected in the CFS, the Maglev line-haul trip time between New York and Boston of about one hour would be within minutes of what the airlines can currently schedule⁸⁹; moreover, with its downtown stations, Maglev would provide much better door-to-door travel times than are feasible by air. These time, comfort, and convenience factors may be expected to influence the modal choices of existing travelers, create new demand, and improve the economics of HSGT, once the question of high initial costs is dealt with.

Potential Disadvantages

The following disadvantages may be inherent in Maglev systems:

Peak versus average speeds. It may not be possible to maintain the Maglev’s promised top speeds (up to 310 mph) in congested corridors—particularly on short, urban systems—because of the difficulty in acquiring the straight alignments needed for operation at the technology’s maximal speed. In the illustrative intercity corridors of the CFS, Maglev was simulated to achieve average speeds exceeding two-thirds of its peak speeds (e.g., 218 mph in California). However, experience with the U.S. Maglev Deployment Program has projected average speeds to be less than one-half peak speeds, bringing into question whether the high speed capability is worth the cost on the short corridors addressed in that Program. Unless planners are willing to be more aggressive in designing Maglev alignments—thereby incurring higher cost and more intense environmental issues—there may be insufficient reason to incur the additional expense to develop Maglev systems entirely within urbanized zones.

Availability of lower-cost alternatives. Although New HSR costs may approach those of Maglev, there is a broad spectrum of available HSR options, including hybrid HSR lines that mix levels of investment. Some of these options may provide competitive and cost-effective trip time savings while avoiding such expensive civil works as are required for both Maglev and New HSR on new rights-of-way.

Switching. Switching is complex in both types of Maglev. In the attractive case, the vehicle wraps around the guideway, and in the repulsive case, the guideway wraps around the vehicle—thus creating a challenging topology for switching. Both German and Japanese

⁸⁹ As of November 2004, the shortest air travel time between Boston Logan (BOS) and New York LaGuardia (LGA) airports is 52 minutes. Most flights are longer than that. (Per Expedia.com.)

systems require movement of a lengthy and massive section of guideway in order to enable route diversion at high speed.

Energy consumption. Transrapid claims that under cruise conditions, its Maglev is more energy-efficient than auto, rail, or air. Cruise conditions, while common in the CFS cases, seldom prevail in the scenarios FRA has studied under the Maglev Deployment Program. With constantly changing speeds and the circuitry of routes, the actual energy expenditure for a route can be several times what it would take to cruise point-to-point at the same average speed. This would work against Maglev in an energy-use comparison with other modes, although the lighter weight of Maglev vehicles (in comparison with high-speed rail trainsets that have to meet FRA strength requirements for mixed operation with heavy freight trains on shared tracks) may offer some opportunities for energy savings.

Guideway construction and maintenance costs. It was once widely believed that, because of the clearance between vehicle and its guideway (especially in the wide-gap Japanese system), the guideway could be built and maintained to less strict tolerance, resulting in reduced cost. Experience has shown this not to be the case, because it is ride quality that dictates how free of irregularities the guideway must be, not ability to track the guideway.

Uncertainties

Maglev is a new mode currently under development in a number of countries, with a sole revenue installation in regular service only since April 2004.⁹⁰ As with any embryonic transport mode, uncertainties characterize—

- The long-term capital, operating, and maintenance costs of currently available technologies;
- The long-term performance characteristics of these technologies—for instance, their all-weather reliability under American conditions, in comparison with currently-available modes;
- The opportunities for technological breakthroughs that might substantially reduce the life-cycle costs of installing, operating, and maintaining a Maglev system;
- Innovative performance upgrades and unforeseen safety drawbacks that might manifest themselves in the decades to come;
- Public reaction to various types of Maglev systems, in terms of demand and revenue over a range of stage lengths; and, more generally—
- The long-term effects of September 11, 2001; ensuing changes in travel demand, the security environment, total travel times, and competitive positions of the air and—potentially—other modes; and structural changes in the airline, rail passenger, and other transportation industries.

⁹⁰ CNN/Reuters, “China to Cut Costs on New Maglev Link,” December 7, 2004, at: <http://www.cnn.com/2004/TRAVEL/12/07/bt.china.maglev.cost.reut/index.html>

The present report necessarily bases its analysis and conclusions on currently available Maglev systems and extant projections of those systems' performance vis-à-vis comparable modes. However, neither the spectrum of Maglev technologies nor the American transportation environment will likely remain static throughout the 21st Century.

Conclusions

Although each region conducting planning under the Maglev Deployment Program is best able to evaluate the benefits and costs of the proposed projects *within its own region*, the Federal Government must view Maglev in the context of national needs and priorities. From a local perspective, a particular project may promise overwhelming benefits in relation to its costs. Nothing in this study should suggest that a State or metropolitan area not act accordingly, within its own financing capabilities and those of its potential partners, and subject to such applicable Federal laws as those bearing on safety and the environment. However, from a strictly Federal viewpoint, this report reaches the following conclusions:

- Intercity systems based on currently available Maglev technologies are expensive, with high per-mile costs.
- Conversely, if implemented, Maglev might provide line-haul travel times that improve on those of any other mode of ground transportation. The following noteworthy factors place Maglev travel times in their broader context:
 - Maglev's line-haul speed advantage can only result in substantial total travel time improvements in markets in which line-haul travel times are a significant proportion of total travel times—i.e., in markets more than approximately 150 miles in length.
 - Beyond trip distances of about 500 miles, air's superior cruising speeds would begin to detract from Maglev's advantages of station location and access.
 - Therefore, Maglev's most appropriate transportation niche is in corridors of extremely high travel density that include strong city-pair markets in the 150-to-500-mile range.
- In the densely populated corridors where Maglev has the greatest potential for yielding significant transportation benefits to recompense its costs, existing development, environmental concerns, and other practical constraints would make it very challenging to acquire and develop an alignment that permits current Maglev technologies to fully achieve their trip time improvement capabilities.
- Maglev, with its expected ability to attract passengers from airlines, might assist in reducing the growth of local highway congestion generated by airport access and egress. The potential for such assistance at a specific air terminal would depend on the market reach of available, air-competitive Maglev service; the origin/destination mix of the air passengers using the terminal; and their habitual modes of ground travel to and from the airport.
- Some direct shifting of intercity automobile trips to Maglev would also be anticipated. The extent of such diversions, and their potential impacts on congestion in affected highways, would depend largely on each corridor's characteristics (for

instance, on comparative total travel times by Maglev and by auto in the constituent city-pairs), on prevailing gasoline prices, and on the fare policy adopted for Maglev.

- In comparison with today's available Maglev systems, other contemporary HSGT technologies (IHSR and, in some cases, New HSR) typically show higher projected transportation and economic benefits, including highway traffic congestion relief, relative to their costs, and could bring many of the advantages of HSGT to many more markets at much less cost.
- The proposed short-distance demonstrations under the Maglev Deployment Program, if any are constructed, could ultimately produce operational, engineering, and financial data on Maglev under American conditions, at a lower level of outlay and risk than would pertain to a lengthier and costlier installation. Such data might augment information gathered in other countries that have already invested significant resources in Maglev technology, in the event that private and public entities in the United States should someday contemplate longer-distance Maglev systems in corridors of the highest density. In and of themselves, however, the short corridors under consideration in the Maglev Deployment Program would not fully demonstrate Maglev's transportation potential, which is best perceived in systems serving intercity corridors over some 150 miles long.
- As a form of transportation based on new technologies, Maglev is subject to a high degree of uncertainty. Consequently, whatever policy the Federal Government adopts toward Maglev in the short term, the American transportation community—including the private sector—might profitably monitor the Maglev industry for noteworthy changes in its prospective costs, benefits, performance, and applicability to the evolving transportation environment in the United States.
- As Maglev's capabilities, challenges, and cost-effectiveness in a particular region must remain speculative until they undergo examination on a site-specific basis, public officials may wish to weigh the desirability of including Maglev, in light of its evolving characteristics through the years, as a technological alternative in future studies of high-density corridors.

Glossary of Terms and Acronyms

Acronym	Definition
CFS	The commercial feasibility study of high-speed ground transportation, undertaken by the Federal Railroad Administration in the mid-1990s at the behest of Congress. The study was published as: U.S. Department of Transportation, Federal Railroad Administration, <i>High-Speed Ground Transportation for America</i> , September 1997. Referred to as the “CFS Report,” the document is available at http://www.fra.dot.gov/us/content/515 as this report goes to press.
FRA	Federal Railroad Administration
IHSR	Incremental high-speed rail,—an improved rail passenger system primarily making use of upgraded existing rights-of-way, and reaching maximum speeds of 90 mph or above. Amtrak’s Acela is an example of IHSR. Unless otherwise noted, in all analytical comparisons “IHSR” and “IHSR 110” refer to a system with a top speed of 110 mph, termed “Accelerail 110” in the CFS report.
HSGT	High-speed ground transportation, which consists of HSR and Maglev.
HSR	High-speed rail, i.e. steel-wheel-on-steel-rail systems.
LSM	Linear Synchronous Motor
Maglev	Magnetic levitation
Maglev Deployment Program	The Magnetic Levitation Transportation Technology Deployment Program established under TEA-21 (23 U.S.C. 322).
mph	Miles per hour
NEC	Northeast Corridor; refers to Amtrak’s main line between Washington, New York, and Boston, or more broadly to the Northeastern megalopolis between Virginia and Maine, as described in Senator Claiborne Pell’s book <i>Megalopolis Unbound</i> .

Annex A:

Comparison of Maglev Projects Planned for U.S. and Germany Using Transrapid Technology⁹¹

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Abstract

Three high-speed Maglev projects in the U.S. and one in Germany have completed initial feasibility studies and have been completing the pre-construction planning necessary to secure financing and proceed to construction and revenue service. This paper presents and compares the performance characteristics and costs of these projects. Information on project capital costs is provided for major categories, and as both absolute levels and per route-mile and track-mile. These costs seem consistent and thus can be useful in planning efforts for other projects. Statistics derived for operations and maintenance costs, because they vary widely, appear to be less useful in providing an indication of their expected level for other projects.

Introduction

The U.S. Federal Railroad Administration (FRA) is currently funding pre-construction planning for four high-speed Maglev projects in the United States.⁹² These projects are being planned by public/private partnerships consisting of a sponsoring state or local unit of government and a group of private sector engineers and/or industrial organizations. These projects have all selected German Transrapid technology and have been under intensive study by the sponsoring public/private partnerships since 1999. For three of the projects, preliminary engineering has been advanced to the point that credible detailed estimates of capital, operating, and maintenance costs have been prepared. Two of the projects are being planned for staged deployment, with the initial operating segment (IOS) planned as a stand-alone project. For those cases the characteristics of both the IOS and the full project are presented in the analysis.

In addition, since January 2001 the German Federal Ministry of Transport, Building and Housing has been providing financial support to the Federal State of Bavaria for the planning of a project deploying Transrapid technology in Munich. Detailed estimates of capital, operating and maintenance costs have also been prepared for this project.

⁹¹ [Please note: This paper was originally delivered by Ronald A. Mauri at the 18th International Conference on Magnetically Levitated Systems and Linear Drives, October 26, 2004, in Shanghai, China. For consistency with the rest of this report, this paper has been reformatted and kilometers have been converted to miles. Otherwise, except in bracketed footnotes, the substance and wording remain those of the original authors.]

⁹² [This statement remains true as this report goes to press in August 2005.]

This paper describes the alignment and station location, engineering and operational features, travel market served, and the estimated costs and financing of construction and operation of each of the four proposed projects. Specifically the paper describes:

- Type of travel and markets to be served
- Service to be provided (e.g., capacity, frequency of service, etc)
- Layout of alignment and structures and engineering features of design
- Design features and numbers of vehicles required to provide service
- Location and design of stations and maintenance facilities
- A breakdown of estimated capital and operating costs

The information provided for the various projects is compared to identify significant differences in concept, design and costs. Unit costs for the major common elements of the projects are presented along with an analysis and explanation of the observed differences among the unit costs.

Description Of Projects

Following is a short description of each project, a summary of project physical and operating characteristics, and estimated project costs. Finally, unit costs (e.g., U.S.\$ per mile, U.S.\$ per vehicle-mile, etc.) are computed for each project and compared. Unit cost differences are discussed and partially explained by the differing physical and operating characteristics of the projects, and assumptions incorporated into the estimating methodology.

Preliminary engineering for a fourth project in the U.S. in Los Angeles, has been initiated, but the detailed cost estimates needed for this analysis are not yet available.

All of the estimates and data presented in this paper were developed by the various public/private partnerships planning each of the projects, as provided to FRA. Each project planning team has retained reputable engineers and planners. However, by reporting this information, it should not be implied that FRA accepts or endorses the information presented. Because the information was developed by different groups using differing methods for design and estimating, there may be some inconsistency in comparing the various projects. Still, it is the best information available at this time, and it is hoped that it may provide some meaningful parameters and insights for the design of Maglev projects.

Baltimore-Washington Maglev Project

This is a 39.1-mile project linking center city Baltimore's Camden Yard (a sports complex and convention center) and Amtrak's Union Station in Washington, DC with an intermediate stop at Baltimore-Washington International (BWI) Airport. This project has been under study by the Maryland Transit Administration and its private partner since 1994. Forecasting models indicate the project would attract 9.2 million passengers in 2010. It would provide residents and visitors to Washington, DC with convenient access to a second airport only 12 minutes from the primary railroad station (Union Station) in Washington, and take some of the pressure off Reagan National Airport which serves as the primary Washington airport for

short and medium distance flights and is currently operating at capacity. At an average speed of 126 mph, the full trip from Baltimore to Washington, with a stop at BWI, would take 18 minutes. It would also serve business travelers, tourists, and commuters in the corridor. The project is visualized as the initial stage of a high-speed Maglev system that would serve the entire NEC between Boston, MA and Charlotte, NC.

The Baltimore-Washington Maglev Project is estimated to cost \$3.74 billion in year 2002 dollars. This cost estimate includes the construction of 39.1 miles of double-tracked guideway (16% in tunnel and 33% elevated), three underground stations, a maintenance facility, substations, transformers, and other electrical distribution facilities, 12 highway bridges and flyovers, and 3,200 parking spaces. Only 22% of the total cost is attributable to the Maglev vehicles, propulsion, control, and communication systems. The total capital unit cost is \$95.8 million per mile. Based upon the level of design information, as well as relative risk potential, a contingency allowance between 10 percent and 30 percent was added to each line item in the estimate.

The estimated annual cost of operation and maintenance (O&M) for the project is estimated at \$53 million, with 21 percent attributable to energy costs. The annual operating and maintenance estimates reflect the staffing plan, fringe benefits, material costs for maintaining the vehicles and guideway, utility costs for vehicle propulsion and station light and air conditioning, insurance, and administrative costs. To reflect uncertainties and the level of detail in the study of operations and maintenance, a contingency factor of 30 percent was applied to the total O&M cost.

A statistical summary of the physical design, operating features and estimated costs of the proposed project is included in the Appendix.

Pittsburgh Maglev Project

This is a 55-mile project linking Pittsburgh Airport to center city Pittsburgh and its eastern suburbs. The project has been under study since 1990. Pre-construction planning for the project is being carried out by the Port Authority of Allegheny County (the provider most of the transit service in the Pittsburgh area) and its private sector partner, Maglev Inc. The rugged physical terrain, a full four-season climate, and stops at an airport, downtown and in the suburbs would demonstrate the full potential of Maglev technology to provide service in a variety of U.S. urban environments. The project has a top speed of 249 mph and an average speed of 87 mph. The project is projected to be the first segment of an extensive Maglev network that would eventually provide high-speed intercity service between Cleveland to the west and Philadelphia to the east.

The project has been designed for staged construction. The 17.4-mile initial operating segment (IOS) between the airport and downtown Pittsburgh was designed as an independent project, and the Full Pittsburgh project would then follow.

Full Pittsburgh Project

The Full Pittsburgh Project is estimated to cost \$3.82 billion in year 2003 constant dollars. This estimate includes the construction of five stations, with 33.6 miles of dual steel guideway linking four of the stations, and 20.5 miles of single steel guideway linking the system

to the less-used fifth station. The project includes a major river crossing, a maintenance/operations control and visitors' facility, and significant highway improvements to accommodate increased traffic generated by the project, primarily in the vicinity of the stations. For safety and aesthetic reasons, the guideway is designed to be supported on elevated structure for the full length of the project (the minimum column design height through cut sections is 3 meters). The estimate includes contingencies of between 10 and 30 percent. The project design team estimates that only 12 percent of the project costs are attributable to the cost of Maglev vehicles, propulsion, control and communication systems. The total capital unit cost is estimated at \$70.3 million per mile.

The estimated annual cost of operation and maintenance is \$37.9 million, with the cost of energy accounting for 23 percent of the total. Included in the costs are all labor, materials and administrative costs, and 12 percent for contingencies.

Pittsburgh Initial Operating Segment (IOS)

The total capital cost of the Pittsburgh IOS is estimated at \$1.6 billion in year 2003 constant dollars (\$90.1 million per mile). The IOS will require the construction of three stations, 17.4 miles of dual guideway, a maintenance facility, a major river crossing, a maintenance/operations control and visitors' facility, and significant highway improvements to accommodate increased traffic generated by the project, primarily in the vicinity of the stations. Because of security and parking considerations, the station at the airport was divided into two stations. The Airport Terminal Station is located adjacent to the airport terminal, and provides convenient access for air travelers arriving and departing flights. The second station is located 1.9 miles away. It includes a substantial parking area, and will primarily serve commuters bound for downtown Pittsburgh. The division of the station effectively separates commuters to downtown jobs from air travelers and airport workers. The trip from the airport to downtown is scheduled for 11 minutes, including a stop at the airport commuter station. The annual cost of operation and maintenance is estimated to be \$16.7 million.

A statistical summary of the physical design, operating features and estimated costs of both the full 54.7-mile project, and the 17.4-mile IOS are included in the Appendix.

Las Vegas–Anaheim Maglev Project

Intensive pre-construction planning for this project was initiated in 1999 by a public/private partnership formed for the purpose of building a 269.1-mile Maglev system between Las Vegas, Nevada (NV) and Anaheim, California (CA). The six-station project, when fully completed, would provide service to intermediate stations at Primm, NV, and Barstow, Victorville, and Ontario, CA. The termini at Las Vegas and Anaheim represent two of the most attractive tourist destinations in the United States (gaming casinos and entertainment attractions in Las Vegas, and Disneyland in Anaheim), and would generate significant ridership between the two points. The intermediate stops would link the system to a major airport and the planned high-speed rail system at Ontario, a regional airport at Victorville, a growing recreational area and new airport being planned to serve Las Vegas near Primm. The full system would also serve growing long distance commuter demand throughout the corridor.

The public partner, the California-Nevada Super Speed Train Commission, and its private partner, the American Magline Group, are planning to implement the project in stages, and have designated the 34.8-mile eastern-most segment of the project, between Las Vegas and Primm, NV, as the first portion to be constructed. It is proposed to implement the 31.7-mile western-most end of the project as the second segment. Detailed studies of these two segments of the alignment as stand-alone projects have been completed.

A statistical summary of the physical design, operating features and estimated costs of the Las Vegas-Primm Segment, and the Anaheim-Ontario Segment of the Las Vegas to Anaheim Maglev Project are included in the Appendix.

Las Vegas-Primm Segment

The 34.8-mile eastern-most segment of the project, between Las Vegas and Primm, NV, runs through a sparsely developed desert area along an existing highway right-of-way (I-15). It is mostly a single-track guideway, constructed largely at grade, and would be the least expensive and likely the easiest project to build among the documented projects.

The total capital cost is estimated at \$1.3 billion in year 2000 constant dollars (\$37 million per mile). The initial segment is designed to operate three eight-section trains between two stations at 20-minute headways. The design includes construction of 23.3 miles of steel single guideway and 11.5 miles of dual guideway, a maintenance facility and a maintenance/operations control and visitors facility. Only 34 percent of the guideway would be elevated, with the remainder constructed at grade. Over 35 percent of the capital cost is attributable to acquisition of Maglev vehicles, propulsion, control and communication systems. The service would be operated at an average speed of 174 mph, with a top speed of 311 mph.

The annual cost of operation and maintenance in 2020 is estimated to be \$36.7 million, with more than 30 percent attributable to energy costs. Initially the primary market served by the project would be as a tourist attraction. However, with the completion of a proposed new airport near Primm, the market would shift to serving as an airport connector.

Anaheim-Ontario Segment

The 31.7-mile Anaheim-Ontario western-most segment of the project would traverse a densely developed urban area with the Ontario station located at Ontario airport, a major facility serving Los Angeles and surrounding communities. The project would serve a large commuter market, as well as providing convenient airport access for Anaheim.

The project is estimated to cost \$2.8 billion in year 2000 constant dollars (\$86.9 million per mile). This estimate includes the construction two stations, 31.7 miles of dual steel guideway, and a maintenance facility. Over 80 percent of guideway is designed to be supported on elevated structure. The estimate includes contingencies of between 10 and 20 percent. The project design team estimates about 20 percent of the project costs are attributable to the cost of Maglev vehicles, propulsion, control and communication systems.

The estimated annual cost of operation and maintenance for the project is estimated at \$45 million, with about 30 percent attributable to energy costs. The annual operating and maintenance estimates reflect the staffing plan, fringe benefits, material costs for maintaining the

vehicles and guideway, utility costs for vehicle propulsion and station light and air conditioning, insurance, and administrative costs.

Munich, Bavaria Maglev Project

In connection with the decision of the German government in February 2000 not to pursue the Maglev line between Berlin and Hamburg, a feasibility study was initiated to identify another location in Germany to showcase Transrapid technology. After considering several candidates a 23-mile route in Bavaria between Munich's main railway station and the new international airport was selected, with direct service between the Munich Central Rail Station and Munich Airport. Its plans call for departures every 10 minutes in peak times, and a travel time of 10 minutes, reducing the trip to the airport by 30 minutes. Bayrische Magnetbahnvorberietungsgesellschaft mbH (BMG) has been charged with the complete planning, design, and analysis of the project.

The service is proposed to operate at a maximum speed of 217.5 mph and an average speed of 136.7 mph. Because over 20 percent of the dual-track guideway runs underground through twin single-track tunnels, and nearly the entire alignment runs alongside motorways, societal impacts are minimized. Only about 35 percent of the alignment is elevated and 45 percent is constructed at grade. The project is estimated to cost €1.6 billion (about \$1.9 billion, at a rate of 0.823 euros per dollar). The unit cost of the project is estimated to be about €41.1 million/km (\$86.4 million per mile). About 28 percent of the total cost is attributable to vehicles, and propulsion, control and communications systems.

The annual cost of operation and maintenance is estimated to be €32.5 million (\$ 42.2 million), with 28 percent of the amount for energy.

A statistical summary of the physical design, operating features and estimated costs of the proposed project is included in the Appendix.

Summary of Project Differences and Similarities

The above descriptions point out the great diversity of the projects currently being planned in the U.S. and Germany. They vary greatly in the type of trips to be served; the length of project; the terrain features, land use and extent of development adjacent to the right-of-way; the grades and curvature of the proposed alignments; the type of guideway structure and the extent to which the guideway will be elevated, at grade, or in tunnel; the extent to which the guideway is single or double track; the number, locations, and types of stations planned; the planned average and maximum operating speeds; the planned headways during peak and off-peak periods; the number of vehicles needed to provide the planned service and the quantity of service provided, as measured in vehicle-miles per year. Each of these factors can have a significant impact on the capital costs of the project and the annual costs of operation and maintenance. Table A - 2 compares selected statistics of the various projects to illustrate their range of diversity.

Type of Trips Served

All of the projects described above would provide service for travelers to an existing or planned airport. Most of the projects also provide service for a large market of non-airport related commuter and business trips. A major portion of the expected market for use of the Las Vegas-Primm Project would be attributable to a tourist-recreational market.

Length of Projects

The projects analyzed range from short airport to downtown connectors of 17.4 and 23.6 miles to a longer multi-purpose project of 54.7 miles.

Terrain Features, Land Use and Extent of Development

With the exception of the Las Vegas-Primm Project, all of the alignments traverse relatively well-developed and growing urban and suburban corridors. To minimize the disruption of adjacent communities, all of the projects are located within, or adjacent to, existing transportation corridors to the extent that they are available and suitable. With the exception of the Pittsburgh Project, the terrain traversed is relatively flat and encounters no major river crossings.

In contrast to the others, the Las Vegas-Primm Project would be built in a sparsely developed, flat, desert area adjacent to an existing Interstate highway (I-15). The Pittsburgh Project traverses a hilly topography dissected by numerous rivers and streams and includes a major river crossing.

Grades and Curvature of Alignments

Because of the hilly nature of the terrain, the Pittsburgh Project includes steep grades of up to 8.1 percent. However, the grades used for the remainder of the projects are relatively flat, with maximum grades of about 3 percent.

To maximize speed and reduce operating costs, the ideal horizontal alignment for a Maglev system is a straight line between two points. However, in practice the alignments must curve to avoid various natural obstacles and man-made development. Route Circuity, the ratio between the actual distance along the alignment, and the ideal straight-line distance between termini, provides an indication of the curvature incorporated into the alignment. The Baltimore-Washington Project with a ratio of 113%, is relatively direct, requiring few curves, while the Pittsburgh project with a ratio of 130% is circuitous and incorporates more curvature in the alignment. The remainder of the projects fall between these two limits.

Guideway Structure

The estimates prepared for the U.S. projects all assume that the guideway will be constructed of precision manufactured steel beams. Dual guideway is designed for the Baltimore-Washington, Pittsburgh IOS, Anaheim-Ontario, and Munich projects. However, the last two stations of the Full Pittsburgh Project are connected by single guideway (20.5 miles, or 38% of the route). The Las Vegas to Primm Project is designed as a single-track guideway

project, with dual track sections providing access to the stations (23.3 miles, or 67% of the route is single guideway).

The Pittsburgh Project is designed to be on elevated structure for the entire route. For safety and aesthetic reasons, the guideway is designed to be supported on elevated structure, even through cut sections (the minimum column design height through cut sections is 3 meters). In contrast, the Anaheim-Ontario Project is designed for 82% of the route to be elevated, and for the remainder of the projects, the percentage varies between 33% and 35%.

To minimize disruption of adjacent communities, and provide access to stations, both the Baltimore-Washington and Munich Projects are designed with significant portions of the guideway to be located in tunnel. For the Baltimore-Washington Project, 5.6 miles of the guideway (16% of the route) are located in tunnel. The Munich Project is designed with 5.0 miles of tunnel (22% of the route)

Number, Locations, and Types of Stations

With the exception of the Baltimore-Washington and the Pittsburgh Projects, all of the projects analyzed are designed for only two stations. The full 269.1-mile Las Vegas-Anaheim Project is planned for six stations, however, the two segments of that project included in this analysis are two-station projects. The Full Pittsburgh Project is designed with 5 stations (airport, center city, and 3 suburban locations). The Pittsburgh IOS and the Baltimore-Washington Projects are each designed with 3 stations (both have airport stations and center city stations; in Pittsburgh the third station is suburban and in Baltimore it is in a second center city). The Anaheim-Ontario Project and the Munich project have located one station in or near a center city and the other at an airport. The Las Vegas-Primm Project has located stations close to an airport and in a growing resort area.

The design of the stations for each project varies greatly from the three elaborate underground stations and additional parking designed for the Baltimore-Washington Project, to the much simpler stations planned in connection with the Las Vegas-Primm Project. Because of their location, the estimated cost of the Pittsburgh Project's suburban stations includes the costs of substantial improvements to the highway network needed to accommodate the increased traffic generated by the stations. The cost estimate for the Munich Project does not separately present the costs of station modification at the Central Rail Station or the airport.

Operating Speeds

Depending upon the horizontal and vertical alignments and spacing of stations, the maximum speed of the various projects varies from 198.8 mph for the Anaheim-Ontario Project to 310.7 mph for the Las Vegas-Primm Project. However, because of the radius of curves in the alignment, acceleration rates limited by passenger comfort, and dwell time at intermediate stations stops, average speeds end-to-end are significantly less than the top speeds. They vary from 88.2 mph for the Pittsburgh IOS Project (about 35% of the maximum speed) to 174 mph for the Las Vegas-Primm Project (56% of the maximum speed).

Headways

With the exception of the Full Pittsburgh Project and the Las Vegas-Primm Project, all of the projects provide 10-minute headways during peak hours. The Full Pittsburgh Project and the Las Vegas-Primm Project provide 8.5 minute and 20-minute peak period frequencies, respectively. During the off-peak period the planned frequency of service varies from 10 minutes to 30 minutes.

Number of Vehicles

The number of trains to be operated (including spares) varies from 3 eight-car trains for the Las Vegas-Primm Project to 8 three-car trains planned for the Full Pittsburgh Project. However, the number of cars required varies from 12 for the Pittsburgh IOS to 24 for the Full Pittsburgh, the Anaheim-Ontario and the Las Vegas-Primm projects.

Annual Service Provided

The quantity of service provided each year, as measured by million vehicle-miles per year, varies significantly among the projects. The Full Pittsburgh Project and the two Las Vegas projects are planning to provide more than 9.9 million vehicle-miles of annual service, while the Baltimore-Washington and Munich projects are planning less than 60% of these levels. The Pittsburgh IOS will provide less than one-third the service provided by the higher intensity projects.

Comparison of Costs

Following is a comparison of the capital, and operating and maintenance costs of the various projects.

Capital Costs

The detailed capital cost estimates prepared by each project and submitted to FRA were summarized into the following broad categories of cost:

- Rights-of-way
- Guideway
- Propulsion, Control and Communication Systems
- Maintenance Facilities
- Power Distribution
- Stations and Parking
- Vehicle Acquisition
- Financial and Other
- Total Capital Cost

Table A - 3 presents a summary of the capital costs of each project by category and the percentage of total cost attributable to each category. It also compares the percentages of each project cost attributable to basic infrastructure elements (i.e., Guideway, Propulsion, Control and Communication Systems, and Power Distribution), and the percentages attributable to equipment that would probably be supplied by Transrapid (i.e., Maglev Vehicles, Propulsion, Control and Communication Systems).

Despite the diverse characteristics and designs of the projects being analyzed, and the various methods used by different engineers to estimate costs, the percentage of total project costs allocated to guideway cost is extremely consistent across projects. With the exception of the Anaheim-Ontario Project, between 45 and 48 percent of Total Capital Cost is attributable to the guideway. However there does not appear to be much consistency regarding the percentage of cost allocated to other elements of each project. The greatest variation appears to be in the percentage of cost allocated to propulsion, control and communications systems, which varies from 6 to 19 percent of project cost. Largely because of the great variability in the estimated cost of propulsion, control and communication systems, the basic project infrastructure consisting of guideway, propulsion, control and communication systems and power distribution, varies between 55 and 74 percent of the total cost and the percentage of each project cost attributable to elements that would probably be acquired from Transrapid varies from 12 to 36 percent.

Comparison of Unit Capital Costs

Several categories of capital cost (i.e., Guideway; Propulsion, Control and Communication Systems; Power Distribution; and Total Capital Cost) are clearly related to the length of the route. For comparison purposes, unit costs for these elements of the various projects were computed on the basis of millions of dollars per route-mile. The costs of vehicle acquisition and the maintenance facility constructed to maintain the vehicles will depend upon the number of vehicles acquired, and unit costs for these elements are expressed as million dollars per vehicle (\$M/vehicle). Each project has adopted a unique philosophy regarding the function, location, and design of stations. They range from the three elaborate underground stations and additional parking designed for the Baltimore-Washington Project that account for 11 percent of project cost, to the much simpler stations planned in connection with the Las Vegas-Primm Project that accounts for less than 2 percent of project cost. Although related, to some degree to the length of trains, most of the station cost is attributable to the architectural treatment, the designed function of the station as an intermodal transfer facility, and the extent to which included in the cost are the parking, and substantial improvements to the adjacent highway network that are needed to accommodate the increased traffic generated by the stations. To give some indication of the range of station costs, the unit cost of stations has been presented as million dollars per station (\$M/station).

Table A - 3 presents the estimated unit capital costs of each project.

Total Capital Unit Cost

Considering the diversity of the projects being compared, the total capital cost per route-mile of project are remarkably similar, ranging from \$86.9 to \$96.6 million per route-mile for the

three projects planned for full dual guideway to \$40.2 million per route-mile for the Las Vegas-Primm project that is planned for single guideway operation. The Las Vegas-Primm project is also to be constructed 66 percent at grade, and this contributes to its lower unit cost. When the variation in the percentage of the route that is dual or single tracked is accounted for by using track-miles to estimate unit costs, the variation between Las Vegas-Primm and the others narrows. Total unit costs vary between \$40.2 and \$48.3 million per track-mile for the other projects, and the Las Vegas-Primm project costs are closer at about \$30.6 million per track-mile.

Guideway Unit Cost

On average, 50 percent of total project cost of a project is attributable to construction of the elevated, at grade or (in two cases) tunneled guideway. Again, with the exception of the Las Vegas-Primm project, unit costs vary between \$33.8 and \$49.9 million per route-mile. Taking into account the mix of dual and single guideway, the costs vary between \$20.9 and \$24.1 million per track-mile.

Propulsion, Control and Communications Unit Cost

On average propulsion, control and communication systems account for only about 13 percent of project costs. However, the computed unit costs appear to vary widely from about \$4.8 to almost \$16.1 million per route-mile. The extent of dual and single guideway does not explain this great variation. The variation may seem surprising, considering that presumably these costs were developed from price quotes or other estimates provided to the various projects by Transrapid, though because various contingency percentages were added to the estimated costs and some costs vary with project length while others are of a relatively fixed nature, some variation among projects is to be expected in both absolute and unit costs.

Basic Infrastructure (Guideway, Propulsion, Control and Communications, and Power Distribution)

The basic infrastructure needed to operate a Maglev system is comprised of the concrete and steel guideway needed to support the vehicles and provide a path to travel, the stator packs, motor windings and electronic equipment installed primarily in the guideway to provide a means of propulsion, control and communications with the vehicles, and the power distribution system needed to power the vehicles. When adjusted to take account of the mix of dual and single guideway, the unit costs are remarkably similar, ranging from \$20.9 to \$29.8 million per track-mile.

Vehicle, Propulsion, Control and Communications Systems

It is presumed that Maglev vehicle, propulsion, control and communications equipment and systems for the projects would be acquired from Transrapid. Local contractors will provide the remainder of the structures and equipment. The vehicles, propulsion, control and communications equipment and systems constitute an average of about 20 percent of the project with a range from about 12% to 36%. The wide range occurs in part because some of the costs do not vary with project length, though other differences in the cost estimates are also likely part of the explanation.

Stations and Parking

As pointed out in 3.6 above, the cost of stations vary greatly from project to project depending upon the location, the architectural treatment, and the need to provide parking and or modifications to the adjacent highway system to accommodate highway traffic generated by the Maglev service. Costs vary from \$10 million to \$132 million per station.

Operating and Maintenance Costs

Each project has developed detailed estimates of the annual costs of operation and maintenance (O&M) that reflect staffing plans, fringe benefits, material costs for maintaining the vehicles and guideway; utility costs for vehicle propulsion, and station light and air-conditioning; insurance and administrative costs. Table A - 4 presents a comparison of the total estimated O&M costs prepared for each of the projects, and the portion allocated to energy consumption

Table A - 4 also presents a comparison of the unit costs of total O&M costs on the basis of annual vehicle-mile of service, and the energy component of O&M on the basis of dollars per megawatt-hour and vehicle-mile of service.

Energy Consumption Costs

On the average energy costs account for about 28 percent of the total annual O&M cost, ranging from 21 to 31 percent. However the unit cost for energy varies widely among the projects, from \$56 per MWh to \$100 per MWh. Reflecting the variation in energy unit cost, the reported cost also varies widely on the basis of vehicle-miles, i.e., from \$1.00 to \$2.10 per vehicle-mile.

Total Annual O&M Costs

Total O&M costs should be closely related to the amount of service provided, expressed as vehicle-miles. However, reported costs vary from about \$3.20 to \$9.70 per vehicle-mile. Some, but not all of this variation, can be explained by the large variation in the cost of energy.

Conclusion

Based upon the above analysis of six diverse projects currently being planned in the U.S. and Germany, preliminary estimates of the capital cost of proposed short Maglev projects of less than 62.1 miles can be prepared with some confidence. The cost of guideway infrastructure (guideway, propulsion, control, and communication and power distribution) ranges between \$20.9 and \$30.6 million per track-mile, depending on the extent to which the project is elevated, at grade, or in tunnel. The cost of vehicles appears to range between \$9 and \$13 million each. Stations can range from \$10 million to \$132 million each, depending upon location and complexity of design. On average these items will account for 79 percent of total capital cost of a project. Statistics derived for O&M costs, because they vary widely, appear to be less useful in providing an indication of their expected level for other projects.

Tables for Annex A

(NOTE: In these tables, all costs are presented as received from the project authorities, i.e., without inflation from the “monetary init base year” indicated in the table.)

Table A - 1: Summary Statistics for Planned Maglev Projects in U.S.& Germany

Project	Baltimore-Washington	Pittsburgh	Pittsburgh IOS	Anaheim-ONT	Las Vegas-Primm	Munich
Date most recent data supplied by project	2/4/2004	8/31/2004	8/31/2004	3/22/2004	2/5/2004	2/4/2004

PROPOSED OPERATING CHARACTERISTICS

Train Sets (initial operation)

Number (including spares)	7	8	4	6	3	5
Sections per Train Set	3	3	3	4	8	3
Seated Capacity per Train	190	148	148	338	720	156
Passenger Capacity per Train	396	344	344	568	940	307
Peak Hour Seated Capacity (one direction)	1,140	1,036	888	2,028	2,160	936
Peak Hour Total Capacity (one direction)	2,376	2,408	2,064	3,408	2,820	1,842

Operational Speed

Average in mph	126	92	88	130	174	137
Maximum in mph	258	250	250	199	311	217
Travel Time End-to-end in minutes	18.5	35	11	14.5	11	10

Frequency of Service (headways)

Peak Period Headway in minutes	10	8.5	10	10	20	10
Off-peak Headways in minutes	20-30	10	10	10	30	20
Peak Period Headway in minutes	10	8.5	10	10	20	10
Million Train-mi per year	1.82	3.47	1.09	2.61	1.24	1.93

Hours of Operation

Daily Operation in Total Hours	20	18	18	19	19	20
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Number of Stations

	3	5	3	2	2	2
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Passengers, Fares & Revenues

Year	2010	2012	2010	2010	2010	2015
Annual Passengers, millions	9.17	14.2	3.3	10.3	13.5	7.9
Pass.-mi , millions	244.4	323.1	58.0	324.5	469.8	180.8

Annual Revenues (\$M)

Farebox	\$184.00	\$96.60	\$18.80	\$93.10	\$78.60	\$71.80
Other	\$12.40	\$43.40		\$6.30	\$4.40	
Total Annual	\$196.40	\$140.00	\$18.80	\$99.40	\$83.00	\$71.80

Average Fares in (\$)

Average Fare/passenger	\$20.07	\$6.80	\$5.70	\$9.00	\$5.82	\$9.09
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Project	Baltimore-Washington	Pittsburgh	Pittsburgh IOS	Anaheim-ONT	Las Vegas-Primm	Munich
Average Fare/passenger-mi	\$0.76	\$0.31	\$0.32	\$0.45	\$0.16	\$0.40

Capital & Operating Costs In Constant Monetary Units

Monetary unit base year	2002	2003	2003	2000	2000	2002
Contingency Factor Applied	10-30%	10-30%	10-30%	10% - 20%	10% - 20%	

Capital Costs, (\$M)

Right-of way	\$92.00	\$151.00	\$66.20	\$67.00	\$10.10	\$37.10
Guideway	\$1,694.00	\$1,802.30	\$725.40	\$1,717.70	\$599.50	\$951.70
Propulsion, Control & Communication Systems	\$589.00	\$246.80	\$88.80	\$310.20	\$244.90	\$358.40
Maintenance Facilities	\$68.00	\$44.40	\$44.40	\$59.90	\$33.60	
Power Distribution	\$47.00	\$64.00	\$32.00	\$26.00	\$36.50	\$34.60
Stations & Parking	\$396.00	\$386.10	\$141.40	\$79.40	\$20.80	
Vehicle Acquisition	\$245.00	\$208.80	\$104.40	\$234.40	\$213.50	\$201.50
Financial & Other	\$610.00	\$821.90	\$347.40	\$276.00	\$127.70	\$394.30
Total Capital Cost	\$3,741.00	\$3,725.30	\$1,550.00	\$2,770.60	\$1,286.70	\$1,977.50

Unit Capital Costs, Initial Yr.

Guideway Cost, (\$M/mi)	\$43.29	\$33.15	\$41.20	\$54.23	\$17.22	\$41.68
Propulsion, Control and Communications, (\$M/mi)	\$15.13	\$4.51	\$4.99	\$9.82	\$7.08	\$15.61
Guideway Cost, passenger-mi / \$	2.67	2.17	4.85	2.05	0.50	2.05
Maintenance Facilities Cost, \$M/vehicle	\$3.20	\$1.90	\$3.70	\$2.50	\$1.40	
Power Distrib. Cost, (\$M/mi)	\$1.13	\$1.13	\$1.77	\$0.80	\$1.13	\$1.45
Average Station Cost, (\$M/station)	\$132.00	\$77.20	\$47.10	\$39.70	\$10.40	
Vehicle Cost, (\$M/vehicle)	\$11.70	\$8.70	\$8.70	\$9.80	\$8.90	\$13.40
Total Capital Cost, (\$M/mi)	\$95.76	\$68.56	\$88.19	\$87.39	\$37.01	\$86.42

Annual Operation & Maintenance Costs, (M\$/yr.)

Year	2020	2012	2010	2020	2020	2015
Energy Consumption Cost	\$11.30	\$10.20	\$5.00	\$13.30	\$11.10	\$11.25
Total Operating & Maintenance Costs	\$53.00	\$37.30	\$16.70	\$44.90	\$35.70	\$40.17

Annual O & M Unit Costs, (\$)/Unit

Energy cost, (\$/MWhr)	\$98.80	\$56.00	\$56.30	\$89.90	\$72.70	
Energy Cost/Train-mi	\$6.21	\$2.95	\$4.60	\$5.10	\$8.93	\$5.84
Total O & M Costs/Train-mi	\$29.13	\$10.78	\$15.29	\$17.22	\$28.81	\$20.92
Total O & M Costs/passenger-mi	\$0.21	\$0.11	\$0.29	\$0.14	\$0.08	\$0.23

* Exchange Rate, 1 Sept. 04, 1 U.S.\$ = 0.82 Euros

Table A - 2: Indicators of Project Diversity

Project	Baltimore to Washington	Full Pittsburgh	Pittsburgh IOS	Anaheim to Ontario	Las Vegas to Primm	Munich
Guideway Length						
Route Length (mi)	39.1	54.4	17.6	31.7	34.8	22.9
Track Length (mi)	78.2	88.0	33.7	63.4	46.3	45.7
% Track Length, Dual	100.0%	61.9%	91.5%	100.0%	33.0%	100.0%
% Track Length Single	0.0%	38.1%	8.5%	0.0%	67.0%	0.0%
% Route Elevated	32.6%	100.0%	100.0%	81.6%	33.9%	34.5%
% Route At-Grade	51.7%	0.0%	0.0%	19.4%	66.1%	46.2%
% Route Tunnel	15.7%	0.0%	0.0%	0.0%	0.0%	21.7%
Annual Ridership						
Passengers	9.2	14.2	3.3	10.3	13.5	7.9
Passenger-mi	244.4	323.1	58.0	324.5	469.8	180.8
Number Vehicles	21	24	12	24	24	15
Stations						
Number	3	5	3	2	2	2
Average Spacing (mi)	19.5	13.6	8.8	31.7	34.8	22.9
Speed (mi/hr)						
Maximum	257.9	249.8	249.8	198.8	310.7	217.5
Average	126.3	92.0	88.2	130.5	174.0	136.7
Maximum Grade (%)	3.2	8.1	6.5	2.0	3.1	NA
Service Provided						
Vehicle Travel (MVehicle-mi)	5.5	10.4	3.3	10.4	9.9	5.8
Energy Use (KWh/Vehicle-mi)	21.0	17.5	27.2	14.2	15.3	NA

Table A - 3: Comparison of Estimated Unit Capital Costs for Currently Planned Maglev Projects (Constant \$)

Project	Baltimore to Washington	Full Pittsburgh	Pittsburgh IOS	Anaheim to Ontario	Las Vegas to Primm	Munich
Year of Constant \$	2002	2003	2003	2000	2000	2002
Contingency Factor Applied	10-30%	10-30%	10-30%	10% - 20%	10% - 20%	
Unit Capital Costs, (\$M)						
Guideway Cost, (\$M/route-mi)	\$43.3	\$33.1	\$41.2	\$54.2	\$17.2	\$41.6
(\$M/track-mi)	\$21.7	\$20.5	\$21.6	\$27.1	\$13.0	\$20.8
Propul., Control and Comm. (\$M/route-mi)	\$15.1	\$4.5	\$5.0	\$9.8	\$7.0	\$15.7
(\$M/track-mi)	\$7.5	\$2.8	\$2.6	\$4.9	\$5.3	\$7.8
Guideway Cost, (\$/passenger-mi)	\$6.9	\$5.6	\$12.6	\$5.3	\$1.3	\$5.3
Maintenance Facilities Cost,(\$M/vehicle)	\$3.2	\$1.9	\$3.7	\$2.5	\$1.4	\$-
Power Distrib. Cost, (\$M/route-mi)	\$1.2	\$1.2	\$1.8	\$0.8	\$1.0	\$1.5
Average Station Cost, (\$M/station)	\$132.0	\$77.2	\$47.1	\$39.7	\$10.4	\$-
Vehicle Cost, (\$M/vehicle)	\$11.7	\$8.7	\$8.7	\$9.8	\$8.9	\$13.4
Total Capital Cost, (\$M/route-mi)	\$95.7	\$68.5	\$88.2	\$87.4	\$37.0	\$86.5
(\$M/track-mi)	\$47.9	\$42.3	\$46.0	\$43.7	\$27.8	\$43.2
Guideway+PC&C+Power (\$M/route-mi)	\$59.6	\$38.9	\$48.1	\$64.8	\$25.3	\$58.8
(\$M/track-mi)	\$29.8	\$24.0	\$25.1	\$32.4	\$19.0	\$29.4
PC&C+ Vehicles, (\$M/route-mi)	\$21.3	\$8.4	\$10.9	\$17.2	\$13.2	\$24.5
(\$M/track-mi)	\$10.7	\$5.2	\$5.8	\$8.6	\$9.9	\$12.2

Table A - 4: Comparison of Estimated Annual O&M Costs, & Unit Costs for Currently Planned Maglev Projects

Project	Baltimore to Washington		Full Pittsburgh		Pittsburgh Initial Op. Seg		Anaheim to Ontario		Las Vegas to Primm		Munich	
	Year of Operation		Year of Operation		Year of Operation		Year of Operation		Year of Operation		Year of Operation	
Year of Operation	2020		2012		2010		2020		2020		2015	
Annual O&M Costs		% of Total		% of Total		% of Total		% of Total		% of Total		% of Total
Energy Consumption Cost (M\$/yr.)	\$11.3	21.3%	\$10.2	27.3%	\$5.0	29.9%	\$13.3	29.6%	\$11.10	31.1%	\$11.1	28.0%
Total Annual O&M Cost (M\$/yr.)	\$53.0	100.0%	\$37.3	100.0%	\$16.7	100.0%	\$44.9	100.0%	\$35.70	100.0%	\$39.5	100.0%

Unit Costs of Annual O&M,

Energy Costs (\$/MWh)	\$98.8		\$56.0		\$56.3		\$89.9		\$72.5		NA	
(\$/Train-mi)	\$6.2		\$2.9		\$4.6		\$5.1		\$8.9		\$5.7	
(\$/Vehicle-mi)	\$2.1		\$1.0		\$1.5		\$1.3		\$1.1		\$1.9	
Total O&M Costs (\$/Train-mi)	\$29.1		\$10.8		\$15.4		\$17.2		\$28.7		\$20.5	
(\$/Vehicle-mi)	\$9.7		\$3.6		\$5.1		\$4.3		\$3.6		\$6.8	

Annex B

California High-Speed Rail Authority's Reasons for Proposing Steel-Wheel Rather Than Maglev Technology

The following section is reproduced verbatim from: California High-Speed Rail Authority and Federal Railroad Administration, *Draft Program Environmental Impact Report/Environmental Impact Statement (EIR/EIS) for the Proposed California High-Speed Train System*, 2004, pp. 2-28 and 2-29. "HST" in the following excerpt means "high-speed train."

B. MAGNETIC LEVITATION TECHNOLOGY AND STEEL-WHEEL-ON-STEEL-RAIL ELECTRIFIED, FULLY DEDICATED SERVICE

While a completely dedicated train technology using a separate track/guideway would be required on the majority of the proposed system, requiring such separation everywhere in the system would prohibit direct HST service to certain heavily constrained terminus sections (i.e., San Francisco Peninsula from San Jose to San Francisco, and the existing [LOSSAN] rail corridor between Los Angeles Union Station [LAUS] and Orange County). Because of extensive urban development and severely constrained right-of-way, HST service in these terminus sections would need to share physical infrastructure (tracks) with existing passenger rail services in existing or slightly modified corridors. Sharing track with existing passenger rail services on these heavily constrained corridors would allow for direct HST service without passenger transfer. However, the HST system would need to be compatible with the other trains sharing the tracks.⁹³ Maglev technology requires separate and distinct guideway configurations that would preclude the sharing of rail infrastructure.

For example, on the San Francisco Peninsula, sharing track with Caltrain express services would be the only practical alternative for providing a direct link to San Francisco. Because of the lack of sufficient right-of-way along the Peninsula, dedicated (exclusive guideway) alignments would require tall elevated structures along Caltrain or U.S. Highway 101 (US-101) rights-of-way and extensive purchases of additional right-of-way. The aerial portions of such an alignment would introduce a major new infrastructure element along the Caltrain corridor that would have visual impacts (intrusion/shade/ shadow) on the adjacent land uses, including residential areas along this alignment. For a Caltrain exclusive guideway alignment option, the introduction of an elevated structure (for the high-speed tracks and stations) would also have adverse impacts on the suburban town centers along the Caltrain corridor (San Mateo, San Carlos, Redwood City, Menlo Park, Palo Alto, and Mountain View). Although the structure would generally be in a commercial area in these centers, it would represent a physical barrier for land use and urban design. The installation of an exclusive guideway alignment would

⁹³ Current FRA safety requirements for rolling stock preclude the use of non-compliant rolling stock (such as off-the-shelf European equipment, which is constructed to different structural design standards) unless otherwise waived.

present major construction issues, involving the construction of an aerial guideway adjacent to and above active existing transportation facilities, while maintaining rail traffic. In San Francisco, major new tunnel construction, in addition to that already proposed for the extension of Caltrain services into the Transbay Terminal, would be required, and would similarly present major construction and cost issues.

In contrast, by taking advantage of the existing rail infrastructure, a shared-use configuration would be mostly at grade. Shared-use options would be less costly and would result in fewer environmental impacts. In addition, for these alignment options improved regional commuter service—electrified, fully grade-separated, with additional tracks and fencing—would help mitigate the impacts of additional rail service along the Peninsula. Shared-use improvements in this corridor would potentially result in safety and service improvements for Peninsula commuters and potentially improve automobile traffic flow at rail crossings and reduce noise impacts, since a grade-separated system could eliminate trains blowing warning horns throughout the alignment. Shared-use options would provide the opportunity for a partnership with the San Mateo County Transit District (SamTrans), the owner of the right-of-way, and operator of the Caltrain service, and would provide the opportunity to incrementally improve a portion of the network. While SamTrans has indicated support for the general concept of a proposed HST system sharing tracks with Caltrain service, it has also commented that a dedicated (exclusive guideway) high-speed rail service along its existing right-of-way would be infeasible, because there would not be enough space for both types of services to operate separately.

Improvements to these heavily constrained urban corridors would be most effectively implemented in an incremental manner to maintain existing services, allow for corresponding improvements to the existing services, limit construction impacts, and reduce immediate funding needs. By contrast, infrastructure for completely dedicated (separate track) steel-wheel-on-steel-rail or maglev technology would not lend itself to incremental improvement.

In summary, these two systems—maglev and steel-wheel-on-steel-rail electrified fully dedicated service—would not allow for direct HST service to major intercity travel markets and therefore would not meet the purpose of and need and objectives for the proposed project.

Annex C

CFS Approach to Traffic Congestion Reduction

Since the Congress expressed particular interest in the question of [highway] traffic congestion reduction that might follow from the installation of HSGT systems, the following excerpt from the CFS report is reproduced verbatim below.

Highway Congestion Delay Savings⁹⁴

Conceptually similar to airport delay savings, the value of reduced congestion and delay on highways from diversion of auto travelers to HSGT would constitute a potential benefit of HSGT. The benefit was estimated in terms of the value to remaining highway users of travel time saved when traffic volumes on major highways in HSGT city-pair markets decrease (or grow at a reduced rate) and travel speeds improve. As in the case of airports, the importance of HSGT's effects on highway delay would vary with the relative prominence of intercity travel in the road's traffic mix; the share of HSGT markets in that intercity travel; and the highway's ambient traffic, capacity, and delay conditions.

Traffic removed from highways was based upon ridership model forecasts of diverted auto passengers, converted to vehicles using a vehicle occupancy of 1.2. Highway conditions and the effects of HSGT trip diversion were approximated by extrapolating from the traffic impacts at selected corridor locations including:

- Each major metropolitan area HSGT terminus,
- Each intermediate major metropolitan area, and
- One intermediate rural/low density area between major metropolitan areas.

The decrease in traffic was assumed to have a measurable effect on auto travel speeds only when facilities are significantly congested (i.e., operating at less than free flow speeds). For rural areas, a level of service of "C" or worse, and in urban areas, a roadway congestion index of 1.0 or higher, were established as thresholds for significant congestion.⁹⁵ Using relationships of the volume-to-capacity for a roadway and associated travel speeds, the decrease in traffic due to HSGT diversions was converted into a change in highway speeds. The change in speed was converted to travel time savings for remaining auto users, whose in-vehicle travel time was valued at \$10.88 per hour.^{96,97}

⁹⁴From FRA, *High-Speed Ground Transportation for America*, pages 6-7 and 6-8.

⁹⁵ *Highway Capacity Manual*, Special Report 209, Transportation Research Board, 1985 (revised), and *Trends in Urban Roadway Congestion - 1982 to 1991*, Volume 1: Annual Report, Texas Transportation Institute, 1994.

⁹⁶ This value of time is derived from studies undertaken by the Texas Transportation Institute for the National Cooperative Highway Research Program, Transportation Research Board, and National Research Council. *Benefit-Cost Evaluation of Highway Improvements, MicroBENCOST Program*, Version 1.0, Texas Transportation Institute, 1993.

⁹⁷ Just as this methodology projects congestion reduction benefits for HSGT in the realm of intercity transportation, so has the Federal Transit Administration (FTA) found that metropolitan public transit reduces annual losses from traffic congestion by about \$15 billion annually. (FTA, *National Transit Report—1996*, p. 4.) Recent research for FTA by the firm of Hickling-Lewis-Brod indicates that transit markedly improves the point-to-point speed of travel for both transit riders and highway users in severely congested urban travel corridors.

Annex D

The Role of Frequency in the Travel Time Comparisons

In this report, the section entitled “Effect on Shorter Trips” (page 16) states that [the need to consider total rather than line-haul travel times] detracts from Maglev’s claimed advantages in shorter-distance trips. The section goes on to add:

Between Baltimore and Washington, for example, the line-haul travel time saving between IHSR (Amtrak’s Acela) at 35 minutes (with one stop) and the proposed Maglev line (also with one stop) at 18 minutes, is 49 percent. However, in an example prepared by the State of Maryland, line-haul travel time for IHSR is only 42 percent of its total time. Thus, the net saving effected by Maglev is approximately 20 percent.⁹⁸

In fairness to Maglev, it is only proper to point out that the above comparison as created by the State of Maryland omits the effects of frequency. It is the purpose of this Annex to explore those effects.

The Meaning of “Frequency”

Frequency is a complicated matter. The following discussion treats frequency almost as part of a future service contract between the proponents of a transportation project, the polities that will fund it, and the general public who will use it and supply tax-based resources for its construction. While this may be true in a practical sense, in the analytical process frequencies are determined iteratively in the demand estimation model runs. The performance capabilities of a 300-mph Maglev system, for example, may be so appealing as to generate the demand projections that impel the addition of more frequencies in order to provide adequate transport capacities, and the added frequencies in turn heighten the demand. Conversely, in the same corridor, an IHSR system with a 110 mph top speed may not garner the demand that would generate the need for multiples of today’s service quantities. Thus, in transport systems analysis, *the frequency is largely inherent in the technology* rather than an element of a preordained service contract. On the other hand, once the initial analysis is completed and a proposal is submitted to public officials and publicized, frequency becomes, not the product of complex iterations, but a descriptive feature of the project. It is in this latter, simplified, sense that the term is used below.

Waiting Times and Frequencies in the Baltimore–Washington Example

With respect to the Baltimore-Washington example employed in the main report (at page 16), the Maglev proposal envisions a peak interval between scheduled trains of ten minutes, and

⁹⁸ State of Maryland, Mass Transit Administration, Office of Planning, “Baltimore-Washington Maglev Project: Cost Comparison: Maglev with Freeway, Light and Heavy Rail,” Technical Paper, September 2003, p. 14.

an off-peak interval of 20 to 30 minutes. On the assumption that the desire for travel is continuous throughout each hour of the day, the typical passenger will have an average waiting time between Maglev trains of 5 minutes (peak) to 15 minutes (off-peak).⁹⁹ This contrasts with the waiting time between trains of 15 minutes (peak) and 30 minutes (off-peak) for Acela and time-equivalent Amtrak services as presently scheduled.¹⁰⁰ Thus, when promised Maglev and existing Amtrak frequencies are fully incorporated into the analysis, the differential between Maglev and Acela expands to 26-27 percent from the 19 percent cited above in the frequency-blind case.

There are three reasons not to include frequency in the comparison, for purposes of this report:

- Omitting frequency emphasizes the limiting physical capabilities of the technology, which are fixed for all practical purposes, rather than the operating pattern projected for the future, which will be at the whim of the operator and may vary to meet the uncertainties of actual demand.
- In general, the cost of incremental improvements to an existing or incremental system (e.g., several dedicated trainsets, some passing tracks, and station capacity betterments) to achieve frequencies approaching those advertised for Maglev, will be much cheaper than building the entire Maglev system.
- In any event, the relative frequencies envisioned for the various modes were included in the CFS and affected demand, revenues, and benefit/cost ratios.

The data for the above discussion appear in Table D-1.

⁹⁹ For purpose of this discussion, the average waiting time between trains is one-half the interval between scheduled trains (or headway). If trains are one hour apart on the hour, and demand is assumed to be continuous, then the average passenger will present him or herself for transport on the half-hour and incur a half-hour average waiting time between trains.

¹⁰⁰ This is based on northbound departures only, and considers Metroliner and fast Regional trains as equivalent to Acela for this comparison.

**Table D-1: Total Travel Time Impacts of Maglev, With and Without Frequency Effects
(Baltimore–Washington Maglev Project Proposal for Example.¹⁰¹)**

	Without frequency effects		With frequency effects			
			Peak		Off-peak	
	Acela	Maglev	Acela	Maglev	Acela	Maglev
Line-haul time	35	18	35	18	35	18
Maglev, percent saving from Acela base—line-haul trip time only		49%		49%		49%
Access/egress/station time	49	50	49	50	49	50
Waiting time between trains			15	5	30	15
Total time	84	68	99	73	114	83
Maglev, minutes saving from base		16		26		31
Maglev, percent saving from Acela base—total trip time		19%		26%		27%

¹⁰¹ Based on State of Maryland, Mass Transit Administration, Office of Planning, “Baltimore-Washington Maglev Project: Cost Comparison: Maglev with Freeway, Light and Heavy Rail,” Technical Paper, September 2003.