SPECIAL REPORT 98-12

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Technical Assessment of Maglev System Concepts

Final Report by the Government Maglev System Assessment Team

James H. Lever, Editor

October 1998

Abstract: The Government Maglev System Assessment Team operated from 1991 to 1993 as part of the National Maglev Initiative. They assessed the technical viability of four U.S. maglev system concepts, using the French TGV high-speed train and the German TR07 maglev system as assessment baselines. Maglev in general offers advantages that include high speed potential, excellent system control, high capacity, low energy consumption, low maintenance, modest land requirements, low operating costs, and ability to meet a variety of transportation missions. Further, the U.S. maglev concepts could provide superior performance to TR07 for similar cost or similar performance for less cost. They also could achieve both lower trip times and lower energy consumption along typical U.S. routes. These advantages result generally from the use of large-gap magnetic suspensions, more powerful linear synchronous motors, and tilting vehicles. Innovative concepts for motors, guideways, suspension, and superconducting magnets all contribute to a potential for superior long-term performance of U.S. maglev systems compared with TGV and TR07.

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Prepared for
NATIONAL MAGLEV INITIATIVE

PREFACE

This report was edited by Dr. James H. Lever, Mechanical Engineer, Ice Engineering Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this work was provided by the U.S. Army Corps of Engineers and the U.S. Department of Transportation Federal Railroad Administration as part of the National Maglev Initiative.

FOREWORD

This report describes the findings of the Government Maglev System Assessment (GMSA) team, which operated from 1991 to 1993 as part of the National Maglev Initiative (NMI). Our task was to assess the technical viability of five maglev system concepts for use in the U.S., using high-speed rail as a baseline. After struggling with what this meant, we adopted a series of cross-system comparisons supported by detailed analyses. The result, I believe, served the NMI's need to assess these systems, and also improved the Government's ability to understand and guide the contracted System Concept Definitions (SCD).

We have not identified specific authors for much of this report, because it reflects consensus of the team as a whole. However, sections describing the detailed subsystem and system analyses were the responsibility of individuals or small groups. Acknowledgment to the identified authors should be given when referencing these sections.

One of the most satisfying moments during the GMSA occurred at the Maglev '93 conference at Argonne National Laboratory, after we presented our preliminary results. Conference attendees were pleased, and surprised, that we had kept up with the flood of technical data generated by the NMI contractors. Moreover, several SCD contractors were grateful to see independent verification of the key features of each concept.

Most of the analyses in this report were completed by September 1993, to provide input to the Final Report on the National Maglev Initiative (USDOTFRA 1993). However, verification issues arose with the system simulations, then being conducted at the Volpe National Transportation Systems Center, just as the NMI ended. We decided to postpone publication until we could simulate the performance of all five maglev systems with confidence. Unfortunately, with team members moving on to other projects, this took much longer than we expected and eventually required a new simulation software. The bottom line is that this report reflects the state of maglev development as we understood it at the end of 1993. We have made no attempt to account for subsequent research. Nevertheless, we hope it will find a place as a thorough, independent technical assessment of different ways to configure this promising technology.

Jim Lever
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EXECUTIVE SUMMARY

The Federal Government organized the National Maglev Initiative (NMI) to determine whether it should actively encourage investment in maglev (magnetically levitated ground transportation). The NMI's principal tasks were to assess the technical and economic viability of maglev in the U.S. and to recommend the most appropriate Federal role for its development.

The NMI sought industry's perspective on the best ways to implement maglev technology. It awarded four System Concept Definition (SCD) contracts to teams led by Bechtel Corp., Foster-Miller, Inc., Grumman Aerospace Corp., and Magneplane International, Inc. These 11-month contracts totaled $8.7 million and resulted in very thorough descriptions and analyses of four different maglev concepts.

The NMI also formed an independent Government Maglev System Assessment (GMSA) team. This team consisted of scientists and engineers from the U.S. Army Corps of Engineers (USACE), the U.S. Department of Transportation (USDOT) and Argonne National Laboratory (ANL), plus contracted transportation specialists. The GMSA team assessed the technical viability of the four SCD concepts, the German TR07 maglev design, and the French TGV high-speed train. This report describes the GMSA's assessment methods, evaluation results, and supporting analyses.

Essentially, we viewed technical viability as encompassing three main issues:

- *Technical feasibility*—Will a concept work as intended?
- *Mission suitability*—How well will a concept fulfill its transportation mission?
- *Relative advantage*—Do U.S. concepts possess superior performance potential relative to foreign ones?

To address these, we developed an assessment process consisting of four main steps.

Verification of subsystem performance

Team members developed numerical models to verify the performance of key high-risk or high-cost subsystems—guideway structures, magnetic suspensions and stray fields, motor and power systems, and vehicle–guideway interaction. These models employed standard engineering approaches and yielded good agreement with published data for TGV and TR07. When applied to the SCD concepts, they produced performance data and identified areas of concern generally comparable to the contractors' results.

Verification of system performance

To compare concept performance at the system level, team members developed two additional models: 1) a system simulator to investigate the performance of each concept along the SCD Severe Segment Test (SST) route, and 2) a standard methodology to estimate guideway technology costs. The system simulator helped us resolve broad technical issues, such as the suitability of each concept along Interstate Highway System rights-of-way. It also yielded estimates of trip times and energy consumption for each concept along a common route. Standardized cost estimates allowed us to reduce cost variability ascribable to different physical assumptions (e.g., column height) and different definitions of subcomponents. It also allowed independent verification of contractors' cost estimates.

Application of SCD system criteria

The NMI targeted intercity transportation as maglev's primary mission. Its SCD request for proposals included a set of system criteria to guide concept development towards that mission. We thus adopted these criteria to assess mission suitability. For each criterion, we developed qualitative and quantitative cross checks on the performance of each concept. These cross checks included checking data sources, analyses used, and the consistency of related characteristics. In many cases, these criteria also dictated the specific data products sought in our modeling effort. We then rated each concept's performance against the criterion.

Application of other criteria

In addition to the SCD system criteria, other characteristics may affect maglev's technical viability in the U.S. We therefore developed additional assessment criteria and applied them to each concept in a similar way to how we applied the SCD system criteria. Several of these other criteria (particularly mission flexibility, aerodynamics, and energy efficiency) became focal points of analysis and debate. We again rated each concept against these other criteria and added the results to those obtained for the SCD system criteria to complete our assessment of mission suitability.

OVERVIEW OF SYSTEM CONCEPTS

Train à Grande Vitesse (TGV)

The TGV is a steel-wheel-on-steel-rail technology, made optimal for high-speed operation (83 m/s [185 mph]). It uses fixed-consist, nontilting trainsets (with articulated coaches and a power car at each end of the consist). Power cars use AC synchronous rotary traction motors for propulsion. Roof-mounted pantographs collect power from an overhead catenary; several voltage options exist. Braking is by a combination of rheostatic brakes, tread brakes on powered axles, and disc brakes mounted on trailer axles; all axles possess anti-lock braking and the powered axles have anti-slip control. Although an operator controls train speed, interlocks exist, including automatic overspeed protection and enforced braking.

The TGV track structure is that of a conventional standard-gauge railroad with a specially engineered base (compacted granular materials). The track consists of continuous-welded rail on concrete and steel ties with elastic fasteners. Its high-speed switch is a conventional-style, precision-built swing-nose turnout.

Transrapid 07 (TR07)

The Transrapid 07 (TR07) is a commercially ready electromagnetic suspension (EMS) system using separate sets of conventional iron-core magnets to generate vehicle lift and guidance. The vehicle wraps around a T-shaped guideway. Attraction between vehicle magnets and edge-mounted guideway rails provides guidance; attraction between a second set of vehicle magnets and the propulsion stator packs on the underside of the guideway generates lift. Control systems regulate levitation and guidance forces to maintain a small (8-mm) air gap. TR07 has demonstrated safe operation at 120 m/s (268 mph) at a test facility in Germany, and its design is capable of achieving cruising speeds of 134 m/s (300 mph).

TR07 uses two or more nontilting vehicles in a consist. Propulsion is by a long-stator linear synchronous motor (LSM). Guideway stator windings generate a traveling wave that interacts with the vehicle levitation magnets for synchronous propulsion. Centrally controlled wayside stations provide the required variable-frequency, variable-voltage power to the LSM. Primary braking is regenerative through the LSM, with eddy-current braking and high-friction skids for emergencies. The TR07 guideway uses steel or concrete beams constructed and erected to very tight tolerances. Its switch is a bendable steel guideway beam.

Bechtel SCD

The Bechtel concept is an innovative, flux-canceling electrodynamic suspension (EDS) system. The vehicle contains six sets of eight superconducting magnets per side. It straddles a concrete box-beam guideway. Interaction between the vehicle magnets and a laminated aluminum ladder on each guideway sidewall generates lift. Similar interaction with guideway-mounted null-flux coils provides guidance. LSM propulsion windings, also attached to the guideway sidewalls, interact with these same vehicle magnets to produce thrust. Centrally controlled wayside stations provide the required variable-frequency, variable-voltage power to the LSM.

The vehicle consists of a single car with an inner tilting shell. It uses aerodynamic control surfaces to augment magnetic guidance forces. In an emergency, it drops onto air-bearing pads. The guideway consists of a post-tensioned concrete box girder. Because of high magnetic fields, the concept calls for nonmagnetic, fiber-reinforced plastic (FRP) reinforcing rods and stirrups in the upper portion of the box beam. The concept's switch is a bendable beam constructed entirely of FRP.

Foster-Miller SCD

The Foster-Miller concept is an EDS generally similar to the Japanese MLU002. Superconducting magnets in the vehicle generate lift by interacting with null-flux levitation coils located in the sidewalls of a U-shaped guideway; similar interaction with series-coupled propulsion coils provides null-flux guidance. Its innovative propulsion scheme is called a locally commutated linear synchronous motor (LCLSM). Individual H-bridge inverters sequentially energize propulsion coils as they become lined up with the vehicle magnets. The inverters synthesize a waveform that moves down the guideway, synchronously with the vehicle.

The vehicle consists of passenger modules and attachable nose sections that create multiple-car consists. These modules have magnet bogies at each end that they share with adjacent cars; each bogie contains four magnets per side. The U-shaped guideway consists of two parallel, post-tensioned concrete beams joined transversely by precast concrete diaphragms. Because of high magnetic fields, the upper post-tensioning rods are FRP. The high-speed switch uses switched null-flux coils to guide the vehicle through a vertical turn-out; it requires no moving structural members.

Grumman SCD

The Grumman concept is an EMS with similarities to Transrapid 07. However, Grumman's vehicles wrap around a Y-shaped guideway and use just one set of vehicle magnets and guideway rails for levitation, guidance, and propulsion. The vehicle magnets are superconducting coils around horseshoe-shaped iron cores. The legs are attracted to iron rails on the underside of the guideway. Normal coils on each iron-core leg modulate levitation and guidance forces to maintain a large (40-mm) air gap. It requires no secondary suspension to maintain adequate ride quality. Propulsion is by conventional LSM embedded in the guideway rail.

Vehicles have tilt capability and may be single- or multi-car consists. Magnets are located along the full vehicle length. The innovative guideway superstructure consists of slender Y-shaped guideway sections (one for each direction) mounted by outriggers every 4.5 m to a single 27-m-span spine girder. Switching is accomplished with a TR07-style bending guideway beam, shortened by use of a sliding or rotating section.

Magneplane SCD

The Magneplane concept is a single-vehicle EDS using a trough-shaped, 0.2-m-thick aluminum guideway for sheet levitation and guidance. Centrifugal forces cause the "Magplanes" to bank in curves. Earlier laboratory work on this concept validated the levitation, guidance, and propulsion schemes.

Superconducting levitation and propulsion magnets are grouped at the front and rear of the vehicle. The centerline magnets interact with conventional LSM windings for propulsion and also generate some electromagnetic guidance force (called the keel effect). The magnets on the sides of each group react against the aluminum guideway sheets to provide levitation.

The vehicle uses aerodynamic control surfaces and LSM-phase control to provide active damping of vehicle motions. The aluminum levitation sheets in the guideway trough form the tops of two structural aluminum box beams. These box beams are supported directly on piers. The high-speed switch uses switched null-flux coils to guide the vehicle through a fork in the guideway trough; it requires no moving structural members.

SPECIFIC CONCLUSIONS

The GMSA revealed that maglev offers significant opportunities to develop a transportation system exceptionally well suited to U.S. transportation needs. Summarized here are those opportunities offered by maglev generally and U.S. maglev particularly. Also summarized are the main innovations resulting from the SCD efforts.

Opportunities for maglev generally

Maglev offers transportation characteristics that we easily recognize as desirable against the backdrop of current modes. Because maglev will be a new mode, such characteristics will complement the existing transportation infrastructure.

High speed

High-speed potential is essentially an inherent characteristic of maglev. Lift, guidance, and propulsion occur without physical contact, and speeds in excess of 220 m/s (500 mph) are well within the technology. Furthermore, magnetic drag is small at high speeds so that only aerodynamic drag consumes appreciable energy. The top speed of maglev is a trade-off decision, not a physical or engineering limit. All maglev technologies investigated here will achieve cruising speeds of 134 m/s (300 mph) and several SCD concepts can substantially exceed this in their present form. By comparison, typical HSR (high-speed rail) commercial speeds of 83 m/s (185 mph) will rise only gradually and with significant development effort and capital investment. Maglev will achieve 300-mph service more easily than HSR, and a desire for future speed increases favors maglev.

From the consumer's view, trip time is the key measure of speed. Here, 134-m/s maglev has a significant advantage over air travel for trips under about 500 km. This advantage is partly attributable to better access to maglev's smaller stations and partly attributable to taxiing and idling overhead for air travel. Maglev remains competitive with nonstop air to about 800 km and with one-stop air to about 2000 km. Compared with HSR, maglev offers higher acceleration and top speed, and better performance on curves, all of which lower trip times.

Excellent system control

Use of dedicated, powered guideways provides maglev with decisive control advantages over air and automobile. A maglev system can be fully automated, with exceptional sensing and control of vehicle locations. Such control capability, coupled with redundant braking modes, allows use of very short vehicle headways (less than 1 minute). Maglev also offers a potential for fully automated freight transport, with goods arriving within seconds of their scheduled time.

High capacity

Short headways allow a dual maglev guideway to achieve very high capacity. The five maglev concepts studied can all deliver 12,000 passengers per hour in each direction. An equivalent air capacity would be 60 Boeing 767's per hour *in each direction* departing and arriving at 1-minute intervals. This would tax even the most efficient airports. Comparable highway traffic would require about 10 full lanes (5 lanes per direction).

Low energy consumption

Maglev can offer trip times competitive with air travel for a small fraction of the energy consumed by an aircraft. The basic physics of magnetic lift and electrical propulsion underlie maglev's energy efficiency.

Based on energy consumed at the system connection (i.e., airport or electrical supply), maglev's energy intensity (energy / seat-meter) ranges from one-eighth to one-quarter that of the efficient Boeing 737-300 for 200- to 1000-km trips. Applying electrical conversions efficiencies typical of modern power plants narrows the gap, yet maglev still consumes only one-quarter to half the energy of a 737-300.

Electric power derives from many sources; aircraft rely exclusively on petroleum. Thus, in addition to being more efficient, maglev can decouple intercity transportation from exclusive dependence on petroleum.

Low wear and maintenance

By its nature, maglev requires no physical contact between vehicles and guideways. Lift and guidance forces are distributed over large areas, producing low contact stresses. Linear synchronous motors (LSMs) offer noncontact propulsion and braking, and avoid the need to transfer propulsion power to the vehicle. These features contrast strongly with HSR, where high stresses from wheel–rail contact and power transfer dictate rigorous maintenance programs. Overall, maglev offers the potential for significantly lower maintenance costs.

Safety, availability, and cost

High-speed rail in Europe and Japan, and air travel generally, have outstanding safety records. However, both technologies require sophisticated preventative maintenance (inspections and adjustments) to achieve such safety. Maglev possesses characteristics than should allow it to operate safely under more extreme conditions and with less maintenance.

Maglev's dedicated guideways, excellent control features, redundant braking, and lower susceptibility to weather should allow it to maintain operations in conditions that would slow or halt air travel. Fog, rain, heavy snow, and high winds should pose fewer safety issues with maglev than with air. Also, maglev has far fewer moving parts, better fault tolerance, and fewer catastrophic failure modes; it should thus have better equipment-related availability, and should require less maintenance than air to ensure adequate safety.

Compared with HSR, maglev concepts offer exceptional "derailment" protection by using either wrap-around vehicles or wrap-around guideways. Large-gap maglev systems will be much more tolerant of earth displacements (e.g., from earthquakes) than HSR. Maglev's noncontact propulsion and braking render it less susceptible to snow, ice, and rain, and elevated guideways are less prone to snow drifting than at-grade railroads. And, as noted, maglev requires less maintenance than HSR to achieve its normal high-speed capability. Maglev should be capable of achieving HSR's outstanding safety record. Its greater tolerance of earthquakes and adverse weather may well be decisive advantages in availability and cost in the demanding U.S. environment.

Modest land requirements

As with HSR, maglev's narrow vehicles permit very modest station sizes. This contrasts strongly with air travel, where land requirement has become a major limit to airport expansion. Between stations, dual maglev guideways require only about 15 m of right-of-way width. Furthermore, elevated guideways can be located along existing rail and highway rights-of-way to bring maglev vehicles directly into inner-city terminals. These features will help maglev offer much lower access times and better intermodal connections compared with air. They also ease concerns over land acquisition issues.

Maglev guideways offer the flexibility of being at-grade or elevated. In areas where land-use issues are important, this flexibility is a significant advantage. For example, elevated guideways may be essential in constricted urban areas, and elevated guideways would minimally disrupt agricultural and other current land uses along rural routes. By comparison, HSR loses its principal advantage, lower capital cost, if elevated viaducts are necessary.

Low operating costs

Maglev's low energy consumption, low-maintenance potential, and fully automated operation combine to offer a potential for extremely low operating costs. Operators should have little difficulty covering such low costs and a portion of capital costs.

Also, while maglev's guideways require substantial initial investment, they offer enormous capacity. Operators can set low incremental ticket prices that will nevertheless exceed incremental costs. This can lead to very large passenger volumes, helping to justify the original capital investment, and making the system attractive in the long term.

Low magnetic fields

All four U.S. maglev concepts and TR07 achieve static magnetic fields in passenger seating areas less than 1 G (about twice the Earth's field). They do this through various combinations of magnet grouping and passive–active shielding. Indeed, the U.S. concepts demonstrate the benefit of dealing with such issues early in conceptual design: all four concepts incurred very little cost or weight penalty to achieve a 1-G limit. Through good design, maglev can achieve fields much lower than those measured on some existing transit vehicles.

Lower noise

Unlike aircraft, maglev and HSR can control their noise emissions near terminals by departing slowly. This is an important advantage that helps permit use of urban terminals. Furthermore, maglev is quieter than HSR by eliminating wheel–rail contact and pantograph–catenary contact. These noise sources predominate at low speeds, and their absence gives maglev a significant performance advantage in urban areas. For example, to meet a noise restriction of 80 dBA, a maglev vehicle should be able to travel at 50 m/s (112 mph) compared with 40 m/s (89 mph) for a quiet HSR train. This speed advantage will yield reduced trip times along noise-limited routes (i.e., most urban areas).

Even at high speeds, maglev is significantly quieter than HSR. For example, at 83 m/s (185 mph), maglev is 5–7 dBA quieter than HSR. This is a significant reduction in noise emissions that will be beneficial along quiet, rural routes.

Mission flexibility

HSR is best suited to short and intermediate intercity trunk service. TGV's fixed-consist, nontilting trains, lower cruise speed, and lower overall acceleration–deceleration render it less well suited to meet other missions or transportation needs. This lack of flexibility ultimately limits the market penetration and profitability of HSR.

Besides offering superior intercity trunk service, maglev concepts (particularly U.S. concepts) show considerable potential for additional uses. This potential derives from the great performance capability of the technology, although flexibility to serve other missions should be considered at the design stage.

Mission flexibility helps to reduce the risk that intercity trunk service is not where the greatest high-speed ground transportation (HSGT) market lies. Also, by offering other services (regional airport connector, commuter trunk, point-point, long-haul trunk), maglev increases its overall ridership potential as a major transportation network. This provides some confidence that an investment in maglev will fulfill a broad spectrum of U.S. transportation needs.

Opportunities for U.S. maglev

The SCD concepts offer numerous performance improvements over TR07. Some of these are concept-specific, while others result from generic improvements that target needs of the U.S. market and environment.

Performance efficiency

Comparison of TR07 with U.S. maglev concepts revealed two important findings: U.S. maglev can offer slightly better performance than TR07 at much lower cost (especially for at-grade sections), and U.S. maglev can offer much better performance than TR07 at similar cost.

For example, the Grumman system offers 9% lower SST trip time and 9% lower energy intensity for about 12% lower elevated-guideway cost (or 37% lower at-grade guideway cost) compared with TR07. Similarly, the Bechtel concept offers a 14% SST trip-time savings for about 2% higher elevated-guideway cost (or 20% lower at-grade guideway cost).

While these are specific SCD concepts, they illustrate the potential performance and cost advantages likely to result from a U.S. maglev development effort. They also suggest some flexibility in the selection of system characteristics to optimize performance and cost for U.S. market conditions.

Suitability to existing rights-of-way

Based on the SCD concepts, a generic U.S. maglev system will be much better suited than TR07 to deployment along existing rights-of-way (ROW). A U.S. system will require about half the curve radius of TR07 at 134 m / s (300 mph); it will climb five-times steeper grades at full speed; and, from a stop, it will reach 134 m / s in about half the time. These characteristics mean that a U.S. maglev system will achieve much shorter trip times along existing, lower-speed rights-of-way. For example, 18 minutes of Bechtel's 21-minute SST trip-time advantage over TR07 occurs in the first, twisty segment that represents an Interstate Highway ROW.

In principle, Transrapid could upgrade TR07 with a tilting vehicle body and a larger LSM. However, the former would require a major redesign of the vehicle, an increase in roll stiffness of the magnetic suspension, and use of stronger curved guideway beams. Upgrading the LSM may prove more difficult because stator slot width limits the diameter (and hence the current capacity) of the stator windings. While these improvements are possible, they would not be possible without significant R&D (research and development) time, costs, and risks.

Energy efficiency

Compared with TR07, the average energy intensity of the two most efficient U.S. concepts is 18% lower at steady cruise and 12% lower for the SST. Interestingly, these same two concepts complete the SST in about 11% less time than TR07. It appears that U.S. maglev may offer superior performance for less energy, an impressive combination.

Several factors account for U.S. maglev's superior trip times and energy efficiency. The most important is the provision of vehicle tilting. Tilting allows a vehicle to maintain good ride comfort at higher speeds through turns. This reduces trip time directly and reduces the energy needed to accelerate the vehicle to cruise speed following the turn. The effect is most pronounced along twisty routes (e.g., typical Interstate ROW). U.S. maglev concepts are also lighter than TR07, which further helps to reduce both trip times and energy consumption.

Another important factor affecting trip time and energy consumption is the aerodynamic drag acting on the vehicle. TR07's aerodynamic drag coefficients are well established and are comparable to those of high-speed trains. Some SCD contractors, however, selected lower drag coefficients that anticipate drag-reduction efforts expected in a U.S. maglev development program. Nevertheless, one of the two most energy-efficient concepts (Foster-Miller's) has drag coefficients similar to TR07's. Its aerodynamic drag is a bit lower because of its lower frontal area. Foster-Miller's higher energy efficiency is also attributable in part to its more efficient motor. Improvements in aerodynamic drag and motor efficiency are reasonable to expect under a comprehensive U.S. maglev development program. Such improvements, combined with lighter, tilting vehicles, would indeed provide U.S. maglev with superior energy efficiency and lower trip times compared with TR07.

High vehicle efficiency

All SCD vehicles use modern aerospace construction techniques, and two of the four use advanced composite construction. Superconducting magnets also have greater lift:magnet-weight ratios than TR07's normal electromagnets and do not require heavy back-up batteries to ensure safe hover. Thus, despite their tilting capability, U.S. maglev vehicles are lighter than TR07. On average, the SCD vehicles are 18% lighter per passenger than TR07, and the composite vehicles average

24% less mass per passenger (values calculated using 0.80 m^2 of cabin area as a standard passenger). Composites also offer superior fatigue and corrosion resistance relative to aluminum construction.

Lower vehicle mass improves energy efficiency and lowers guideway costs by reducing vehicle loads. Although composite construction currently carries a capital-cost premium, system life-cycle costs may favor its use. Also, further developments in the aerospace industry should reduce the cost of composite vehicles. The U.S. aerospace industry leads the world in composite aircraft construction; it is thus reasonable to expect that U.S. maglev vehicles will benefit from this expertise.

Large-gap, active vehicle suspensions

Three of the four SCDs possess active vehicle suspensions. Coupled with a large gap, an active suspension can maintain a safe, smooth ride over very flexible and rough guideways. This allows use of, respectively, less structural material and less stringent construction tolerances, reducing guideway costs.

Maglev's large magnetic forces make active control of the primary suspension an attractive option; Grumman selected this approach. Bechtel and Magneplane chose to use active control of aerodynamic surfaces. All three concepts have sufficiently large gaps to realize guideway cost reductions resulting from active suspensions. While TR07 also has an active suspension, it must use a small gap and thus requires a very stiff, well aligned, and expensive guideway.

Electromagnetic switches

Foster-Miller and Magneplane proposed electromagnetic (EM) switches as their high-speed switches, and Betchel investigated an EM switch as an alternate concept. Relative to TR07's bending-beam switch, EM switches offer much shorter cycle times, no moving structural members, less maintenance, and lower susceptibility to snow, ice, and dust. Additionally, Foster-Miller's and Magneplane's vehicles both retain their tilt capability in the turnout direction. This permits higher exit speeds than is possible with TR07 for a given switch length.

Higher speed potential

GMSA motor and suspension analyses showed that TR07 is near its speed limit at 134 m / s (300 mph). To meet levitation requirements, TR07's LSM has a shorter pole pitch than the SCD concepts. It thus operates at a higher frequency (255 Hz compared with less than 100 Hz for the SCD concepts). This increases performance demands on converter-station power electronics. As noted, stator slot width also limits the LSM current and hence peak thrust. Altering these parameters would entail a major redesign of TR07's motor and levitation systems.

Despite very tight guideway tolerances, TR07's suspension appears to be near its ride-comfort and safety limits at 134 m / s. Power transfer to the vehicle, saturation of the levitation magnets, and the use of a passive secondary suspension provide a second set of limits to the speed potential of TR07.

The U.S. concepts, by comparison, are much farther from their ultimate speed limits at 134 m / s than is TR07. They use lower frequency LSMs and have greater freedom in stator conductor sizing. They also require much less onboard power. Furthermore, several concepts have adopted active suspensions to maintain adequate safety and ride comfort over rougher, more flexible guideways than TR07's; if these concepts used guideways built to TR07's tolerances, their suspensions could handle much higher speeds.

Innovations

Large-gap EMS

A major concern about TR07's suitability for the U.S. environment is its small, 8-mm suspension gap. To achieve adequate ride comfort and safety margin, TR07's guideway must be very stiff and well aligned. These requirements increase the guideway's cost and its susceptibility to foundation settlement, earthquake movement, thermal expansion, and ice accretion.

Grumman uses iron core, superconducting magnets to increase the suspension gap of its EDS concept to 40 mm. It actively controls this gap with normal electromagnets (for high-frequency disturbances) and by slowly varying currents in the superconducting magnets. The vehicle requires no secondary suspension, and it maintains adequate ride comfort and safety over irregularities many times larger than TR07's limits. This suspension also simplifies hardware requirements by using the same magnets and reaction rails to provide all lift and guidance forces. Overall, these improvements should simplify guideway design and construction, lower guideway costs, and reduce susceptibility to environmental disturbances.

Locally commutated linear synchronous motor (LCLSM)

Foster-Miller's LCLSM energizes discrete guideway coils through individual inverters to propel a maglev vehicle. A computer controls the current and synthesizes a three-phase wave form through each set of coils using pulse-width modulation of a DC supply voltage.

The LCLSM could become a very significant innovation in vehicle propulsion. Its advantages include very high overall efficiency (91% as seen at electrical supply), significant capability to operate in a degraded mode, very flexible vehicle control, and use of the same coils for power transfer.

Its principal risk is that the IGBT-based inverters are at present too expensive for the LCLSM to be economical. Foster-Miller has argued that the large number of inverters needed (about 2400 per kilometer of dual guideway) will enable mass production to reduce their cost by a factor of 10. Experience with other semiconductor products suggests that this cost reduction may be possible.

Spine-girder dual guideway

Grumman has proposed an innovative dual guideway concept called a spine girder. A central structural "spine" girder carries, on outriggers, a narrow EMS guideway along each side. Government cost estimates confirm that this is a very efficient structure in terms of performance and cost. Indeed, it is responsible for Grumman's 10% cost advantage over TR07's guideway (also an EMS concept).

Power transfer

Both Magneplane and Grumman developed concepts that use the LSM stator winding as an inductive linear generator to transfer auxiliary power from the wayside to the vehicle. Foster-Miller's concept for power transfer uses its LCLSM. These innovations offer potential for noncontact power transfer to high-speed maglev vehicles sufficient for all onboard needs.

Cable-in-conduit superconducting magnets

To date EDS maglev vehicles have used niobium-titanium (NbTi) superconductors immersed in liquid helium near its boiling point of 4.2 K. This cooling scheme places tremendous demands on its refrigerator and can also result in "flashing" or evaporation of the sloshing liquid as the vehicle moves.

Two of the SCD concepts use cable-in-conduit magnets. This approach offers a higher operating temperature by using niobium-tin (Nb_3Sn) superconductors with supercritical helium as the coolant. Each cable consists of many wires of Nb_3Sn conductor contained in a tube that is then wound to form the magnet. Supercritical helium is circulated through the tube to cool the superconductor. A coolant temperature about 8 K is adequate, resulting in much less refrigeration power. Also, the coolant is a single phase, so there is no danger of flashing. Such magnets appear well suited for use in maglev vehicles compared with existing NbTi magnets.

Fiber-reinforced plastic (FRP)

Bechtel and Foster-Miller have sufficiently high magnetic fields in portions of their concrete guideway beams that they may not be able to use conventional steel reinforcing rods. Thus, they have both proposed using FRP rods. Bechtel has also proposed a bending-beam switch constructed entirely of FRP.

Although well established as an aerospace structural material, FRPs have not significantly penetrated civil construction. However, they possess many potential advantages over steel reinforcing, including high strength vs. weight, good corrosion resistance, and high failure stress. Many researchers expect that FRPs will eventually be commonplace in civil structures. Maglev may well prove to be the first broad construction use of these materials.

Despite their higher cost, FRPs do not pose a significant overall capital cost penalty on guideways employing them. Because they are new, however, FRPs have unknown durability for long-life civil structures (typically 50 years). The effects of long-term, cyclic loading on the attachments for post-tensioning rods are particularly difficult to predict. This durability risk is critical for concepts that must employ FRP, and research is currently underway to address it.

High efficiency EDS

At cruise speed, Bechtel's ladder EDS concept achieves a magnetic lift:drag ratio greater than 100, and Foster-Miller's coil EDS approach has a magnetic lift:drag over 170. These are very efficient EDS suspensions. Their benefits include low energy consumption, high payload:weight ratio, and low liftoff and landing speeds. Indeed, Bechtel's 10-m / s liftoff speed could allow it to use vertical motor thrust to support its vehicle into and out of stations (it would use air bearings only for emergencies). Essentially, high-efficiency EDS suspensions offer similar low-speed support and low energy consumption to EMS concepts.

Cryosystems

To date, EDS maglev vehicles have used niobium-titanium (NbTi) superconductors immersed in liquid helium, with cryogenic refrigerators reliquefying the helium vapor. Such refrigerators consume significant power and are considered the least reliable component in the maglev suspension. All four SCD concepts have avoided using this approach.

The two concepts using liquid-helium baths (Foster-Miller and Grumman) recompress the helium vapor and store it, rather than reliquefying it. They replenish the required liquid helium as a daily maintenance operation. This avoids need for an energy-intensive, unreliable onboard refrigerator; stationary reliquefaction is more efficient and reliable.

The other two SCD concepts, Bechtel and Magneplane, use cable-in-conduit superconductors. These Nb_3Sn superconductors operate at 6–8 K with supercritical helium as the coolant. Bechtel proposes to use an isochoric (constant volume) system. It accepts daily charges of liquid helium into a sealed reservoir and magnet loop; as the coolant warms up, it pressurizes the loop but retains sufficient heat capacity for the day's cooling needs. Magneplane uses a cryorefrigerator to keep its supercritical helium in the working temperature range. However, the energy required to do so is much less than that needed to reliquefy the helium, and the refrigerator needed is much more reliable.

Air bearings

Bechtel and Magneplane proposed using air bearings for low-speed support rather than wheels. Such bearing have been used for very low speed (less than 5 m/s) support of freight pallets. The vehicles are supported by a thin air film trapped between the vehicle and the guideway. Relatively low flow rates are needed, so equipment and power requirements are very modest. Air bearings offer a potential for lower weight, cost, and stresses vs. conventional wheels. However, they will require some development for application at the higher speeds (10–50 m/s [22–112 mph]) needed to support these maglev vehicles.

OVERALL CONCLUSIONS

The GMSA's main goal was to assess the technical viability of maglev in the U.S. We examined in detail the NMI's four contracted SCD concepts and compared their performance potential with that of TGV and TR07.

We found that all maglev concepts studied are potentially technically feasible. As expected, verification of the feasibility and practicality of some features clearly requires further work.

All five maglev concepts studied offer much greater performance potential than TGV. Maglev offers higher speed, better acceleration and performance in curves, and potentially lower maintenance and higher availability for comparable safety.

The four U.S. concepts also offer a performance advantage over TR07, and they could do so for similar or lower cost.

Further development will likely improve the performance of both TGV and TR07. However, such development work will necessarily entail additional time and cost.