Technical Assessment of Maglev System Concepts
Final Report by the Government Maglev System Assessment Team

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CHAPTER 1. INTRODUCTION

1.1 MAGLEV DEVELOPMENT HISTORY

Magnetic levitation (or maglev) uses magnetic forces to lift, guide, and propel vehicles. Both attractive and repulsive magnetic forces may be used, and many maglev concepts have been developed using various lift, guidance, and propulsion schemes.

In the early part of the 20th century, Emile Bachelet conceived of a magnetic suspension utilizing repulsive forces generated by alternating currents. Bachelet's concept required impractical amounts of power for conventional conductors, however. It remained dormant until the 1960s, when superconducting magnets became available. At that point, practical development of repulsive-mode magnetically levitated transportation systems began.

In the early 1920s, work by Hermann Kemper in Germany pioneered attractive-mode maglev. Kemper pursued this concept through the 1930s and 40s and established the basic design for practical, attractive-mode maglev in a 1953 paper. During the 1970s, German interest in developing a maglev transportation system eventually focused on an attractive-mode magnetic suspension.

Maglev development in the U.S. began in earnest as a result of the High-Speed Ground Transportation (HSGT) Act. This act authorized Federal funding for HSGT research projects, including those involving magnetic levitation. This government stimulus enabled U.S. investigators to jump to an early lead over their foreign counterparts in maglev research; for example, Americans pioneered the concept of superconducting magnetic levitation and dominated the early experimental work in this area.

As early as 1963, James Powell (1963) and Gordon Danby of Brookhaven National Laboratory recognized that superconductivity could overcome the power limitations in Bachelet's concept. In 1966 the two researchers (Powell and Danby 1966) presented their maglev concept of using superconducting magnets in a vehicle and discrete coils on a guideway. Rapid passage of the magnets over the conducting coils generates currents in the coils; these currents in turn establish magnetic fields of the same polarity as the imposed fields. The resulting repulsive forces are sufficient to lift and guide passenger-carrying vehicles, provided powerful (i.e., superconducting) magnets are used. This technique became known as an electrodynamic suspension (EDS) system. Their subsequent design improvement, known as the "null-flux" system (Powell and Danby 1967), was eventually adopted by the Japanese for use in the only high-speed superconducting maglev system in operation today. The presence of powerful magnets aboard the vehicles also makes practical the use of an air-core linear synchronous motor (LSM) for propulsion.

Subsequently, researchers from Stanford Research Institute (SRI) (Barbee et al. 1969), Atomics International (Guderjahn et al. 1969), and

Sandia Corporation (Guderjahn et al. 1969) developed a continuous-sheet guideway (CSG) concept. This EDS concept also used superconducting magnets aboard a vehicle. Here, the moving magnetic fields of the vehicle magnets induce currents in a continuous sheet of conducting material such as aluminum. CSG tests involving "rotating drum" simulations and test guideways up to 150 m long continued through the early 1970s at SRI, at Ford Motor Company (Reitz 1970), General Motors Corporation (Dukowicz et al. 1973), and MIT (Kolm and Thornton 1972). During this period, a locally commutated linear motor was invented at GM, and the original "Magneplane" was invented at MIT. The latter CGS concept underwent model testing at $1/25^{th}$ scale, eventually operating at speeds as high as 27 m / s.

Other significant U.S. maglev work during the early 1970s included development by Rohr Corporation of its ROMAG people-mover demonstration vehicle. In this system, normally conducting electromagnets generated attractive forces between the vehicle and ferromagnetic material in the guideway. This is termed an electromagnetic suspension (EMS) system. Unlike EDS, an EMS is statically unstable; a control system must vary the currents in the electromagnets to maintain proper clearance between the vehicle and the guideway. This technology was later transferred to the Boeing Company and ultimately licensed by Carnegie-Mellon University.

Maglev research in the U.S. came to a standstill in 1975 owing to an abrupt halt in government funding of HSGT research and a slowdown in the growth of U.S. transportation demands.

Maglev transportation research outside of the U.S. has been dominated by the Japanese and Germans. The Japanese began on a relatively modest level in the early 1960s. By 1970, Japanese efforts, under the sponsorship of the Japanese National Railway (JNR), had significantly expanded. At the same time, research in West Germany began and quickly grew. The Japanese were successfully levitating a demonstration vehicle in 1972 and constructing a large-scale test track in 1974. In West Germany, proof-of-concept test vehicles were operating as early as 1970 under two government sponsored maglev research programs. When U.S. Government funding of HSGT ended in 1975, high-speed rail and maglev research in Japan and West Germany continued to expand. Considerable progress toward commercial maglev transportation was made by both countries during the late 1970s and 1980s (Wyczalek 1990).

The Japanese have pursued two distinct maglev concepts: one (MLU series) employs an EDS while the other (HSST series [high-speed surface transportation]) employs an EMS. The MLU series full-scale prototypes have achieved speeds of 139 m / s, while HSST series prototypes have traveled as fast as 83 m / s. German research, in the meantime, has culminated in the development of a single EMS concept known as the Transrapid system (TR series). The latest full-scale version of the Transrapid vehicle and guideway (TR07) has been in operation for several years at a test track in Emsland, Germany. The TR07, with a projected maximum speed of 139 m / s, is the only maglev system in the world that is immediately available for commercial service. It is currently competing against high-speed rail systems for ground transportation projects in the U.S.

In 1988, owing to a renewed desire for a national HSGT capability, the U.S. Congress investigated the possibility of reviving maglev research and development. Studies revealed that maglev was attractive as a means of relieving the congestion and delays in our ground- and air-transport systems (Johnson et al. 1989, Grumman Corp. 1989a,b). The transportation "niche" envisioned for maglev was generally 160- to 960-km (100- to 600-mile) trips, where the personal car is too slow and uncomfortable, and the commercial airplane is too inefficient. A maglev technical advisory committee, made up of representatives from a wide range of government and private transportation organizations, reviewed the situation and reported to Congress in June of 1989. It recommended that the U.S. develop and demonstrate a second-generation maglev concept utilizing superconducting technology that will be usable along the Interstate Highway network, and well suited to U.S. weather conditions (Grumman Corp. 1989a, b). Congress responded by authorizing the formation in 1990 of the National Maglev Initiative (NMI) (USACE 1990).

1.2 ROLE OF THE NATIONAL MAGLEV INITIATIVE

Maglev makes possible high-speed, high-capacity travel with potentially low operating costs and convenient access. Yet, despite these attributes, U.S. firms have been reluctant to invest in the technology. Maglev's development risks, large capital cost, and uncertain market response are likely reasons for this reluctance.

To determine whether it should actively

encourage maglev investment, the Federal Government organized the National Maglev Initiative (NMI). 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 and implementation.

The NMI executed these tasks within a three-phase strategic plan:

- Phase I—Planning and coordination.
- Phase II—Assessment of technology and economics.
- Decision.
- Phase III—Development and implementation.

Phase II culminated with a report summarizing the NMI's findings (USDOTFRA 1993) and outlining possible implementation strategies. The work described here, technical assessment of maglev system concepts, was the primary assessment of maglev technology conducted in Phase II. Economic assessments performed in Phase II are described in the NMI's final report.

The NMI obtained maglev technical data through two sets of procurements. The first was a set of contracts exploring specific technological issues, so-called *Broad Agency Announcements* (BAA). The second consisted of four relatively larger contracts seeking conceptual definitions of maglev systems suitable for the U.S., so-called *System Concept Definitions* (SCDs). The resulting SCD reports contain quite thorough descriptions and analyses of the major subsystems, their interconnections, and the resulting performance of potential maglev systems (Bechtel 1992a,b; Foster-Miller, Inc. 1992a,b; Grumman Aerospace Corp. 1992a,b; Magneplane International, Inc. 1992a,b).

1.3 ROLE OF THE GOVERNMENT MAGLEV SYSTEM ASSESSMENT

The Government Maglev System Assessment (GMSA) team consisted of scientists and engineers from the U.S. Army Corps of Engineers (USACE), the U.S. Department of Transportation (USDOT) and the Department of Energy's Argonne National Laboratory (ANL), plus contracted transportation specialists. Its overall role was to assist the NMI with its assessment of maglev technology. The GMSA's specific tasks were as follows:

- Develop a process to evaluate the technical viability of maglev system concepts.
- Apply this evaluation process to Transrapid 07 (TR07) maglev and to TGV high-speed rail to establish comparative baselines.
- Apply this process to alternative U.S. maglev concepts.
- Assess the overall technical viability of maglev generally, and TR07 and alternative U.S. concepts specifically. Where appropriate, use TGV as a baseline to describe the performance potential of maglev in the U.S.

Insofar as possible, we sought to integrate our process for assessing maglev's technical viability with that of the NMI's process for assessing economic viability. Note also that our assessment pertained to maglev system concepts, not contractor performance. This report describes the results of our assessment of maglev's technical viability for the U.S.

1.4 DEFINITIONS OF TECHNICAL VIABILITY

As noted, the NMI was tasked to assess the technical and economic viability of maglev systems for use in the U.S. In effect, this assessment must determine whether maglev can fulfill a significant transportation role in a commercially acceptable way. Also, the NMI must consider whether a U.S. maglev system would fulfill this role better than existing foreign HSGT systems. To this end, we may group issues of maglev's technical viability into three broad categories:

- *Technical feasibility*—Will a particular system concept work as intended? This involves assessing the soundness of the physical principles and engineering sciences upon which the concept is based.
- *Mission suitability*—Given its performance characteristics, how well will such a system concept fulfill its required mission? This involves examining the concept's performance characteristics and simulating its behavior along realistic routes.
- *Relative advantage*—Do U.S.-developed concepts possess superior performance potential compared with foreign HSGT alternatives? This requires comparing U.S. concepts to foreign ones, and assessing their potential for superior performance and the attendant development risks.

We structured our evaluation process to address issues in all three categories of technical viability.

1.5 MAGLEV'S TRANSPORTATION MISSION

Several studies have identified an urgent need to improve U.S. intercity transportation. High-Speed Ground Transportation (HSGT) technologies, including maglev, appear well suited to address this need. Thus, the NMI targeted this intercity role for maglev in its SCD request for proposals (SCD-RFP, USDOTFRA [1991], sections C - 2.2 and 2.3):

> In soliciting the system concepts, the National Maglev Initiative views Maglev as an intercity transportation system which will supplement and interconnect with existing modes... Maglev systems should be safe and reliable. In the 160-km to 1000-km (100- to 600-mi-) trip range, Maglev should be competitive in terms of travel times, cost, reliability and comfort.
>
> It should be clean and energy efficient. It should provide good connections with airports and major centers. Insofar as possible, it should utilize existing highway, railroad, and utility rights-of-way. Its design should anticipate upgrade. It should be economically and financially attractive. It should be robust in terms of its susceptibility to adverse weather and its requirements for maintenance. It should efficiently handle passengers and consideration should be given to its mail and freight handling capability.

We used these statements for our basic evaluation of the "mission suitability" aspects of technical viability. However, we also recognized that maglev may address other national transportation needs, and that adaptability of concepts to those missions is also an important viability issue. Thus, we developed four additional mission statements (see section 3.4.1) and examined how well each HSGT technology fitted those missions.

1.6 EVALUATION BASELINES AND MAGLEV SYSTEM CONCEPTS

HSGT is not yet widely available in the U.S. It basically provides service in a speed range intermediate to automobiles and jet aircraft (say, 50–200 m / s). Maglev is one possible HSGT technology; high-speed rail (HSR) is another.

Several recently developed HSR systems have impressive performance characteristics and could meet many of the requirements for broad market appeal in the U.S. Indeed, the French-built TGV (train à grande vitesse) offers a proven, commercially successful 83-m / s service, and this service is available for the U.S. with essentially no development risk. In addition, its performance limits appear to be governed more by cost / benefit calculation rather than by physical constraints. Further development will undoubtedly raise these limits, albeit with some attendant costs and risks.

We adopted the view that the lack of development costs and risks is critical in the debate over the merits of HSR and maglev. Thus, we chose a commercially available HSR technology, TGV-Atlantique (TGV-A), as one of our evaluation baselines. We did not try to anticipate further performance improvements. Such improvements will undoubtedly occur, but their associated costs and risks offset TGV-A's critical advantage. On this basis, we feel that TGV-A serves as a fair baseline for comparison with maglev.

For similar reasons, we selected the German Transrapid 07 (TR07) electromagnetic maglev system as a second evaluation baseline. Transrapid has extensively tested this technology at its Emsland test facility. Although it has not yet been integrated into a commercial system, it has been proposed for use along several corridors in the U.S. Again, its critical advantage over possible U.S.-designed systems is the perceived lack of development costs and risks. However, because of its lack of system-level integration and commercial history, TR07 represents a greater risk than TGV; it also offers potentially greater performance.

The NMI's four contracted SCD's were by far the most well defined U.S. maglev concepts available to us. Each contractor produced a detailed report describing the concept's major components, the interconnection between them, analyses of component and system performance, and capital and operating cost estimates. We thus chose to examine in detail these four concepts as representative U.S. maglev systems. In over-simplified terms, they represent an updated EMS comparable to TR07 (Grumman), an updated discrete-coil EDS comparable to the Japanese MLU002 (Foster-Miller), a well known sheet-guideway EDS (Magneplane), and a new ladder-coil EDS (Bechtel).

1.7 OVERVIEW OF EVALUATION PROCESS

To assess the technical viability of maglev concepts, the GMSA developed an evaluation process consisting of four main steps:

- *Applying the SCD-RFP system criteria as assessment criteria.* We developed qualitative and quantitative cross-checks to determine whether a maglev concept met each of the criteria defined in the SCD-RFP (USDOTFRA 1991).
- *Verifying subsystem performance.* We developed numerical models to verify the performance characteristics of critical subsystems for each concept.
- *Verifying system performance.* We developed a numerical model to simulate the overall performance of each system concept. We also estimated the main technology-dependent capital costs for the maglev concepts using a standardized procedure.
- *Applying other criteria.* We developed qualitative and quantitative cross-checks to determine whether a maglev concept met performance criteria that reflect technical viability but that were not included in the SCD-RFP (USDOTFRA 1991).

These four evaluation steps generated much of the input for our overall assessment of the technical viability of maglev for the U.S. As noted, we evaluated both TGV-A and TR07 as baseline concepts and the four SCD concepts as representative U.S. maglev systems. Insofar as possible, we referenced our conclusions regarding the viability of these concepts to specific evaluation data products.

Chapter 2 of this report describes the relevant characteristics of the HSGT technologies examined. Chapter 3 describes in detail each of the four evaluation steps discussed above, and presents for each concept the resulting evaluation data products. Chapter 4 presents our specific conclusions regarding the technical viability of maglev in the U.S. It is structured to reflect the key issues in the debate over maglev's technical viability.

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CHAPTER 2. CHARACTERISTICS OF SPECIFIC HSGT CONCEPTS

Sections 2.1–2.6 briefly describe each of the HSGT concepts examined. Section 2.7 summarizes their general characteristics and lists performance parameters useful for evaluations.

2.1 HIGH-SPEED RAIL—TGV*

2.1.1 Concept

The TGV (train à grande vitesse) uses steel wheels on steel rails. It is based on essentially conventional railroad vehicles, tracks, and propulsion, power distribution, and signaling and control subsystems, albeit very highly developed and made optimal for high-speed operation (83-m / s service speed). Figure 1 shows a typical trainset, its track, and overhead catenary power lines. The rolling stock is operated in fixed-consist trainsets (1-8-1 for the first-generation PSE [Paris–Sud–Est], 1-10-1 for the second-generation TGV-A [Atlantique], 1-8-1 for the third generation TGV-R [Reseau] and TGV-Bilevel); the trainsets can be operated as coupled pairs.

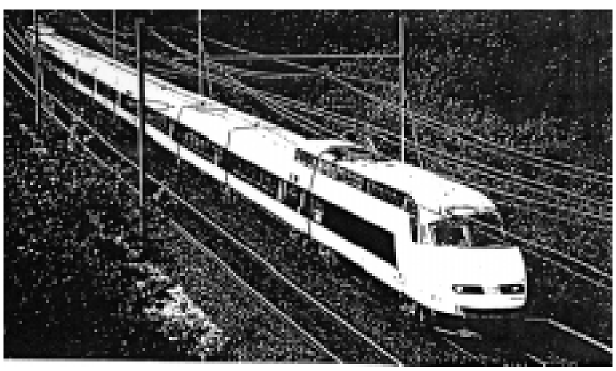


Figure 1. TGV–Atlantique.

2.1.2 Vehicles

All TGV trainsets have a power car on each end, followed by a transition car with one regular and one articulated truck; all other cars are articulated, sharing trucks at either end. The unpowered trucks are equipped with coil-spring primary and airbag secondary suspensions. The powered trucks have coil-spring primary and secondary suspensions. TGV-A and later trainsets are propelled by eight body-suspended 1100-kW AC synchronous rotary traction motors. The maximum axle load is limited to 17 tonnes, and the maximum unsprung mass to 2.2 tonnes / axle. Trainset seating capacity ranges between 376 (TGV-R) and 547 (TGV-Bilevel). The trainsets do not incorporate active or passive tilting.

Propulsion power and hotel power are collected from an overhead catenary through roof-mounted pantographs. The TGV fleet in SNCF (French National Railways) service carries at least two pantographs per power car, for 25 kV, 50 Hz, and 1.5 kV DC. Some trainsets are equipped for operation under three or even four different voltages. A 25-kV roof-mounted trainline is used to permit operation with only one pantograph raised. Braking on the TGV-A is by means of a combination of rheostatic, axle-mounted disc brakes (four per unpowered axle) and tread brakes (on powered axles). The TGV-R and later versions will eliminate the tread brakes in favor of disc brakes, even on the powered axles. All axles are equipped with anti-lock braking and the powered axles have anti-slip control. Top commercial speed is 83 m / s, though a modified 1-3-1 version of the TGV-A set the world wheel-on-rail speed record of 143 m / s. Sustained operation at 134 m / s on a 3.5% gradient is not possible.

2.1.3 Guideway

The basic TGV track structure is that of a conventional standard-gauge railroad, but built on an engineered support structure of granular materials selected to ensure free drainage and compacted to achieve a uniformly high track modulus. Minimum ballast depth is 30 cm. The track consists of continuously welded rail on twin-block concrete–steel ties with elastic fasteners and a 9-mm stiff rubber pad. All viaducts and bridge structures are ballast-decked and are built to span-length deflection tolerances. Alignment geometry for 83 m / s calls for 6000-m radius horizontal curves, although 4000-m radius curves are used exceptionally. Vertical curve radius at crests and troughs is 25,000 m, with 16,000 m used exceptionally at crests and 14,000 m exceptionally in troughs. Gradients of up to 3.5% are acceptable. Tunnel cross-sections range between 46 m^2 (single-track, 56 m / s) and 71 m^2 (double-track, 75 m / s).

The high-speed lines are built with full double track having bidirectional signals. Crossovers at 25-km intervals are 1:46 units, permitting 44 m / s in the diverted direction and full line speed in the

* Written by Christopher J. Boon, Canadian Institute of Guided Ground Transport.

through direction. High-speed (1:65) swing-nose turnouts permit 61 m / s in the diverted direction currently; SNCF expects to increase this to 64 m / s when concrete switch ties replace the wooden ties used in the original switch installations.

Propulsion and hotel power is supplied through a 2- $\times$ 25-kV overhead catenary system (OCS) in phase opposition. The OCS contact wire is 150 mm^2 at 5.1 m height. Substations have 220-kV single-phase supply feed with 60- to 120-MVA installed capacity.

Signaling and control is by means of full CTC (computerized train control), employing coded track circuits, track-to train voice and data links, and in-cab signals, with an automatic train protection system having speed adherence override and enforced braking.

2.1.4 Status

TGV-A has been in regular commercial service between Paris and west–southwest France since 1989. Its predecessor, TGV-Paris-Sud-Est, has been in commercial service since 1981. Both lines have been extremely popular and have experienced steady ridership increases. The French federal government and SNCF plan additional lines in France, and the technology has been deployed or proposed for commercial operation in corridors in Spain, Australia, Korea, Taiwan, Canada, and the U.S.

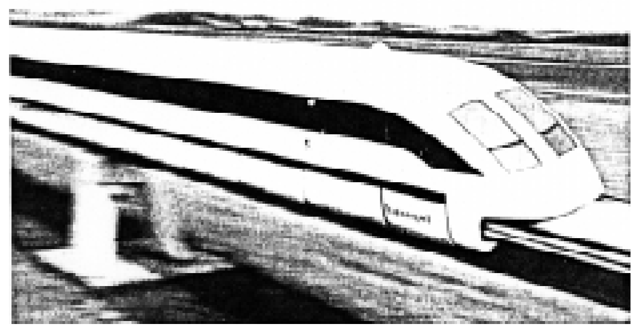
2.2 TRANSRAPID 07 (TR07)*

2.2.1 Concept

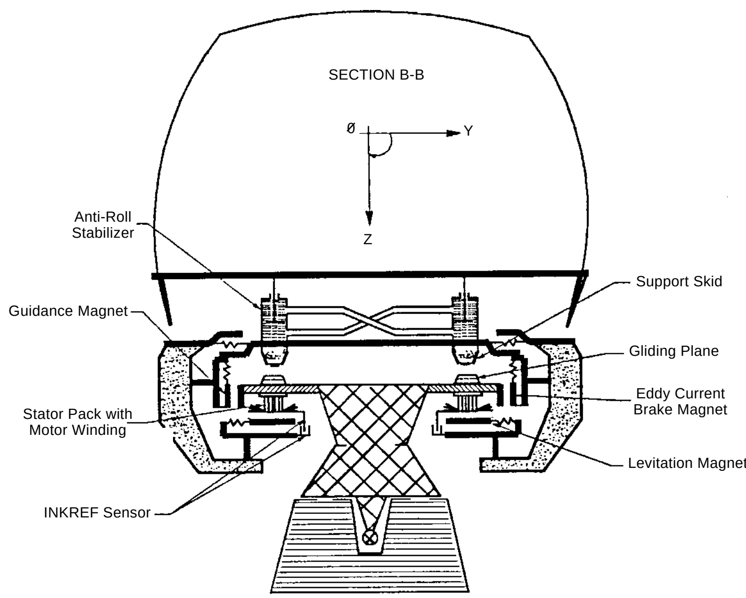
The TR07 has an electromagnetic suspension (EMS) system that uses separate sets of conventional iron-core magnets to generate vehicle lift and guidance by means of magnetic attraction (Fig. 2). It is capable of achieving cruising speeds of 134 m / s. Both the levitation and guidance systems have their own dedicated control systems for regulating the air gap between magnet and guideway rail. The control systems maintain the air gap at 8 mm nominally. The levitation system operates at all speeds. Propulsion is provided by a synchronous long-stator linear motor using the levitation magnets to interact with propulsion windings mounted in the stator packs on the guideway. The vehicle wraps around a T-shaped guideway, with the guidance rails mounted on the outside edges and the levitation and propulsion stator packs mounted underneath the guideway.

2.2.2 Vehicle

Transrapid 07 uses two or more vehicles in a consist, with each designed to carry 100 passengers (72 in first-class). Each vehicle is 25.5 m long, 3.92 m high, and 3.7 m wide. It is constructed of aluminum frames with sandwich shells of glass-fiber reinforced plastic panels. The reported weight is 106,000 kg per two-vehicle consist. Each TR07 vehicle in a consist is capable of independent operation and each has 32 levitation and 30 guidance magnets. The stator pack, which is



a. Exterior view.



b. Cross section showing principal lift, guidance, and propulsion elements (INKREF is a displacement sensor).

Figure 2. TR07 vehicle.

* Written by Richard Armstrong and Robert Hasse, U.S. Army Engineer Division, Huntsville.

mounted on the guideway, is composed of a laminated iron core, stator winding, and attachment hardware. The stator windings are 300 mm^2, soft aluminum, with double shields and an external conductive sheath, in a three-phase configuration. The propulsion force is generated by the interaction of the vehicle magnet exciter windings and the guideway stator windings. The primary braking is regenerative, through linear motor current reversal in response to phase angle modulation. An eddy-current braking system is used only if the regenerative braking fails. On board hotel and levitation power is provided by Ni-Cd batteries at low speeds (below 28 m / s) and by linear generators at increased speeds. The power is transferred using harmonic frequencies of the LSM fields. The proposed maximum speed for the TR07 in a commercial service is 138 m / s (311 mph), with a maximum operational speed of 118 m / s (265 mph). The top speed that has been recorded at Emsland is 120 m / s (270 mph).

2.2.3 Guideway

The TR07 guideway uses beams supported by A-shaped, steel-reinforced concrete piers. The piers are supported on either spread or pile foundations, depending on the soil conditions. The Emsland test track has both steel and concrete beams, while Transrapid has proposed only the steel beams for commercial service. The concrete beam is post-tensioned over a single span and steel reinforced, having a single cell, hollow box cross-section, with slanted webs. The steel beam also has a single cell, hollow box cross-section, with slanted webs, but it is continuous over two spans and is welded out of steel plates. Both beams are constructed and erected to very tight tolerances. The stator packs are bolted to the beams. Maximum guideway superelevation (tilt or banking) is 12°. Switching is accomplished by bending a special guideway beam section, in which the continuous steel beam is fixed at one end and laterally bent to the proper alignment by eight actuators.

Electrical power is distributed along the guideway at 110 kV, 50 Hz to wayside power conditioning stations. There are two 5–6 MW, variable-frequency–variable-voltage power conditioning units operating in parallel to power the guideway.

2.2.4 Status

TR07 is a proven technology that is currently undergoing performance testing at Transrapid's Emsland test facility. It has yet to be deployed commercially, although it has been proposed for commercial operation along several European and U.S. corridors. The GSMA's (1992) *Transrapid TR07 Baseline Report* contains a more thorough description of this technology.

2.3 BECHTEL*

2.3.1 Concept

The Bechtel concept is a novel, 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 null-flux coils mounted on the guideway provides guidance. LSM propulsion windings, also attached to the guideway sidewalls, interact with these same vehicle magnets to produce thrust. Figure 3 shows the overall layout of Bechtel's concept.

2.3.2 Vehicle

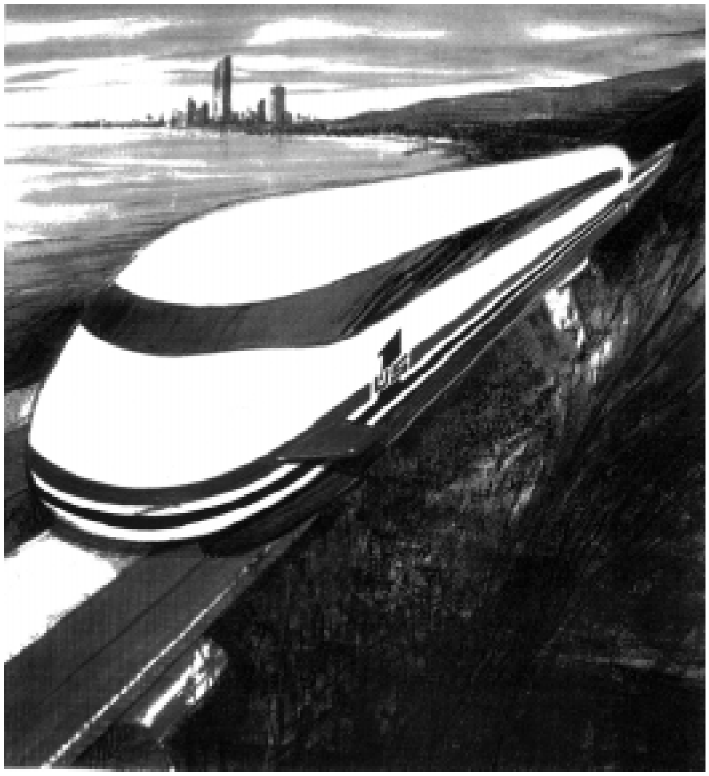
The baseline vehicle consists of a single 106- to 120-passenger car. The 106-passenger vehicle provides 90 coach seats with six abreast seating and 16 first-class seats with four abreast seating. The 120-passenger vehicle has only coach seats. The Bechtel vehicle uses aerodynamic control surfaces to augment magnetic guidance and damping forces. When it is not levitating (at low speeds or in emergencies), the vehicle operates on air-bearing pads. By incorporating special lift coils in the guideway, the vehicle may liftoff at zero speed. Two methanol-powered fuel cells provide a total of 186 kW of onboard power.

The vehicle is constructed with an outer aluminum shell and an inner shell made of composite material. The intent of this construction is to enable tilting of the inner shell while maintaining a smooth aerodynamic outer surface. The vehicle can tilt to 15°.

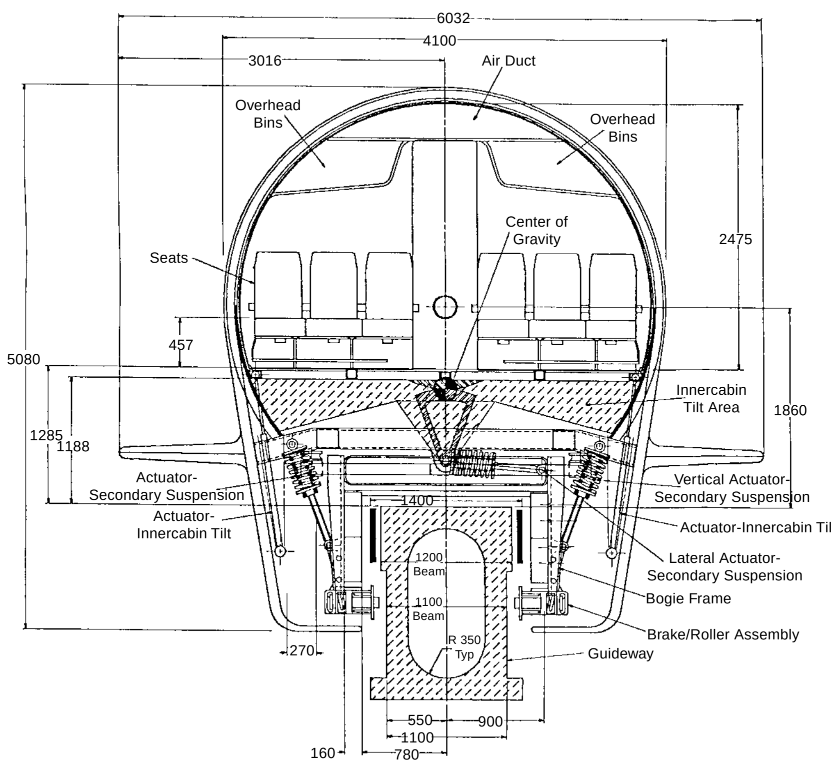
2.3.3 Guideway

The baseline guideway consists of single-span, post-tensioned concrete box beams supported on concrete piers with 25-m spacing. The laminated aluminum suspension ladder, null-flux guidance coils, and six-phase LSM windings are all compactly mounted on the upper portion of each

* Written by Dr. John Potter, U.S. Army Engineer Division, Huntsville.



a. Exterior view.



b. Cross section.

Figure 3. Bechtel vehicle on box-shaped guideway (dimensions in mm).

guideway sidewall; this assembly is then enclosed with a cover plate. The critical gap for this concept is the 50-mm horizontal gap between the superconducting coils and the cover plate. Because of high magnetic fields, the concept calls for nonmagnetic, FRP reinforcing rods in the upper portion of the box beam. Guideway superelevation of up to 15° is planned. The concept's baseline switch is a bendable beam constructed of FRP.

The guideway mounted propulsion coils are conventionally constructed and configured as a six-phase system. DC power is distributed along the guideway at 24 kV to frequency converters located near the guideway. The typical zone length for a frequency converter is 4000 m and an LSM blocklength is 2000 m.

2.3.4 Status

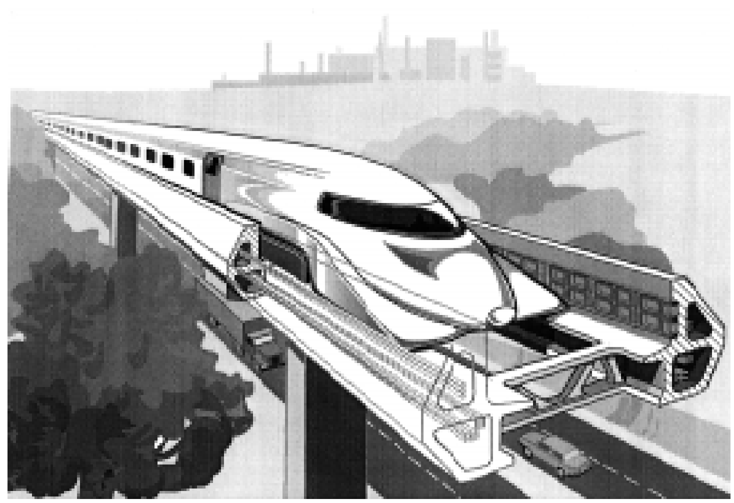
This concept is one of the four NMI-contracted SCDs. These contracts did not call for proof-of-concept or subsystem tests and none had been conducted prior to this work.

2.4 FOSTER-MILLER*

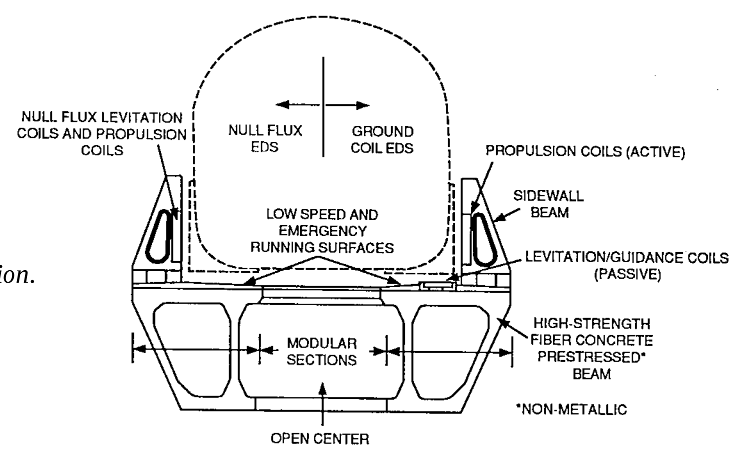
2.4.1 Concept

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 line up with the vehicle magnets.

* Written by Frank L. Raposa, Consulting Engineer.



a. Exterior view.



b. Cross section.

Figure 4. Foster-Miller vehicle in U-shaped guideway.

These inverters synthesize a waveform that moves down the guideway, synchronously with the vehicle. Figure 4 shows the overall layout of Foster-Miller's concept.

2.4.2 Vehicle

The baseline vehicle consists of two 75-passenger modules with attached nose and tail sections. Smaller or larger vehicles can be made up by incorporating fewer or additional passenger modules. These modules have magnet bogies at each end, containing four magnets per side, that they share with adjacent cars. The port and starboard superconducting magnets are series-connected electrically to provide balanced guidance in the event of a magnet quench (catastrophic loss of superconductivity). To reduce exposure to magnetic fields, there are no passenger seats over the bogies.

The vehicles are made of lightweight composite materials with five across seating. The vehicles have 12° tilting capability.

2.4.3 Guideway

The U-shaped guideway consists of two parallel, post-tensioned concrete beams joined transversely by precast concrete diaphragms. The baseline guideway uses two-span assemblies of such beams supported at 27-m intervals. Each beam has an integral sidewall that carries the null-flux levitation coils and the propulsion coils. Because of high magnetic fields, the upper post-tensioning rods are FRP. The space between the beams is open to allow direct runoff of rain, snow, and debris. Guideway superelevation may be up to 16°. The baseline high-speed switch uses switched null-flux coils to guide the vehicle through a vertical turnout. It requires no moving structural members.

The propulsion coils are located in the sidewall behind the levitation coils. Each sidewall coil is electrically connected in series to a corresponding coil on the opposite sidewall. The superconducting coils on each side of the bogie interact with the connected sidewall propulsion coils to provide guidance. The design air gap for guidance is 100 mm and the system is designed to be very stiff.

The sidewall propulsion coils do not overlap and are individually switched from H-bridge inverters. Each is controlled by its own H-bridge that is adjacent to its coil. As mentioned the system is called the LCLSM. The LCLSM will energize the propulsion coils as they become lined up with the superconducting magnets mounted on the bogies. The H-bridge inverters synthesize a three-phase waveform that moves down the guideway in synchrony with the vehicle.

The LCLSM coils that are located between the bogies also operate as the high-frequency primary of an air-core transformer. This method of operation is also produced by the H-bridge inverters. The LCLSM coils interact with adjacent coils on the vehicle to transfer power to the vehicle inductively for onboard electrical loads.

2.4.4 Status

This concept is one of the four NMI-contracted SCDs. Although the contractor conducted no proof-of-concept tests, the Japanese MLU002 is similar (superconducting EDS with U-shaped guideway and vertical null-flux levitation). Because the Japanese have conducted extensive tests and development work on the MLU002, it must be viewed as a proven concept (although not yet a commercial product). However, a significant departure of the Foster-Miller concept from the MLU002 is the LCLSM; this propulsion scheme is as yet unproven.

2.5 GRUMMAN*

2.5.1 Concept

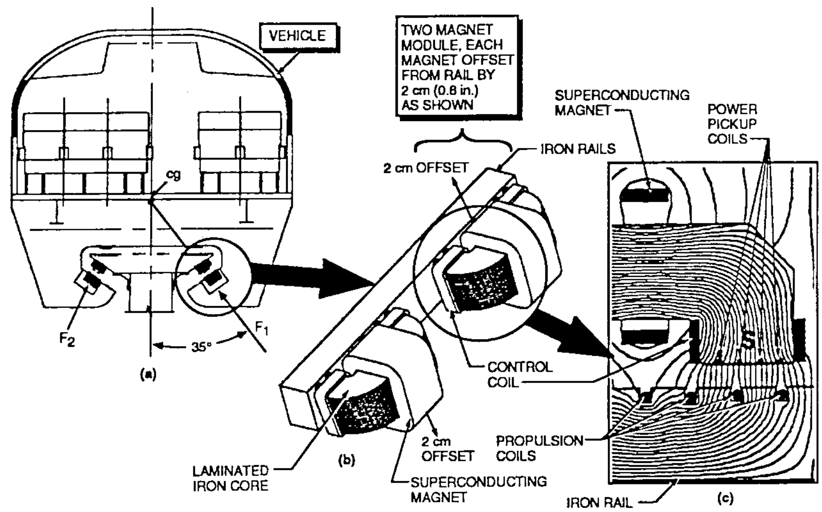
The Grumman concept is an EMS with similarities to Transrapid 07. However, Grumman's vehicles wrap around a Y-shaped guideway (as opposed to the TR07's T-shaped guideway) and use just one set of vehicle magnets and guideway rails for levitation, guidance, and propulsion (Fig. 5). The vehicle magnets are superconducting coils around Vanadium-Permendur iron cores that are horseshoe shaped. The horseshoe 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. Propulsion is by conventional LSM embedded in the guideway rail.

2.5.2 Vehicle

The baseline consist is a two-vehicle configuration for 100 passengers; it can be shortened to a single 50-passenger vehicle or lengthened to a 150-passenger, three-vehicle consist. Passengers are seated in two groups of ten rows of two-by-

* Written by Dr. John Potter, U.S. Army Engineer Division, Huntsville.

a. Exterior view.



b. Levitation, propulsion, and guidance system.

Figure 5. Grumman vehicle.

three. The vehicles are made of lightweight composite materials.

The vehicle body is attached to the chassis by tilting mechanisms that provide for up to 9° of body tilt. Each chassis provides the secondary suspension and mounting for two pairs of magnets on each side and actuators for lateral magnet movement for guideway clearance in curves. The magnets are alternately offset 1.5 cm to the left and right of the guideway rail to provide roll control. Normal coils on each of the iron-core legs modulate levitation and guidance forces while keeping the superconducting magnets operating at nearly constant current.

Each magnet consists of 1020 turns of NbTi conductor carrying 53 A (for 54 kAT) at 4.5 K. The cryostats are mostly aluminum, with reservoirs for both liquid helium and liquid nitrogen. N_2 vapor is vented, while He vapor is compressed and stored for later reliquefaction at a fixed plant.

Onboard power is provided by conventional inductive coils mounted on the ends (or faces) of the magnet cores. This system provides up to 170 kW per car using a combination of slot harmonics and high-frequency current injected into the LSM.

2.5.3 Guideway

The innovative guideway superstructure consists of slender Y-shaped guideway sections (one for each direction) mounted by outriggers every 4.5 m to a 27-m main beam or “spine girder.” The structural spine girder serves both directions and is in turn supported by conventional piers on piled or spread footings (as foundation conditions dictate). Maximum guideway superelevation is 15°.

Switching is accomplished with a TR07-style bending guideway beam, except that the Grumman bending section is complemented by a sliding or rotating, elongated frog section that allows for a shorter length of bending guideway. Propulsion is by conventional, three-phase LSM embedded in the guideway rail in 500-m blocks.

2.5.4. Status

This concept is one of the four NMI-contracted SCDs. Although the contractor conducted no proof-of-concept tests, the concept is similar to the well-tested Transrapid 07 (EDS levitation and guidance, conventional LSM, bending-beam switch). However, Grumman's use of a single set of magnets and reaction rails for levitation and guidance, and its use of superconducting magnets to achieve a larger suspension gap, are essentially unproven innovations.

2.6 MAGNEPLANE*

2.6.1 Concept

The Magneplane concept is a single-vehicle EDS system using a trough-shaped, 0.2-m-thick aluminum guideway for sheet levitation and guidance (Fig. 6). Centrifugal force rotates the vehicle (or "Magplane") in the trough for coordinated banking in curves. No additional tilting suspension is required even for 45° bank angles. Superconducting levitation and propulsion magnets are grouped at the front and rear of the vehicle The centerline magnets interact with conventional LSM windings 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 (at a 0.15-m gap).

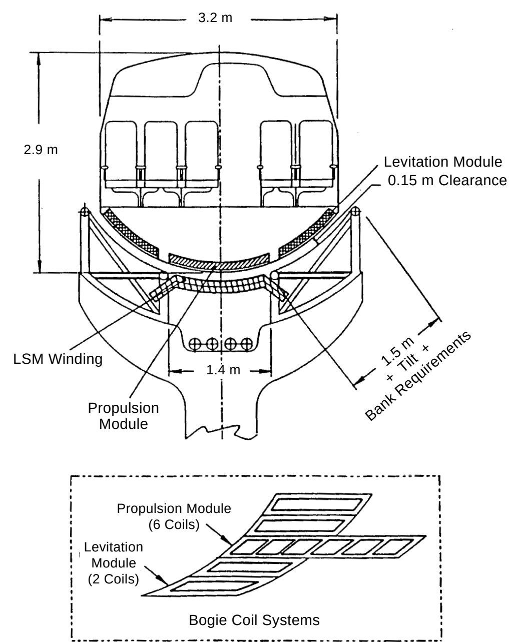
2.6.2 Vehicle

The baseline vehicle is a 140-passenger "Magplane," which can be complemented by a 45-seat version. The seats are configured in 28 rows of two-by-three in a lightweight composite body.

The magnets are grouped at each end of the vehicle for cryogenic and magnetic field considerations; there is no secondary suspension or body tilting system. Vertical and horizontal control surfaces are mounted on the nose and tail of the vehicle to provide damping (especially in roll) and increased directional stability. Air bearings support the vehicle at speeds below about 40 m/s.

Each magnet group consists of six superconducting propulsion coils along the centerline and two superconducting levitation coils on each side. Each end propulsion coil is designed for 390 kAT, while the mid coils are designed for 780 kAT. Each levitation coil is sized for 252 kAT. All of the coils are Nb_3Sn cable-in-conduit-conductors, which use steel conduit to carry supercritical He for cool-

a. Exterior view.



b. Vehicle cross-section and bogie coils.

Figure 6. Magneplane vehicle in aluminum guideway trough.

* Written by Dr. John Potter, U.S. Army Engineer Division, Huntsville.

ing to between 6 and 8 K. A closed-cycle onboard refrigeration system provides the recycled supercritical He at 6 K.

Onboard power (185 kW) is generated by inductive coupling to high-frequency currents injected into the LSM.

2.6.3 Guideway

The aluminum levitation sheets in the guideway trough form the tops of two aluminum box beams that support the LSM winding located in the center of the trough. These box beams are supported every 9.14 m by columns on piles or spread footings, as foundation conditions dictate.

The baseline switch uses switched null-flux coils to guide the vehicle through a fork in the guideway trough. It requires no moving structural members.

The centrally mounted LSM is a conventional, single-phase winding with 2000-m blocklengths. Through phase-angle control, the LSM also provides additional vertical damping forces to the vehicle.

2.6.4 Status

This concept is one of the four NMI-contracted SCDs. Although the contractor conducted no tests, earlier laboratory work on this concept has essentially proven the levitation, guidance, and propulsion schemes. No full-scale system or subsystem tests have yet been conducted. A Magneplane consortium has proposed the concept for a commercial route in Florida.

2.7 PHYSICAL CHARACTERISTICS AND PERFORMANCE PARAMETERS*

It is frequently helpful to compare general physical characteristics of each HSGT system, such as consist mass, number of passengers per consist, etc. Table 1 presents a summary of such physical parameters for the concepts studied here. Because of rounding, these numbers may differ

* Written by Dr. James Lever, CRREL, and Dr. John Potter, U.S. Army Engineer Division, Huntsville.

Table 1. General physical characteristics of concepts studied.

Parameter Basic concept	*TGV-Atlantique steel wheel-on-rail*	*TR07 EMS, separate lift and guidance*	*Bechtel EDS, ladder levitation*	*Foster-Miller EDS, sidewall null-flux*	*Grumman EMS, common lift and guidance*	*Magneplane EDS, sheet levitation*
Vehicles / consist	1-10-1	2	1	2	2	1
Seats / consist	485	156	106	150	100	140
Gross mass (10^3 kg)	490	106	63	73	61	48
Cabin area / seat (m^2)	1.2	0.83	0.80	0.74	0.93	0.61
Cabin volume / seat (m^3)	—	2.2	1.7	1.5	1.8	1.1
Cruise speed (m / s)	83	134	134	134	134	134
Minimum headway (s)	240	57	36	55	30	45
Total bank angle (°)	7	12	30	28	24	35
Primary suspension	passive	active	passive	passive	active	semi-active
Secondary suspension	passive	passive	active	passive	none	none
Critical air gap (mm)	N / A	8	50	75	40	150
Low-speed support	N / A	maglev	air bearings	wheels	maglev	air bearings
Liftoff speed (m / s)	N / A	0	10	50	0	50
Primary braking	rheostatic	regen.	regen.	regen.	regen.	regen.
Secondary braking	friction	eddy	aero.	wheel, aero.	eddy	skids
Emergency braking	—	skids	drouge	skids	friction	aero.
Normal braking (g)	0.045	0.12	0.20	0.16	0.16	0.16
Emergency braking (g)	0.10	0.30	0.25	0.25	0.20	0.50
Cryogenic system	N / A	none	isochoric	recompress.	recompress.	refrigerator
Onboard power (kW)	9000	460	190	220	170	190
Guideway type	ballasted rail	T-shaped	box beam	sidewall	Y-shaped	trough
Span length, *L* (m)	N / A	25	25	27	27	9.1
Static *L* / deflection	—	5600	3500	5000	3000	2400
Dynamic *L* / deflection	4000	4000	2500	2300	2500	2000
Switch concept	swing-nose rails	bendable steel beam	bendable FRP beam	vertical elect.-mag.	bendable steel beam	horizontal elect.-mag.

slightly from those in the SCD reports or elsewhere in this report.

We also computed several performance parameters suitable for comparative evaluation of each concept, such as energy efficiency, guideway unit cost, etc. Table 2 shows these. For these parameters, we attempted to compare concepts equally, insofar as possible. For example, we computed energy efficiency as energy consumption per passenger-meter to allow for differing numbers of passengers per consist. However, each concept also allotted a different amount of cabin space per passenger. We corrected for this by defining a standard passenger (SP) as one occupying 0.80 m^2 of cabin floor area (including galleys and lavatories). This value is roughly the average floor area per passenger for the five maglev concepts studied, and it approximates business-class airline seating. This correction prevents indirect penalization of concepts with more spacious passenger cabins. We used cabin floor area rather than, say, cabin volume to define our standard passenger because we felt it reflected the spatial measure of greatest relevance to paying passengers. Other normalization approaches may be equally valid, but we feel this one is fair and relevant.

Table 2. Evaluation parameters for each concept. All performance values reflect GMSA analyses unless noted.

Parameter	*TGV-A*	*TR07*	*Bechtel*	*Foster-Miller*	*Grumman*	*Magneplane*
Standard passengers						
per consist (SP)	700	160	110	140	120	110
Gross mass / SP (kg)	700	650	600	520	530	440
Max. low-speed accel. (g)	0.044	0.10	0.23	0.16	0.093	0.23
Reserve accel. at 134 m / s (g)	N / A	0.006	0.12	0.044	0.048	0.039
3.5% Grade speed (m / s)	30	110	140	140	140	140
10% Grade speed (m / s)	N / A	14	140	100	5	90
0–134 m / s time (s)	N / A	320	77	120	180	123
Minimum radius* (m)	*6000*	5800	2600	2800	3300	2200
Prop. efficiency† at 134 m / s	*[0.82]*	0.83	0.85	0.91	0.78	0.84
Power factor† at 134 m / s	*[0.91]*	0.74	0.98	0.97	0.98	0.99
Aero. drag / SP at 134 m / s (N)	220	360	430	280	240	160
Total drag / SP at 134 m / s (N)	240	380	480	350	270	350
Energy intensity						
at 134 m / s (J / SP-m)	310	460	560	390	340	400
SST energy intensity (J / SP-m)	N / A	540	720	450	490	580
SST trip time (min.)	N / A	140	120	130	130	130
Guideway tolerance limits						
Ride comfort (mm)	1–3	2	3	12	5	20
Safety (mm)		5	6	25	30	50
Consist cost** / SP ($K)	41	58	39	93	71	190
Dual elevated cost						
SCD** ($M / km)		9.7	15	8.1	9.4	14
GMSA ($M / km)	14	12	13	17	11	16

*TGV 83 m / s, 0.05 g unbalanced acceleration, maglev 134 m / s, 0.10 g unbalanced acceleration.
†Propulsion efficiency and power factor measured at utility connection for steady cruise *[TGV 83 m/s]*.
**Cost directly from SCD, TGV or TR07 reports; variations compared with GMSA costs are primarily ascribable to differences in unit costs, subcomponent groupings and guideway heights used (see section 3.3.2).