CHAPTER 4. OVERALL TECHNICAL VIABILITY OF CONCEPTS

The GMSA effort described in chapters 2 and 3 above concentrated on generating data and examining technical characteristics for each concept. Essentially, this provided the input necessary for evaluating the technical viability of maglev in the U.S. In chapter 4, we use this information to address specific aspects of technical viability (see Tables 1 and 3, which list the general performance features of each concept).

4.1 LONG-TERM POTENTIAL OF MAGLEV COMPARED WITH HSR

High-speed rail possesses impressive performance characteristics and could meet many of the requirements thought to be important for a favorable market response to maglev. Indeed, TGV 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 current performance limits may be governed more by cost–benefit optimization than by physical constraints, and further development will undoubtedly raise these limits. We may then ask whether maglev possesses specific attributes that, in the long term, will provide it a clear performance advantage over HSR. If it does, this provides some rationale for bypassing HSR in favor of developing maglev, despite the latter's significant development cost and risk.

We discussed several technological issues that appear to favor maglev over HSR. In most cases, HSR's shortcomings are not absolute physical constraints and could be mitigated with sufficient development and maintenance efforts. Indeed, HSR's present performance levels have resulted from just such efforts. While laudable, this process has been slow and costly, and future improvements will require proportionately greater investment.

By comparison, maglev is a new technology specifically intended to start with performance capability beyond that of current HSR. While its development costs and risks are substantial, they may be no greater than those required to bring HSR to a similar performance level. More importantly, future incremental improvements should be much easier for maglev than HSR. This difference in incremental effort to achieve incremental performance gains is a basis for identifying long-term advantages of maglev over HSR. Other authors have expressed this same argument for maglev (Gran 1990) and for new technologies generally (Foster 1986).

The following sections (4.1.1 to 4.1.9) contain the technical issues that we feel best reflect the long-term advantages of maglev vs. HSR. Note that commercial service speed (or service speed) denotes a speed that is sustainable in commercial operation with acceptable margins of safety and life-cycle costs. We use TGV-A as our primary HSR example, although we note differing technical characteristics of other HSR systems where appropriate.

4.1.1. Speed

TGV-A offers 83-m / s commercial service, and has demonstrated a sustained speed of 133 m / s and a peak speed of 143 m / s. Thus, steel-wheel-on-rail technology is directionally stable at maglev's design-goal speed of 134 m / s. Nevertheless, such speeds were not the original design target of this technology; high-speed stability has been achieved through incremental improvements in aerodynamics, truck design, and rail-bed stiffness and alignment. For reasons of safety margin or life-cycle costs, TGV does not currently operate at 134 m / s, and it would require further improvements to do so. By their nature, such improvements would entail development, capital, and maintenance costs that are even higher than the significant costs incurred for 83-m / s service.

Power transfer by pantograph–catenary contact may be HSR's most immediate speed limiter. Observers noted that arching between the pantograph and catenary was almost continuous throughout TGV's 143-m / s run. Such arching leads to rapid deterioration of both components. Even with steady contact, pantograph–catenary wear will increase with speed, thereby increasing maintenance costs. TGV must solve both the contact and wear problems to use pantograph–catenary power transfer at service speeds of 134 m / s and higher.

SNCF / Gec Alsthom have begun work to develop an actively controlled pantograph to enable TGV to reach higher speeds. They have allocated $120 million for this and other improvements to TGV to raise its cruise speed to 97 m / s by 1995. Their effort is also supplemented by the general HSR R&D effort worldwide. Such large investments for incremental speed increases are characteristic of mature technologies such as steel wheels on rails. Indeed, both Japan and Germany see 97-m / s service as a goal requiring substantial R&D investment over the next 5–10 years.

By comparison, high-speed potential is essentially an inherent characteristic of maglev. Guidance and propulsion occur without physical contact. Magnetic elements (coil layout, reaction components, field strengths, etc.) are broadly adjustable to achieve the guidance forces necessary for very high speed. Similar flexibility in design exists for guideway structural members. Furthermore, with a long-stator LSM, propulsion power does not need to be transferred to the vehicle. In essence, maglev comes “out-of-the-box” ready for 134-m/s service. Higher-speed service is well within the technology, and its associated higher capital and operating costs become simply part of the system-level trade-off with expected market demand for the service. If run in evacuated tubes, maglev has an extremely high ultimate-speed potential.

In principle, HSR could utilize a long-stator LSM for propulsion to circumvent pantograph–catenary power transfer. However, this would entail high development costs and an enormous infrastructure investment on par with those for a maglev LSM. Essentially, such a system would substitute steel-wheel-on-rail guidance for magnetic guidance and would thus still encounter high incremental development costs for that element.

Speed, through its influence on trip time, strongly influences forecasts of the U.S. market response to HSGT. However, the question of how much speed is enough depends on how much the traveler must pay for it. It seems likely that maglev will achieve service speeds of 134 m/s more easily than will HSR; this should translate into lower costs and hence lower ticket prices for the traveler. While maglev requires development investment just to begin commercial service, HSR will also require substantial R&D to reach 134 m/s (given that 97 m/s is viewed as a significant challenge). Even if the two are comparable in performance and cost at 134 m/s, a desire for future speed increases favors maglev.

4.1.2. Trip time

Trip time strongly influences ridership for transportation systems. In addition to a much higher speed potential, maglev possesses other performance characteristics that combine to deliver shorter trip times than HSR.

TVG’s maximum acceleration is 0.04 g from 0–16 m/s, and this falls to 0.03 g at 50 m/s. By comparison, maglev’s maximum low-speed acceleration is four times TGV’s, constrained basically by ride comfort. Additionally, the U.S. maglev concepts have reserve acceleration in access of 0.04 g at 134 m/s. Superior acceleration capability permits maglev to maintain higher speeds on grades (e.g., 140 m/s on a 3.5% grade for the U.S. concepts compared with 30 m/s for TGV). It also allows for more rapid return to full speed following reduced-speed curves.

TGV’s trip times along existing ROW also suffer from lack of vehicle tilting capability. TGV’s total bank angle is only 7° compared with an average of about 30° for U.S. maglev concepts. Although tilting HSR systems exist, none are capable of even 83-m/s service.

Longer trip times makes HSR less attractive than air travel, as well as other transportation modes, resulting in lower ridership and revenues. Relative to maglev, such lower revenues can offset HSR’s capital cost advantage and yield lower profitability.

4.1.3. Mission flexibility

HSR is best suited to short to intermediate intercity trunk service. TGV’s fixed-consist, non-tilting trains, lower cruise speed, and lower overall acceleration–deceleration render it poorly suited to other transportation needs beyond this. This lack of flexibility ultimately limits the market penetration and profitability of HSR.

Besides offering superior intercity trunk service, U.S. maglev concepts show considerable potential to serve additional missions. Such flexibility derives from the much greater performance capability of the technology. Mission flexibility helps to reduce the risk that intercity trunk service is not where the greatest HSGT market lies. Also, by offering other services (regional airport connector, commuter trunk, point-point, long-haul trunk), maglev increases its overall ridership potential in a major transportation network. This provides some confidence that an investment in maglev will fulfill a broad spectrum of U.S. transportation needs.

4.1.4. Maintenance

HSR relies on wheel–rail contact for lift, guidance, acceleration, and braking, and pantograph–catenary contact for power transfer. To achieve low rolling resistance and adequate adhesion, the wheels and rails contact each other over an extremely small area; to avoid arching, the pantograph must firmly press against the catenary. In both cases, the resulting contact stresses are high and thus produce wear. TGV conducts scheduled maintenance to ensure that wheels are smooth and round, rails are correctly profiled and accurately aligned, and pantograph and catenary wear are within allowable limits. This is costly and time consuming. Because wear rates increase with speed, the cost and effort necessary to alleviate them are significant impediments to higher service speeds.

By its nature, maglev requires no physical contact between vehicles and guideways. Lift and guidance forces are distributed over large areas, yielding much lower stresses than wheel–rail contact. Furthermore, an LSM offers contactless propulsion and braking; in long-stator form, it also avoids the need to transfer propulsion power to the vehicle. Through good design, attachments securing magnetic elements to either vehicles or guideways should require little maintenance. Overall, maglev offers a potential for very low maintenance costs.

4.1.5. Adhesion

Wheel–rail adhesion (or contact friction) poses physical limits on HSR's propulsion and braking forces. In normal operation, adhesion limits HSR's grade-climbing ability and maximum acceleration rate. It also limits maximum deceleration during emergency stopping. This results in increased trip times for routes with frequent accelerations and stops. To decouple braking from adhesion limits, Germany's ICE train uses an eddy current brake; it is capable of 0.2–0.25 g of deceleration for speeds over about 10 m / s.

TGV's dependence on adhesion for braking directly affects headway allotments: the maximum no-skid deceleration rate (plus safety margin) limits TGV-A's minimum headway to 4 minutes (expected to be reduced to 3 minutes). Because adhesion depends strongly on the condition of the wheel / rail interface, rain, wet leaves, snow, and ice will tend to worsen HSR performance. TGV-A must reduce speed in heavy rain or snow to maintain its minimum headway.

By comparison, there are no physical limits on maglev's propulsion and braking forces. Its practical limits are subject to design trade-offs involving ride comfort, motor thrust and power, guideway and vehicle structural strength, etc. Because magnetic fields transmit these forces without contact, adverse weather does not alter them. For emergency stopping, maglev may use skids specifically designed for generating high frictional forces rather than being limited to steel-wheel-on-rail friction. These characteristics lead to shorter trip times and substantially reduced headways (less than 1 minute) compared with HSR.

4.1.6. Safety, availability, and cost

HSR in both Europe and Japan have exemplary safety records. However, the technology requires extensive maintenance (inspections and adjustments) to achieve such safety. Maglev possesses characteristics that should permit it to maintain safe, high-speed operations under more extreme conditions and with less maintenance. That is, maglev offers the potential for higher system availability and lower cost at safety levels comparable to HSR.

Several maglev concepts employ vehicles that wrap around their guideways. Others have guideways that partially wrap around their vehicles. Such approaches can provide more than 1 g of "derailment" containment in the event of extreme environmental disturbances or component failures.

Large-gap maglev systems are much more tolerant of ground displacements caused by earthquakes than is HSR. These displacements can be larger for maglev before triggering ride-comfort-, safety-, or wear-related maintenance. Greater tolerance also provides an added margin for bringing high-speed vehicles safely to rest during earthquakes. Such features are extremely important for safety of HSGT in many parts of the U.S.

Maglev's contactless propulsion and braking render it less susceptible to snow, ice, and rain than HSR. Also, maglev concepts with wrap-around guideways offer some protection from crosswinds. These features offer maglev a potential of higher availability in adverse weather for safety comparable to HSR.

Maglev should be capable of achieving HSR's outstanding safety record. Its greater tolerance to both earthquakes and adverse weather may well be decisive advantages in availability and cost in the more demanding U.S. environment.

4.1.7. Noise

Maglev avoids a major source of noise generated by HSR—wheel–rail contact. It also generates no pantograph–catenary noise. These noise sources predominate at low speeds and thus may trigger speed limitations or mitigation measures for HSR sections in urban areas. Maglev at low speeds can be considerably quieter than HSR—it will travel faster through an area with a set noise limit.

Figure 121 shows peak sound-pressure levels (*Lmax*) measured at 25-m distance for several HSGT systems (Hanson et al. 1993). To meet an 80-dBA limit, Shinkansen and Amtrak must stay below about 25 m / s, and ICE must stay below about 40 m / s (data for TGV do not extent to these lower speeds). By comparison, TR07 may proceed as fast as 50 m / s and still meet an 80-dBA noise limit. This is a 25% performance advantage. For noise limits from 85 to 95 dBA, TR07's speed advantage over ICE and TGV is 15–20 m / s. This will yield reduced trip times for routes with noise-limited sections,

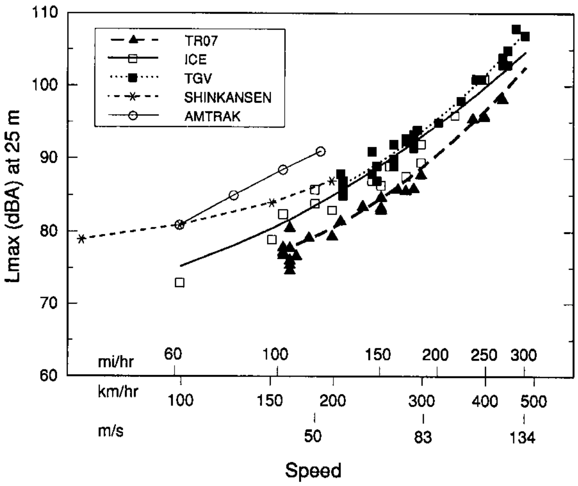

Figure 121. Noise from maglev and high-speed rail systems. (From Hanson et al. 1993.)

such as those along the northeast corridor. Although current high-speed trains cannot achieve cruising speeds of 134 m / s, the data indicate that maglev would be 5–7 dBA quieter at this speed. Such lower noise emissions will be important along high-speed, rural route sections.

4.1.8. Use of existing infrastructure

Despite being able to run at low speed on existing rail lines and use existing railroad stations, HSR has serious shortcomings in its use of existing infrastructure. HSR vehicles are heavier than maglev vehicles (700 kg / SP for TGV-A vs. 530 kg / SP for the SCD concepts). This increases HSR's expense as an elevated system, which may be necessary along existing ROW. HSR also has poorer curving and grade-climbing capability than maglev, and it generates more noise. Collectively, these features place HSR at a serious disadvantage relative to maglev along routes using existing highway and railroad ROW.

4.1.9. Strategic technology

Maglev and HSR represent radically different technologies. HSR represents the end-product of two centuries of incremental development. By comparison, maglev encapsulates many of the best technologies that the late 20th century has to offer. It may well drive the refinement and commercialization of many strategically important spin-off technologies. The country that leads maglev R&D will also be poised to lead this commercialization effort.

The following is a list of the most significant strategic technologies associated with maglev. Note that these technologies have applications in many fields, including military, aerospace, medical, and civil infrastructure:

- Superconductivity
- Cryogenics
- Power electronics
- Composite vehicle structures
- Composite reinforced concrete
- Smart structures (for integrity monitoring)
- Advanced manufacturing and construction techniques
- Active vehicle suspensions
- Automated system controls
- Intrusion / obstacle detection
- Maglev launchers
- EMF shielding
- EMF biological effects
- Market demand modeling (especially verification)
- Ride-comfort modeling
- Public–private joint venturing.

4.2. PERFORMANCE POTENTIAL OF GENERIC U.S. MAGLEV COMPARED WITH TR07

The GMSA team has carefully examined and analyzed the performance of TR07 and four well-defined U.S. maglev concepts. Here, we compare the potential for a U.S. concept to offer superior performance to TR07 in the U.S. market. Because the four SCD concepts differ in detail, some conclusions are valid for specific concepts. However, several performance features are not concept-specific; with care, we may aggregate such characteristics into what may be termed a "generic U.S. maglev" system.

As with our comparison between maglev and TGV, we recognize that TR07 will undoubtedly benefit from further R&D. Nevertheless, the predominant argument in favor of beginning maglev deployment with TR07 is to avoid development costs and risks. This argument assumes that TR07 is basically already in the form needed for rapid commercial acceptance in the U.S. We are, thus, free to compare the possible performance of U.S. maglev concepts against the existing characteristics of TR07. Any significant R&D needed to upgrade TR07 offsets its principal advantage—the perceived lack of development costs and risks.

We may note here that, unlike TGV, TR07 does not offer commercial service anywhere in the world.

Indeed, it has not yet entered production. Apparently, investors have not yet agreed that its performance characteristics justify its costs, particularly its high (guideway-dominated) capital costs. Transrapid may need to conduct additional R&D to rectify this situation. This requirement may place TR07 on a more equal basis with a concerted U.S. maglev development effort.

4.2.1. Performance efficiency

Comparisons of performance and cost of TR07 and U.S. maglev concepts revealed two important findings: 1) U.S. maglev can offer slightly better performance than TR07 at much lower cost (especially for at-grade sections), and 2) 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 about 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–cost advantages likely to result from a U.S. maglev development effort. Furthermore, the performance advantages of the SCDs increase along twisty routes (e.g., Interstate Highway ROW) and for more aggressive ride-comfort criteria. These results give designers some flexibility in the selection of system characteristics to make performance cost optimal for U.S. market conditions.

4.2.2. Suitability to existing rights-of-way

The SCD concepts indicate that a generic U.S. maglev system will be much better suited than TR07 to deployment along existing ROW. A U.S. system will require about half the curve radius of TR07 at 134 m/s (about 3 vs. 6 km). It will climb much steeper grades at full speed (more than 4% grade vs. less than 1%). From a stop, it will reach 134 m/s in less than half the time (about 130 vs. 320 s). These characteristics mean that a U.S. maglev system will achieve much shorter trip times along existing, lower-speed ROW (e.g., Interstate Highways, conventional rail). For example, 18 minutes of Bechtel's 21-minute SST trip-time savings take place in the first, twisty segment that represents an Interstate ROW. Essentially, greater curving and acceleration capability allows U.S. maglev to have an average trip speed closer to its peak speed than TR07.

In principle, Transrapid could upgrade TR07 with a tilting vehicle body to improve curving performance and a larger LSM to increase grade climbing ability and peak acceleration. However, the former would involve a major redesign of the vehicle, an increase in roll stiffness of the magnetic suspension, and strengthened curved guideway beams. Upgrading the LSM may prove more difficult because the slots in the stator pack limit the diameter (and hence the current capacity) of the stator windings. While these improvements are possible, they would not occur without significant R&D time, costs, and risks.

4.2.3. Gap size

By using normal electromagnets, TR07 must operate with a small, 8-mm suspension gap. It must, therefore, maintain very tight guideway tolerances to avoid magnet contact and ensure adequate ride comfort. It achieves these tolerances by precision machining of steel guideway beams and using very conservative foundation designs. These measures come with significant cost penalties, including the inability to use conventional concrete beam construction. Tight tolerances also imply that even small earthquake deformations may require a costly system shut-down and realignment of beams. This could render TR07 impractical along several important U.S. corridors.

By comparison, all U.S. concepts operate with much larger suspension gaps (40–150 mm) by using powerful, superconducting magnets. Such large gaps provide greater design freedom—larger construction tolerances are permissible, as are more flexible guideways (provided active suspensions are used). Both effects can substantially reduce the cost of guideway structures (10–40%). Larger gaps also provide much more leeway in foundation design and much greater operational and safety margins in earthquake-prone regions. Indeed, earthquake considerations are thought to be among the reasons that workers in Japan elected to develop a large-gap EDS.

Typically, maglev vehicles may safely transit step irregularities about half as high as their gap clearance. For the U.S. systems, with their much larger gap, this implies greater tolerance of debris, snow, and ice, and guideway misalignment from earthquakes. Also, large-gap systems are less susceptible to thermal disturbances. As with HSR, U.S. maglev should be capable of higher availability than TR07 at similar safety levels. To ensure adequate ride comfort over very rough or flexible guideways, vehicles may require active suspensions (three of the four SCD concepts incorporate active suspensions). However, improvements in availability and reductions in guideway costs more than compensate for this added complexity.

4.2.4. Energy efficiency

Energy consumption can be the largest variable cost for high-speed ground transportation systems. Energy usage in transportation is also a national strategic concern. Systems with high energy efficiency are therefore more desirable, other factors being equal, than those of lower energy efficiency.

We have used energy intensity, EI (joules / standard-passenger-meter), as a measure for the HSGT systems studied here. 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 energy needed to accelerate the vehicle back 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) has similar drag coefficients as TR07. Its aerodynamic drag is lower because of its lower frontal area. Foster-Miller's higher energy efficiency also in part comes from 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.

4.2.5. Vehicle efficiency

All SCD vehicles will be built with modern aerospace construction techniques, and two of the four use advanced composite construction. Superconducting magnets also have greater lift per magnet-weight than TR07's normal electromagnets and do not require heavy backup batteries to ensure safe hover. Thus, despite including the vehicle tilting capability, U.S. maglev vehicles are lighter than TR07. On average, the SCD vehicles are 18% lighter per standard passenger than TR07, and the composite vehicles average 24% less mass per standard passenger. Composites also better resist fatigue and corrosion than does aluminum construction.

Lower vehicle mass improves energy efficiency and lowers guideway costs by reducing vehicle loads. Although composite construction currently carries a cost premium, system life-cycle costs may favor its use. Also, further developments in the aerospace industry should improve the cost effectiveness 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.

4.2.6. Switching

TR07's switch is a steel guideway section that is bent elastically in the turnout direction. This high-precision mechanical switch moves relatively slowly and may be susceptible to adverse weather effects (ice, blown sand, thermal expansion, etc.). These factors also suggest that TR07's switches will require frequent maintenance (inspections and adjustments).

Two of the SCD concepts (Foster-Miller and Magneplane) have electromagnetic switches that require no moving structural elements. They switch null-flux coils to guide their vehicles though turnouts. A third SCD (Bechtel) explored an electromagnetic switch as an alternative to their bendable-beam switch. Such electromagnetic switching can be very fast, leading to shorter possible headways. Without moving parts, these switches should also be less susceptible to adverse weather. They should thus require less frequent maintenance compared to mechanical switches. That is, U.S. maglev offers a potential for higher-performance, more-reliable guideway switches than TR07.

4.2.7. Higher speed potential

GMSA motor and suspension analyses showed that TR07 is near its speed limit at 134 m / s. 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), increasing performance demands on converter-station power electronics. As noted, stator slot width also limits the LSM current and hence its 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 had guideways built to TR07's tolerances, their suspensions could handle much higher speeds.

4.3 ADVANTAGES AND DISADVANTAGES OF U.S. MAGLEV CONCEPTS

As noted in Chapter 1, the goals of the GMSA were to assess the technical feasibility of maglev concepts, to assess their abilities to meet U.S. transportation needs, and to compare their performance potential with foreign HSGT alternatives. Neither the GMSA nor the National Maglev Initiative sought to pick a "winning" U.S. maglev concept. As reflected in sections 4.1 and 4.2, our interest was primarily in determining the range of technical capability represented by the SCD concepts.

Nevertheless, every technical approach to HSGT carries with it advantages and disadvantages. Through our modeling efforts and comparative assessments, these features became apparent. Sections 4.1 and 4.2 discussed the merits of the U.S. concepts compared with TGV and TR07. Here, we discuss the advantages and disadvantages of each SCD concept. We have made no attempt to rate these systems relative to each other. Again, this was not our goal, and it would not be meaningful at this concept-definition stage.

4.3.1 Bechtel

Advantages

- Octapole magnet configuration:
  - Fields fall rapidly with distance (reduces passenger shielding requirements).
  - Transferable to other concepts.
- Powerful LSM:
  - High acceleration throughout speed range reduces trip times (0.16-g acceleration maintained to 118 m / s).
  - Can climb 10% grade at 140 m / s.
- High magnetic lift / drag (magnetic *L/D* > 100 at 134 m / s):
  - High payload:weight ratio possible.
  - Low-speed liftoff out of stations does not require auxiliary support (assisted by vertical motor thrust to about 10 m / s).
- No landing wheels (air bearings used): this provides weight, reliability, and cost advantages.
- Fault-tolerant headway, suspension, and propulsion control:
  - Greater safety, reliability, and availability.
  - Six-phase LSM offers significant degraded-mode capability.
- Cable-in-conduit superconducting magnets:
  - Potential for greater stability, lower weight, and lower thermal losses.
  - No external leads needed.
- Sidewall null-flux levitation provides more than 3-g vertical derailment protection.
- Some flexibility in vehicle outer dimensions.
- Tilting inner cabin allows aerodynamically clean exterior.
- Door sizes and spacing, and interior dimensions, permit rapid loading and unloading.

Disadvantages

- Large aerodynamic loads (especially side loads) from wrap-around vehicle:
  - Low crosswinds limit for ride comfort and safety (lower weather-related availability).
  - Large aerodynamic drag per standard passenger (high energy intensity).
- Aerodynamic control surfaces:
  - Increased control complexity.
  - Susceptible to atmospheric turbulence.
  - Increased aerodynamic drag.
- Bending-beam switch:
  - Must be made of FRP (expensive, unproven durability).
  - Long cycle times.
  - Moving load-bearing parts (lower reliability, higher cost).
- May require FRP reinforcing rods:
  - Expensive compared with conventional steel rods.
  - Unproven durability of rods and anchorages.
- Tilting inner cabin increases weight and complexity.

4.3.2 Foster-Miller

Advantages

- Locally commutated linear synchronous motor (LCLMS):
  - High efficiency (short energized length).
  - Power transfer possible with same guideway coils and switches.
  - Very short headways possible, and it is easy to vary headways operationally.
  - Can use motor to bring emergency vehicle to a stationary vehicle.
  - Transferable to other concepts.
  - Individually controlled coils offer significant degraded-mode capability.
- U-shaped guideway:
  - Partially protects vehicle from crosswinds (improves safety and ride comfort).
  - Together with null-flux levitation, provides more than 3-g vertical derailment protection.
  - Yields low cross-sectional area, hence low aerodynamic drag.
- High-speed electromagnetic switch:
  - Load-bearing parts are stationary (low maintenance, high reliability).
  - Very fast cycle times possible.
- Magnets in bogies at ends of vehicles:
  - Reduces suspension weight.
  - Reduces frontal area and hence aerodynamic drag.
  - Separation from passengers reduces shielding requirements.
  - Permits simple pivot arrangement for tilting.
- Most well developed EDS levitation and guidance configuration, provides low development risk.
- High magnetic lift / drag (magnetic *L/D* > 140 at 134 m / s):
  - High payload:weight ratio possible.
  - Low magnetic losses.
  - Low-speed liftoff out of stations possible using vertical motor thrust (although not proposed by contractor).
- Series coupled propulsion coils for guidance:
  - High lateral stiffness.
  - Less complex than independent guidance configurations.
- High guideway roll stiffness.

Disadvantages

- High risk with LCLSM:
  - Critically dependent on high-volume cost reductions (factor of 10) for IGBT-based inverters rated for the required voltages and currents.
  - Unproven concept for vehicle control (requires real-time computer control of individual H-bridges).
- May require FRP post-tensioning rods:
  - Expensive compared with conventional steel rods.
  - Unproven durability of rods and anchorages.
- Bogie design increases dynamic amplification factor so that a stiffer guideway is needed to meet ride comfort criteria.
- Complex vehicle and bogie fairing needed to permit tilting.
- High liftoff speed proposed (50-m / s takeoff, 20-m / s landing). This requires low-speed equipment for normal operation, with associated weight, reliability, and cost penalties.
- Highest magnetic fields to mitigate (although the design achieved 1 G at a modest weight penalty).
- Vehicle width fixed by U-shaped guideway.
- At-grade U-shaped guideway susceptible to snow drifting.

4.3.3 Grumman

Advantages

- Large-gap electromagnetic suspension:
  - Active primary suspension offers potential to meet safety and ride-comfort constraints over rougher, more flexible (hence cheaper) guideways.
  - No secondary suspension needed (saves weight, cost, maintenance).
  - Integrated lift–guidance–propulsion saves weight, space, and cost (vehicle and guideway).
  - Active control of magnetic suspension avoids need for aerodynamic control surfaces (saves weight, complexity, and cost, and there is less influence of turbulence).
- Innovative spine-girder dual guideway:
  - Structurally very efficient, yields low cost for dual guideway.
  - At-grade guideway costs also low because inexpensive Y-shaped beams can be supported directly on piers.
- Conventional guideway materials and construction techniques:
  - No FRP needed.
  - Close tolerances needed only at Y-shaped beams (lowers cost for spine-girder and outriggers).

- Distributed magnets lower guideway stresses and dynamic amplification factors, giving a smoother ride for a given guideway roughness than bogies.
- Zero-speed levitation eliminates routine need for low-speed support (wheels, etc.).
- Low stray magnetic fields, so little or no shielding needed to meet 1-G level, which saves weight, and cost.
- Simple, conservative superconducting magnet design, having a good quench margin.
- Recompression of helium vapor avoids liquefying refrigerator, giving improved reliability and energy consumption.
- Small onboard power storage requirements since main levitation force derives from superconducting magnets

Disadvantages

- High-risk active primary suspension:
  – Demanding active control of electromagnets superimposed on superconducting magnets.
  – All control modes coupled.
- Wrap-around vehicle requires bending-beam switch:
  – Longer cycle times.
  – Mechanically complex, and susceptible to adverse weather.
- Large frontal area from wrap-around vehicle increases aerodynamic drag.
- Complex outrigger, slab girder (Y-shaped beam) and LSM attachments:
  – Some tensile stresses in concrete outriggers.
  – Tight packaging of LSM.
- Demanding packaging of superconducting and normal magnets:
  – Space limits iron-core size (Vanadium-Permendur near saturation).
  – Limited liquid helium reservoir.

4.3.4 Magneplane

Advantages

- Self-banking vehicle, so no tilting mechanism needed (saves weight, complexity, cost).
- Very smooth lift and guidance forces from sheet guideway.
- Trough guideway:
  – Provides some crosswind protection.
  – Permits small vehicle cross-section (low aerodynamic drag).
- High-speed electromagnetic switch:
  – Load-bearing parts are stationary (low maintenance, high reliability).
  – Very fast cycle times possible.
- Active suspension and very large gap:
  – Permits use of rough, flexible (hence less costly) guideway.
  – Gap of 150-mm provides significant tolerance to settlement and earthquake displacements before triggering safety- or ride-comfort-driven maintenance.
  – No secondary suspension needed (lower weight, complexity and cost).
- Simple guideway magnetics (sheet guideway):
  – Fewer attachments and adjustments needed.
  – Potentially low maintenance.
- Very short headway possible:
  – Electromagnet switch permits fast cycle times, high turnout speed.
  – High braking rate possible.

Disadvantages

- Expensive guideway:
  – Nationally significant aluminum content.
  – Most sensitive to energy prices.
- Aerodynamic control surfaces:
  – Increased control complexity.
  – Susceptible to atmospheric turbulence.
  – Increased aerodynamic drag.
- High magnetic drag:
  – High, nearly constant thrust requirements even at low speeds.
  – High liftoff (50 m / s) and landing (30 m / s) speeds increases performance demands on low-speed supports.
- Single LSM, no redundancy in phases, which increases the risk of single-point failure.
- Unproven low-speed air bearings, which is a substantially higher speed application of this technology than current state-of-the-art (about 5 m / s).
- Fewer suspension magnets, which means increased consequences of magnet failure.

4.4 KEY INNOVATIONS: RISKS AND BENEFITS

The SCD concepts contain numerous innovations in maglev technology. Many of these offer the potential for significant performance or cost advantage over existing German and Japanese technology. Naturally, these same innovations carry some development risk. Here, we summarize the key innovations revealed by the SCDs, describe their potential benefits, and indicate the level of risk associated with each. The order below is random.

4.4.1 LCLSM

Foster-Miller's locally commutated linear synchronous motor (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. Foster-Miller proposes to use fast IGBTs as the necessary switches for these inverters. The LCLSM could become a very significant innovation in vehicle propulsion.

This motor achieves very high efficiency (99%) because it energizes only that section of the guideway opposite vehicle magnets. By activating individual coils on a 0.86-m spacing, it provides very flexible thrust and regenerative-braking control of the vehicles.

Another significant advantage is the ability of the LCLSM system to operate in a degraded mode in the presence of disabled LSM coils. All coils are electrically connected in parallel with respect to the power source and disabled coils can be disconnected without adversely affecting the operation of the remaining LSM coils. This is in contrast to the more conventional blocklength LSM, where a failure of the LSM could disable the entire block (a few hundred to a few thousand meters in length) and either stop the system or severely curtail its operation until repaired.

The LCLSM also acts as the power-transfer mechanism, where the guideway coils form the primary of an inductively coupled system. The computer switches the guideway coils located between vehicle bogies from propulsion mode to power-transfer mode. Power is then inductively transferred to auxiliary power coils located between bogies on the vehicle.

Its principal risk is that the IGBT-based inverters are at present much too expensive for the LCLSM to be economical. Foster-Miller has argued that the large number of inverters needed (about 2400 / km of dual guideway) will enable mass production to reduce their cost by a factor of 10. This will be difficult to prove until there actually is mass production. However, any serious commitment to maglev development could become one of the device's major development drivers in much the same way that electrification in transit and railroads has driven the development of the GTO power electronics device. The historical trend in the costs of electronics, including power devices, has been downward, and there is no reason to think that this trend will reverse in foreseeable future.

Vehicle control with an LCLSM is also unproven. Issues include the LCLSM's ability to control acceleration and speed, and to maintain adequate lateral stability. Lateral stability may become a concern because the LCLSM, as currently configured, also provides the lateral guidance forces. Real-time computer control of the individual coils is also a demanding technical requirement. However, reduced-scale testing can address these issues sufficiently to establish the technical feasibility of the LCLSM in a reasonably short period.

4.4.2 Fiber-reinforced plastics

Two of the four SCD concepts (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 post-tensioning 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 to weight, high 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. Indeed, FRP rods become enabling technology for such concepts.

4.4.3 Active vehicle suspensions

Three of the four SCDs use some form of active vehicle suspension (actuators driven by control signals to minimize vehicle response to disturbances). With sufficient control authority and the proper control algorithm, an actively controlled vehicle can maintain a smooth ride over very flexible and rough guideways. This allows use of, respectively, less structural material and less stringent construction tolerances than would be the case for passively suspended vehicles. Both of these benefits significantly reduce guideway costs.

Modern control technology appears sufficient to ensure that active vehicle suspensions are technically feasible. Maglev's large magnetic forces make active control of the primary suspension an attractive option; Grumman selected this approach. Active control of aerodynamic surfaces is also an option, although unsteady air flow may complicate its implementation. For example, Bechtel's proposed side-mounted ailerons may not see clean air flow during crosswinds. However, overhead ailerons, similar to those proposed by Magneplane, may alleviate such concerns.

The main risks with active suspensions are their added weight, cost, and reliability penalties compared with passive suspensions. A reasonable R&D effort should minimize these risks. Small-scale testing of active magnetic suspensions should quickly demonstrate their feasibility. Similarly, wind-tunnel testing and computational fluid-dynamics may be used to establish the feasibility of active aerodynamic control.

4.4.4 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 such as guideway irregularities) and by varying currents in the superconducting magnets (for low-frequency disturbances such as payload changes and curves). With this suspension, the vehicle maintains good ride comfort and a safety margin over irregularities that are an order of magnitude larger than TR07's limits. This suspension also uses the same magnets and reaction rails to provide all necessary lift and guidance forces. These improvements offer the potential to simplify guideway design and construction, and increase allowable guideway tolerances to permit use of standard concrete beam construction. This system also incorporates desirable active control in the primary suspension, eliminating completely the need for a secondary suspension.

The main risks with this approach are with the details of the suspension itself. The control coils must deliver adequate control forces to ensure stability and safety under all possible conditions. The high currents needed must not induce excess losses in the superconducting magnets. Furthermore, the control algorithm must take advantage of the hardware's capabilities. These issues may be addressed quickly through laboratory testing of a complete magnet–control system. Also, an EMS suspension with integrated lift and guidance magnets is an unproven concept. Its verification may require complete vehicle tests at either full or reduced scale.

4.4.5 Power transfer

Both the Magneplane and Grumman concepts use the LSM stator winding as an inductive linear generator to transfer auxiliary power from the wayside to the vehicle. Their vehicles have power pickup coils directly opposite the LSM stator windings.

The Grumman concept uses high-frequency (600-Hz) single-phase power in conjunction with a linear generator. The single-phase power is injected into the LSM feeder cables, which also supply three-phase propulsion power. This single-phase current is a control that provides the dominant power transfer at low vehicle speeds. At high speeds, the linear generator, which uses the harmonics of the three-phase propulsion current, provides the dominant power transfer.

The Magneplane concept uses three-phase auxiliary current in the LSM winding that is connected 180° out of phase from the main propulsion current. This connection produces auxiliary-current traveling waves in the opposite direction to those of the propulsion currents. The opposite-direction traveling waves produce a slip frequency that transfers power from the from the LSM windings to the pickup coil.

Both concepts have potentially adverse effects on LSM performance, but they reduce onboard battery requirements and hence save weight. These concepts warrant reduced-scale investigation to demonstrate their feasibility and to establish cost to weight trade-offs.

4.4.6 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 ratio that is over 170. These are very efficient EDSs. Their benefits include lower energy consumption, higher payload to weight ratio, and lower liftoff and landing speeds. Indeed, Bechtel's

10-m / s liftoff speed allowed it to propose 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 EDSs offer low-speed support capability and low energy consumption, similar to EMS concepts.

4.4.7 Cable-in-conduit superconducting magnets

Superconducting magnets used to date for levitating test or prototype maglev vehicles are made with niobium-titanium (NbTi) superconductors immersed in liquid helium near its boiling point of 4.2 K. Since the refrigeration efficiency increases as the temperature of the refrigerant increases, it is desirable to operate the magnets at the highest temperature possible. In addition, it may be desirable to avoid the use of liquid helium in transportation—sloshing of the liquid can result in "flashing" or evaporation of the liquid as it comes into contact with surfaces at temperatures only marginally higher than it is.

The cable-in-conduit magnets proposed in some of the concepts offer the opportunity of operating at higher temperatures without liquid helium by using niobium-tin (Nb_3Sn) superconductors with supercritical helium as the coolant. This approach is not practical with NbTi, since the transition temperature of this material is too close to the temperature of the coolant (about 8 K). In this approach, many wires of Nb_3Sn conductor (a cable) are contained in a tube that is then wound to form the magnet. Supercritical helium is circulated through the tube to cool the superconductor.

From a refrigeration viewpoint, this approach could be much superior to the method of using NbTi cooled in a helium bath. However, vibratory levitation, guidance, and propulsion forces acting on the superconductors are a concern. Most NbTi magnets are completely potted in epoxies to avoid motion of the conductor, so forces are transmitted to the entire body of the magnet through the epoxy. This will not be possible in a cable-in-conduit magnet, since coolant must circulate through the windings contained in the tube, and epoxy would block its flow.

Furthermore, Nb_3Sn is a brittle intermetallic compound that is much more subject to fracture than NbTi. To mitigate this problem, hundreds or thousands of filaments of Nb_3Sn are often contained in a copper matrix, so that the overall conductor is much more flexible than a single Nb_3Sn conductor of the same diameter. Also, the SCD designs propose swaging the conductors inside the conduit. Still, the conductors appear to be susceptible to flexing, and any resulting filament breakage would reduce the critical current of the conductor.

The adequacy of the safety and reliability of cable-in-conduit conductors used with superconducting magnets has not been demonstrated, but the benefits appear sufficient to warrant detailed analytical and experimental evaluations.

4.4.8 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 for TR07 for a given switch length.

4.4.9 Spine-girder dual guideway

Grumman has proposed an innovative dual guideway concept called a spine girder. A central structural "spine" girder carries a narrow Y-shaped EMS guideway along either side on outriggers. Government cost estimates confirm that this is a very efficient structure in terms of performance and cost. Indeed, it is responsible for Grumman's 20% cost advantage over TR07's guideway (also an EMS concept).

Its risks appear to be limited. Detailed stress analysis and design optimization are needed to ensure that tensile stresses in the concrete outriggers are within allowable limits for durability. Also, adequate alignment of the Y-shaped guideways on the outriggers must be achievable and maintainable, although Grumman's large-gap EMS permits fairly loose alignment tolerances. Lastly, high-speed air flow past the outriggers may induce unacceptably large vehicle drag; mitigating this effect will require detailed aerodynamic modeling (and may lead to fairing of the outriggers).

4.4.10 Air bearings

Two of the three EDS concepts (Bechtel and Magneplane) proposed using air bearings for low-speed support rather than wheels. Such bearings, which have been used for very low speed (less than 5 m / s) support of freight pallets, use 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. They offer a potential for lower weight, cost, and stresses relative to conventional wheels.

Their main risk is that the application here requires support at speeds that are 2–10 times higher than common for existing air bearings. That is, they will require further work to be applied to maglev vehicles. Also, the mating guideway surface must be fairly smooth and well aligned to minimize air flow requirements and ensure adequate support pressure. Such issues should be resolvable with laboratory and reduced scale tests.

4.4.11 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 reliquefy it. They replenish the liquid helium as a daily maintenance operation. This avoids the need for a reliquefying onboard refrigerator that uses much energy and is unreliable; 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. The vehicle is charged daily with liquid helium, which resides in a sealed reservoir–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 cryo-refrigerator to keep the supercritical helium in the working temperature range. However, the energy required to do so is much less than that needed to reliquify the helium, and the refrigerator needed is much more reliable.

Provided that they allow adequate liquid helium storage and minimize sloshing, the Foster-Miller and Grumman approaches carry little risk. Magnets of this type may be tested as an assembly in a laboratory. The two cable-in-conduit magnet concepts carry an additional risk associated with the brittleness of Nb_3Sn superconductors. This material will not tolerate high cyclic stresses, so that load variations caused by moving vehicles must be examined. Such testing can also be conducted in a laboratory but would likely require validation at reduced or full scale.

4.5 SPECIFIC TECHNICAL ISSUES

In conducting its work, the GMSA team has gathered and analyzed technical data pertaining to high-speed rail (TGV), a commercially ready maglev system (TR07), and four well-defined U.S. maglev concepts. Here, we apply this knowledge to address a number of technical issues frequently raised concerning the viability of maglev for the U.S. market. Where appropriate, we may again judiciously aggregate the performance characteristics of the four SCD concepts and consider some issues as they pertain to a generic U.S. maglev concept.

4.5.1 What is the feasibility of routing HSGT along existing transportation and utility rights-of-way?

The routing of maglev along existing ROW was contemplated early in the NMI program. Indeed, the SCD-RFP reflected this possibility by containing system criteria appropriate to such routing. Thus, we find that all SCD concepts can negotiate very tight curves, possess very good performance in curves at high speed, climb steep grades, and accelerate very quickly to full speed. Without question, generic U.S. maglev is significantly better suited to routing along existing ROW than either TGV or TR07 in their present forms.

TGV is unlikely ever to be well suited to this mission. Traction limits its maximum acceleration and grade-climbing ability; its modest 7° superelevation and nontilting body limit maximum speeds in curves. These limitations would require very significant R&D investment to overcome. Although other HSR systems incorporate tilting vehicles, none achieve even TGV's 83-m / s service. Safety may limit HSR cornering speeds—the higher guidance forces needed for high-speed cornering may be beyond the capability of standard-gauge rail.

TR07 could be more easily adapted to this mission. LSM and power system capacity limit its maximum acceleration and grade-climbing ability. These are subject to design trade-offs, although ultimately the size of the stator slots limits stator current and, hence, maximum thrust. As with U.S. maglev, wheel–rail contact does not limit TR07's cornering speeds. However, significant R&D investment (for both vehicle and guideway) would be needed to incorporate vehicle tilting to increase TR07's curving performance. Increased roll stiffness of the magnetic suspension would be needed, as would stronger, curved guideway beams.

As noted earlier, U.S. maglev vehicles are about 20% lighter than TR07 vehicles, despite having tilting capability. If straight maglev routes become the norm so that tilting vehicles become unnecessary, U.S. maglev vehicles could be made even lighter. This would reduce both vehicle and guideway costs (lighter vehicles deliver smaller loads to the guideway).

The superiority of generic U.S. maglev here is an example of good engineering practice—define the problem you wish to solve, specify the characteristics that the solution must possess to be acceptable, then develop the product that possesses these characteristics. This process invariably leads to better results than attempting to use existing products to solve problems that they were not specifically designed to solve.

4.5.2 Can HSGT be constructed along existing rights-of-way?

HSR's cost advantage over maglev is for at-grade construction. But this poses problems along existing ROW where numerous grade separations will be necessary. The structures needed for grade separation of HSR (viaducts and tunnels) are expensive and hence erode HSR's cost advantage.

Maglev vehicles are lighter and more easily elevated than trains. Only support columns need intrude on an existing ROW. Also, maglev construction can be highly automated and modular. Essentially, only footings must be constructed at the site. Piers may be prefabricated and guideway beams certainly will be. This type of modular construction offers the potential for minimal disruption of collocated services. In particular, overhead construction permits much lower impact on ROW entry–exit points and existing bridges than does at-grade construction.

4.5.3 What design features or construction methods will reduce maglev guideway costs?

Maglev guideways will benefit from several basic cost-saving measures. All guideways are highly modular, making them naturals for high-volume, automated production. Most concepts use concrete beams. Over time, such beams will drop in cost or increase in performance because of general improvements in high-strength–low-weight concrete and the fabrication methods being pursued throughout the construction industry.

Both TR07's steel beams and Magneplane's aluminum ones also lend themselves to automated production and should drop in price with time. Unfortunately, steel and especially aluminum are much more sensitive to energy prices than is concrete.

Because maglev is a new technology, guideway designs incorporate conservatism owing to unknown loads. As these loads become better established, guideways will become more efficient and hence less costly.

Lastly, near-grade guideways, where applicable, offer the potential for significant cost reductions. Maglev offers the potential for normally elevated guideways where they are necessary but will benefit from lower costs where they are not.

4.5.4 What advanced construction materials and techniques are likely to improve guideway performance and reduce costs in the long term?

Several emerging technologies appear likely to improve guideway performance and reduce costs in the long term. By its conservative nature, the construction industry has been slow to develop and adopt these technologies. However, maglev's guideways are its most expensive component; any improvements will pay large dividends. Thus, maglev will be a significant driver for innovation in the entire construction industry. Other sectors of the industry will benefit as a result.

- All SCD-EDS concepts avoid the use of steel reinforcing in the vicinity of their powerful superconducting magnets. The resulting demand for FRP rods to post-tension concrete will be by far the most significant construction use of this material. The performance and cost of the various FRP rods will undoubtedly improve with time.
- In essence, maglev represents a high-tech, high-volume application of the most basic of construction materials: concrete. It will thus accelerate the development of high-strength–low-weight concrete, including fiber-reinforced concrete.
- At present, composite materials have found commercial use primarily in the aerospace industry. Although they are currently much more expensive than concrete and steel as structural materials, this could change with further development. Maglev vehicles will likely use advanced composite structures, and

guideway switches may also. Maglev's high-volume demand will spur development of more efficient, cheaper fabrication methods. Because they possess tremendous performance advantages, composite materials could eventually become the preferred choice for maglev guideways.

- New, so-called "smart materials" have recently emerged. These materials fall into categories according to their properties. Some provide self-diagnostics for structural integrity; others self-heal small fractures or surface damage; still others vary their mechanical properties such as stiffness and damping in response to applied signals. Again, maglev will represent a high-volume application for these materials.
- To avoid disruption along an existing ROW, maglev will likely use cantilever (bridge) construction off the end of the guideway. This construction method will become more efficient and less costly with wide-scale application.

4.5.5 What methods exist to minimize maglev's stray magnetic fields?

Stray magnetic fields represent perhaps the greatest uncertainty in eventual public acceptance of maglev. However, several design options exist to minimize these fields:

- *Maglev approach*—EMS concepts use iron-core magnets that intrinsically concentrate magnetic fields near the magnets. They thus generate much smaller stray fields both inside and outside of vehicles than do EDS concepts. However, EMS iron-core magnets carry a weight penalty relative to EDS air-core magnets.
- *Magnet grouping*—Grouping magnets so that their poles alternate causes stray fields to drop very rapidly with distance. This reduces field strengths both inside and outside of vehicles. All three SCD-EDS concepts take this approach, and they require no shielding to achieve less than 50-G static fields in passenger seating areas.
- *Distance*—Stray fields drop rapidly with distance. Thus, two of the three SCD-EDS concepts contain magnets in bogies located at the ends of vehicles, as far as possible from passenger seating areas. The other SCD-EDS concept makes the vertical separation of passengers above distributed magnets as large as possible.
- *Diamagnetic shielding*—Good conductors such as copper resist the penetration of AC magnetic fields by establishing eddy currents that generate opposing fields. A superconductor will in fact resist all magnetic field penetration (DC and AC) provided the incident fields are sufficiently small. High-temperature superconductors might soon be available for the task of passenger-compartment shielding.
- *Bucking coils*—Energized copper coils may be placed over magnet bogies or at bulkheads to generate opposing DC magnetic fields. Such coils provide very effective shielding with modest weight, cost, and power penalties. Coils of high-temperature superconductors may soon be available that will fully shield 10-G fields at bulkheads. Such coils would incur very little penalty by using inexpensive liquid nitrogen for cooling.
- *Ferromagnetic shielding*—Ferromagnetic materials such as iron and steel may be incorporated into a vehicle's structure to reduce stray fields in passenger seating areas. Indeed, Foster-Miller incorporated a ferromagnetic box shield to meet the 1-G limit with a modest weight penalty (2000 kg or 3% of baseline consist mass). Despite this, their vehicle is 20% lighter per standard passenger than TR07. Ferromagnetic materials may also be incorporated into station platforms to shield passengers entering and exiting vehicles. Here, the weight penalty is not an important issue, although the magnetic forces attracting the vehicle to the shield will be significant and must be accommodated.
- *Exposure limits*—Prudent operation of a maglev system may include limits on the duration of exposure to very high fields. For passengers, these would occur during entry and exit and will require careful station design. Consideration of exposure limits for crew and maintenance personnel will also be necessary. Design considerations might include extra shielding around galleys, placement of inspection and service hatches away from magnets, etc.

4.5.6 What are the advantages and disadvantages of various maglev propulsion options?

Several options exist to propel maglev vehicles along guideways. Here, we discuss only electric motors using the vehicle and the guideway as the two halves of a motor (an active primary and an active or passive secondary). Other propulsion options, such as jets, turbofans, or electrically driven fans, generally are less efficient, more noisy, and require greater maintenance to overcome mechanical wear. Also, use of electric power permits flexibility in selection of the generating source (fossil, nuclear, hydro, etc.) and control of pollution from that source.

As with the construction industry, the electric power industry is very conservative. Maglev will be a significant driver for the development of low-cost, high-power electronics. This will bring down the cost of power conditioning over time, which should in turn improve the performance and reduce both the capital and operating costs of maglev motors.

Long-stator linear synchronous motor (LSM)

This motor has its primary or stator windings imbedded in the guideway; energized magnets on the vehicle are the secondary. These magnets may be ones also used for generating lift or may be separate propulsion magnets. The wayside power supply energizes long sections of the stator windings (typically a few kilometers) and generates a traveling magnetic wave that pulls the vehicle along. The vehicle remains synchronous with this traveling wave. TR07 and all four SCD concepts employ a long-stator LSM.

Advantages.

- Avoids the critical need to transfer high power for propulsion to vehicles traveling at 134 m / s.
- Vehicles are lighter and less costly because power conditioning equipment is along the wayside.

Disadvantages.

- Guideway capital costs are high because of frequently spaced power supplies.
- Wayside power supplies occupy significant land areas.
- Peak capacity of the system is constrained by stator current density and, ultimately, stator slot width; increasing it would require a change-out of the entire stator pack.

Short-stator linear induction motor (LIM)

The LIM has its active primary on the vehicle (a short length of stator windings) and uses a passive secondary on the guideway (typically iron structures). The vehicle must pick up propulsion power from the guideway and condition it on board. Such motors are well proven for low speeds, and several people-movers use LIMs for both propulsion and levitation.

Advantages.

- Less expensive guideways (assuming costs for power transfer equipment and motor secondaries are less than long stator windings and additional wayside power supplies).
- Simpler, cheaper wayside power distribution because all frequency conversion occurs on vehicles.
- May increase peak capacity by allowing additional vehicles without the need to change-out guideway power equipment (although this has not yet been proven for very high system capacities).

Disadvantages.

- High power transfer to vehicles at high speeds is an enabling technology. Extensive R&D would be necessary to develop reliable and cost-effective multi-megawatt power transfer at 134 m / s. It is unlikely that pantograph–catenary power transfer will work satisfactorily at such high speeds.
- Vehicles are more expensive and heavier because of onboard stator and power conditioning equipment.

Other LSMs

Several experimental linear motors exist that use passive secondaries. The secondaries are typically made of iron and would mount on the vehicle to avoid the limitations of high-power transfer technology. These motors include the homopolar LSM and the transverse flux LSM (in the European literature sometimes called the magnetic river). Each of these concepts have been shown experimentally to provide thrust, levitation, and lateral control capabilities. Attractive because of their simplicity over conventional iron- and air-core LSMs, these machines warrant R&D to determine their costs and performance compared with conventional LSMs.

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