CHAPTER 3. APPLICATION OF EVALUATION PROCESS

As noted, the GMSA's main role was to assess the technical viability of maglev for use in the U.S. This assessment addressed issues concerning the feasibility of the technical approach, the suitability of the concept to a desired transportation mission, and the possible advantages of U.S. maglev vs. foreign alternatives. To this end, we developed an evaluation process consisting of four main steps:

1. Application of the maglev *System Concept Definition-Request for Proposals* (USDOTFRA 1991, hereafter SCD-RFP) system criteria as assessment criteria (section 3.1).
2. Verification of subsystem performance (section 3.2).
3. Verification of system performance (section 3.3).
4. Application of other criteria (section 3.4).

These four steps gave us a common way to assess all aspects of the technical viability of each concept. They also generated the data necessary to support our conclusions. We evaluated both TGV-A and TR07 as baseline concepts and the four SCD concepts as representative U.S. maglev systems. This chapter describes the methodology used for each evaluation step and presents the results for each system studied. Chapter 4 presents our conclusions based on this work.

3.1 SYSTEM CRITERIA*

3.1.1 Source and rationale

The NMI's SCD-RFP sought a "system level conceptual definition and analysis effort resulting in a description of all the major subsystems and components of a maglev transportation system ..." It provided a mission statement (USDOTFRA 1991, sections C-2.2 and 2.3) defining how the NMI viewed the role for maglev in the national transportation network. It also contained a more specific set of system criteria (USDOTFRA 1991, section C-3.1) that described required or desirable performance characteristics of a maglev system, its vehicles, and guideways.

Participants in a July 1990 workshop at Argonne National Laboratory developed these maglev system criteria by consensus. They were intended to guide the SCDs towards performance characteristics thought to be important for maglev to fulfill its transportation mission. We adopted these criteria as assessment criteria for this very reason; measuring a concept against these criteria gives one indication of how well it fulfills its mission. Furthermore, by checking SCD characteristics against the TGV and TR07 baselines, we may assess each U.S. concept's potential for superior relative performance. This process thus provided us with data on both the mission suitability and the relative advantages of each concept's technical attributes.

3.1.2 Application

For each SCD-RFP system criterion, we developed both qualitative and quantitative cross-checks on the stated performance of TR07 and the four SCD concepts. Because of its proven commercial record, we accepted TGV data as fact. We examined technical data used to derive these performance characteristics and cross-checked such data against those of closely related characteristics. For SCD concepts, we also examined the contractors' modeling methods and trade-off analyses used to justify each performance characteristic.

As done in the SCD-RFP, those criteria followed by MR (minimum requirements) are performance specifications that a system must meet to be acceptable. Those that are preceded by DG (design goals) are target performance levels and are considered important but not essential conditions of acceptability. We recognized this distinction for evaluation by prioritizing the system criteria (high, medium, low). We also assigned a numerical weighting to these priorities: high = 3, medium = 2, low = 1.

The following three subsections show our use of the SCD-RFP system criteria list as a technical-viability evaluation step. Listed first for each criterion is its description from section C-3.1 of USDOTFRA (1991). Next are the cross-checks that we developed to assess concept performance against the criterion. Lastly, for each criterion, we prepared a table containing the actual assessments for TGV, TR07, and the four SCDs. Each assessment consists of a descriptive component and a numerical rating as derived in Table 3. The product of the rating and the priority values forms the net result for the assessment.

* Written by Dr. James Lever, CRREL.

Table 3. Numerical rating scheme.

Rating	*Score*
1. Can't evaluate concept against criterion	0
2. Concept doesn't meet criterion	–1
3. Concept meets criterion	1
4. Concept exceeds criterion	1.2

Table 4. Actual assessments for speed.

System	*Evaluation comments*	*Rating*
TGV-A	83 m / s service speed Tested at 133 m / s sustained speed, 143 m / s downhill Operates at full speed through switches (demonstrated 143 m / s), operates at 64 m / s along turnouts Speed through curves limited by nontilting body and 7.15° superelevation of track Insufficient residual acceleration to achieve 134 m / s in reasonable time Brakes not designed for 134 m / s Significant power transfer and maintenance issues must be resolved to achieve 134-m / s cruising speed in commercial service Significant additional investment needed to meet criterion	–1
TR07	TR07 demonstrated 121 m / s on test track Motor analyses indicate that concept can achieve 134 m / s Thrust capability motor limits operation on 10% grade to very low speeds (about 14 m / s) Structural analyses indicate guideway is capable of supporting 134-m / s loads Vehicle-dynamics model confirms that vehicle can meet ride-comfort criteria and can safely maintain gap at 134 m / s Switch through-speed demonstrated at 112 m / s (probably can do 134 m / s), demonstrated turnout speed of 56 m / s Speed through curve limited by nontilting body and 12° guideway tilt (min. radius of 5800 m at 134 m / s with 0.10-g unbalanced lateral acceleration)	1
Bechtel	Motor analysis indicates sufficient power and reserve acceleration to exceed 134 m / s Thrust capability enables 134-m / s sustained speed on 10% grade Structural analyses show guideway to be strong enough, but FRP reinforcing is unproven Vehicle dynamics not verified owing to insufficient detail on active suspension in final report Primary suspension has required lift and guidance forces	1.2
Foster-Miller	Motor analysis indicates sufficient power and reserve acceleration to exceed 134 m / s Thrust capability enables 100-m / s sustained speed on 10% grade LCLSM is unproven and must work as intended Structural analyses show guideway to be strong enough, but FRP post-tensioning tendons are unproven and must work Vehicle-dynamics model shows need for tuning of passive secondary suspension, but should not pose problems Primary suspension has required lift and guidance forces	1.2
Grumman	Motor analysis indicates sufficient power and reserve acceleration to exceed 134 m / s Thrust capability of 60-kN baseline motor limits operation on 10% grade to very low speeds (about 5 m / s) Structural analyses show guideway to be strong enough, steel reinforcing adequate Control of primary suspension may not capitalize on large gap, but vehicle should meet ride-comfort and safety requirements at 134 m / s Lift, lateral-guidance, and roll forces are adequate	1
Magneplane	Motor analysis indicates sufficient power and reserve acceleration to exceed 134 m / s Thrust capability enables 90-m / s sustained speed on 10% grade Need to correct power factor, conduct cost vs. performance trade-offs Structural analyses show guideway to be strong enough Vehicle suspension relies on active aerodynamic control surfaces—this system requires significant engineering research for implementation (actuators, control software, etc.) Lift and guidance forces are probably adequate (unable to verify magnetic keel effect, but it seems reasonable)	1.2

System Requirements

*Speed (DG)**. A cruising speed of 134 m / s (300 mph) or more is desirable. The cruising speed for a particular system is the result of trade-offs of route alignment, power supply capacity, and passenger throughput, along with other parameters. The maglev system speed should be sufficient to allow total trip times equal to or better than those achieved by current commercial air systems.

This is a high priority item. We checked the following:

- Aerodynamic drag, magnetic drag, motor drag.
- Motor thrust, power consumption.
- Vehicle structural capability (load transmission).
- Guideway structural capability, including bending and torsion.
- Acceleration achievable, including residual at 134 m / s.
- Reserve thrust in headwinds.
- Guidance force available in crosswinds.
- Increased drag in crosswinds.
- Aerodynamic consequences of tilting vehicles.
- Considerations given to tunnel design.
- Induced drag from vertical lift, lift in curves.
- Control implications from aerodynamic loads (damping, vortex).
- Dynamics related to vehicle–guideway geometry.
- Speed though switches.
- Time and distance to achieve 0 to 134 m / s.

Table 4 gives the evaluation comments and ratings for speed.

Capacity (DG). Capacity should be in the range of 4,000 to 12,000 passenger seats per hour in each direction. The lower figure would be appropriate with a guideway of low cost. The higher figure would appear to be required to serve the very highest volume markets, possibly with some increase in capital cost.

This is a high priority item. We checked the following:

- Vehicle headway and braking requirements.
- Vehicle capacity.
- Power system capacity.
- Cyclic loading capability of motor. (Data or past experience?)
- Cyclic loading capability of power supply.
- System control.
- Cycle time on switches, including mechanical movement, acknowledgment of safe closure, response time to problems, transit speed through switch.
- Passenger and baggage handling time implications, dwell time.
- Operational strategy, control system characteristics.
- Effect of power consumption on electric utility.

Table 5 gives the evaluation comments and ratings for capacity.

Ride comfort. The NMI forwarded new ride-comfort guidelines to the SCD contractors following awarding of the contracts. These set design goals and minimum requirements for ride vibration and motion sickness, and added a seated–belted category for curving performance and jerk. See Appendix A for these requirements.

This is a high priority item. We checked the following:

- Suspension system analysis.
- Guideway tolerances and flexibility.
- Banking, tilt control.

Table 6 gives the evaluation comments and ratings for ride comfort.

Noise and vibration (DG). The noise and vibration produced by total system operation should be designed to meet existing Federal standards and industry practices, as appropriate, for stationary facilities such as maintenance areas and stations. Noise and vibration produced by the vehicle traversing the guideway should be minimized. Potential noise and vibration effects and possible mitigation methods in urban areas should be given special attention. The Code of Federal Regulations, Title 40, Chapter I, part 201, *Noise Emission Standards for Transportation Equipment; Interstate Rail Carriers*, should be used for guidance but caution must be used in extrapolating such information to high-speed operations at or near grade.

This has been given a medium priority. We checked Transrapid data for comparison and the BAA on this topic. However, this criterion was not usable for our evaluation. The Federal Code permits speed reduction or abatement measures. More useful evaluation would be to compute noise emissions at 134 m / s, but this is beyond our scope. So, Table 7 contains comments only.

* DG means that this item is a design goal, and MR means that it is a minimum requirement.

Table 5. Actual assessments of capacity.

System	*Evaluation comments*	*Rating*
TGV-A	4-minute headway, large train capacities including bilevel cars Can now do 14,550 seats / hr at 83 m / s, will do 22,000 seats / hr with bilevel cars	1.2
TR07	Can meet 12,000 seats / hr with current concept (no guideway upgrade needed); e.g., six vehicle-consist every 3 minutes 57-second minimum headway Power supply and motor can meet demand, but current densities would be 50–100 times higher than standard practice—reduces life of conductor (potentially significant cost issue) Cannot easily increase conductor diameter because of limited slot width	1.2
Bechtel	36-second minimum headway Uses 120-passenger (all coach-class) vehicles to meet capacity using 36-second headways Guideway strength O.K. with larger vehicle Unable to analyze vehicle dynamics	1
Foster-Miller	55-second minimum headway Six-car consists at 2-minute headways will meet 12,000 seats / hr (headway well within capability of switch) Could run vehicles very close together (nose-to-tail) if locally commutated motor could take cycling Cost analysis accounts for frequent replacement of LCLSM coils due to high current densities Structural analyses show guideway can handle four-car consists, should also handle six-car consists Vehicle dynamics should be O.K. with six-car consists, provided secondary suspension is correctly tuned	1.2
Grumman	30-second minimum headway Three-vehicle consists at 45-second headways will meet 12,000 seats / hr, can add more vehicle modules Guideway structure O.K.	1.2
Magneplane	45-second minimum headway using power leap-frog strategy, 20-second minimum headway with each block fully powered 42-second headways needed to reach 12,000 seats / hr with single (140-passenger) vehicles	1.2

Magnetic fields (DG). Human exposure to steady and fluctuating magnetic fields must be minimized. So, current research findings must be examined. This is a high priority item. We checked the following:

- Approach to field control.
- Modeling methods used.
- Results with independent calculations (Government models).
- Approaches and cost to achieve the following levels at floor level where passengers and crew are seated (USDOTFRA 1991, section C-3.2.1): 1) maximum 50-G static and 1-G alternating fields, 2) maximum 5-G static and 1-G alternating fields, and 3) maximum 1-G static and 0.1-G alternating fields.

We reviewed all available models and the BAA on this topic. We can analyze static fields, but alternating fields are beyond our scope. We calculated static stray fields for stationary vehicles for all EDS concepts examined. These are worst-case fields—currents induced by vehicle motion generate canceling magnetic fields. At cruise speeds, stray fields in EDS concepts will be much smaller than values cited here. Table 8 gives the evaluation comments and ratings for magnetic fields.

Weather (DG). Operation should be compatible with all common U.S. weather conditions (e.g., wind, snow, rain, fog, icing, heat, lightning, etc.) with minimal degradation in system performance. In the region of operation, maglev should be the transportation mode least affected by adverse weather conditions.

In addition to the foregoing, some contractors requested and received guidance on wind conditions suitable as input to guideway structural analyses and vehicle dynamics calculations. This guidance is reproduced in Appendix B.

This item has been given a medium priority. We checked the following:

- Guideway configuration for susceptibility to weather.
- Concept of operations (mitigation, control system response).
- Sensors used for hazard detection, integrity monitoring.
- Susceptibility to blown abrasive or magnetic material.

Table 6. Actual assessments of ride comfort.

System	*Evaluation Comments*	*Rating*
TGV	A good ride experienced by team member at 83 m / s Ride comfort at 83 m / s is clearly commercially acceptable and it meets or exceeds design goal of ISO 1-hr reduced-comfort limits Good ride requires very tight tolerances (i.e., rigorous rail and wheel maintenance) and stiff rail bed	1
TR07	Uses a linear, passive secondary suspension between magnet bogies and vehicle body, so can't relax guideway flexibility (as analyses show) Ride comfort (not magnet clashing) governs guideway flexibility Meets most criteria (Appendix A) Good ride requires very tight tolerances and stiff guideway	1
Bechtel	Requires active aerodynamic control surfaces Also uses an active secondary suspension—details not available in final report (although contractor claims ride comfort is acceptable) Without secondary suspension details, we cannot confirm that vehicle meets ride-comfort criteria	0
Foster-Miller	Discrete coils cause ripple in lift, guidance, and low-speed thrust forces, but these are probably smoothed out by suspension Very stiff guideway required for use with passive secondary suspension (and to lesser extent discrete-bogie vehicles) Passive secondary suspension needs tuning, but not likely to be a problem	1
Grumman	Single active suspension, large gap Has potential to achieve acceptable ride over rough and flexible guideways, but control algorithm does not appear to capitalize on this potential Can be made to meet ride comfort with simple control algorithm, but requires guideway comparable to TR07	1
Magneplane	Sheet guideway (smoother forces) Single, semi-active suspension (active damping using aerodynamic control surfaces and LSM phase angle) Hardware to achieve active aerodynamic damping is critical and may push state-of-the-art Must use coordinated turns (reduced speed through turn puts vehicle in wrong place) Nevertheless, expect vehicle to meet ride-comfort criteria	1

Table 7. Comments on noise and vibration.

System	*Evaluation comments*
TGV	Maintenance needed to meet ride quality; also keeps wheel rumble low Nevertheless, wheel–rail contact produces additional noise that can predominate at low speeds
TR07	Noise appears to be acceptable (lower than HSR at low speeds, comparable at high speeds)
Bechtel	Wings for aerodynamic control are noise sources
Foster-Miller	Diaphragms are potential noise sources
Grumman	Outriggers are potential noise sources Control of suspension at 70–80 Hz may transfer guideway irregularities to vehicle
Magneplane	Wings for roll control are noise sources

Table 8. Actual assessments of magnetic fields.

System	*Evaluation comments*	*Rating*
TGV	DC fields not an issue	1
	Dietrich and Feero (1992) and Dietrich et al. (1993) did not measure TGV fields	
	Check fields for Amtrak, which uses 12 kV, 60 Hz (versus 25 kV, 50 Hz for TGV)	
	Catenary fields important, as could be fields from 25-kV trainline in roof of cars used to transfer power from single catenary to second powered car	
TR07	Iron-core magnets inherently confine fields	1
	Dietrich and Feero (1992) and analyses agree	
	Measured static field maximum of 1.5 G at floor level	
	Mean static field at floor below 1 G	
	Not sure how Earth's field of 0.5 G influenced these measurements	
	Measured alternating field maximum of 0.25 G	
	Mean alternating field below 0.1 G	1
Bechtel	Distributed magnets well below passengers	
	Analysis shows about a 31-G static field at floor without shielding (meets 50-G limit unshielded)	
	5-G level met with active shielding coils (1 kW extra power, 500 kg or 0.8% extra weight, $55,000 or 1% extra cost for vehicle)	
	1-G level met with active shielding coils (2 kW extra power, 1500 kg or 2% extra weight, $165,000 or 4% extra cost for vehicle)	
	Baseline vehicle weight does not include shielding coils	
Foster-Miller	Very high fields over bogies (walkway–baggage compartment)	1
	Power transfer coils along center of vehicle also of concern	
	Passengers seated away from bogies	
	Analysis shows about a 20-G static field at floor without shielding (meets 50-G limit unshielded)	
	5-G limit met with ferromagnetic box (800 kg or 1% extra weight for baseline vehicle)	
	1-G limit met with ferromagnetic box (2000 kg or 3% extra weight for baseline vehicle)	
	Baseline vehicle weight includes 2000 kg shield for 1-G limit	
Grumman	Iron-core magnets inherently confine fields	1
	Static fields about 1 G at a distance of 1 m above magnets and 1.5 m to side	
	Minimal or no shielding required to meet 1-G level	
Magneplane	Fields in cabin above bogies very high, passengers seated away from bogies	1
	50-G limit met with no shielding (maximum 50 G at floor of first row of seats)	
	5-G level met with active shielding coils (22 kW extra power, 2300 kg or 5% extra weight for vehicle)	
	1-G level met with active shielding coils (33 kW extra power, 3400 kg or 7% extra weight for vehicle)	
	Baseline vehicle weight includes 2400 kg shield for 5-G limit	

We also reviewed existing DOT guidelines, as well as the BAA, on sensors. Table 9 presents the evaluation comments and the ratings for weather effects.

Controls (MR). All controls must be fully automated and fail-safe (DG). A central facility will operate the system, receiving and integrating data regarding the status and integrity of all vehicles and guideways, the locations of all vehicles, guideway power requirements, vehicle routing requests, etc. (MR). The system control software must also be fail-safe, equivalent to the level of reliability defined by the Federal Aviation Administration (FAA) for flight control software for military and civilian aircraft.*

* See *Federal Aviation Regulation* 25.1309, *Amendment* 25-23 and *Advisory Circular* 25.1309-1.

This is a high priority item. We checked the following:

- Methodology—fault tolerance.
- Response to faults.
- Results with available tools.
- Operating strategy.
- Redundancy management, containment of faults.
- Availability and reliability estimates.

In addition, software design for fault tolerance requires very specific approaches but we were not able to assess quantitative level of reliability. We considered the methodology used for fault tolerance (with guidance). Table 10 provides the evaluation comments and ratings for controls.

Safety (MR). A system safety plan must be included that discusses possible failure modes,

Table 9. Actual assessments of weather effects.

System	*Evaluation comments*	*Rating*
TGV	TGV has experienced some wind-related damage; modified catenary and pantograph as a result Train slows down when winds exceed 19 m/s because of catenary dynamics Icing also affects catenary dynamics Train may be slowed at operator's request because of low visibility in fog, heavy rain, or snow Reduced adhesion likely in heavy rain, snow, and ice; may reduce braking performance (although thresholds for reduced performance not known) Dust increases maintenance Must manage thermal expansion for continuous rails Very well grounded—good lightning protection	1
TR07	40-GHz communication link examined—may have some attenuation problems in wet snow, sleet, and rain Redundancy in control system—communication link with vehicle not required Icing on guideway a potentially serious problem (small gap) Emergency braking skids may not be as effective when wet or icy Good lightning protection, small LSM gap is preferred path to ground	1
Bechtel	Recesses in guideway may accumulate snow and ice Smallest gap, 50 mm, still quite large but will be reduced by icing Tallest vehicle (5.3 vs. 4.1 m for TGV) Active aerodynamic control will be affected by windshear and icing Wind-induced yaw moment is design limit for primary suspension (full-speed operation for lateral winds less than 18 m/s, reduced speed operation for lateral winds to 27 m/s) Vehicle safe on guideway for 54 m/s, bare guideway designed for 89-m/s lateral wind	1
Foster-Miller	Partial trough may collect snow and ice, but relatively large gap (75 mm) Guideway provides partial wind protection, but increases turbulence incident to vehicle No aerodynamic control surfaces needed Vehicle operational wind limit not known Guideway designed for basic wind speed of 38 m/s with stationary vehicle present	1
Grumman	40-mm gap under vehicle, largely protected from freezing rain Bare guideway designed for steady lateral wind of 45 m/s Vehicle can operate at full speed with steady cross-wind of 22 m/s and peak gusts of 33 m/s, significantly higher winds than guidelines above (guideway designed for these added loads) Contractor's specifications call for unaffected vehicle operation with snow accumulations of up to 50 mm, rain rates up to 50 mm/hr and up to 63 mm of ice on the guideway However, friction-brake performance would likely worsen in rainy or icy conditions	1.2
Magneplane	Curved guideway may collect snow and ice, although magnetic-drag losses will significantly heat guideway (for frequent vehicle passings) and reduce or eliminate this concern Bare guideway designed for 38-m/s basic wind speed Vehicle can operate at full speed with steady cross-wind of 13 m/s and peak gusts of 21 m/s (guideway also designed for these loads) Guideway provides partial wind protection, but may increase turbulence incident to vehicle Active aerodynamic control will be affected by wind shear (design calls for de-icing and anti-icing provisions)	1.2
All HSGT	Visibility affects obstacle detection—may need to reduce speeds in low visibility	NA
All maglev concepts	No traction problems for acceleration or normal braking Noncontact power transfer Emergency braking performance using skids will deteriorate in snow, ice, and rain	NA

human operation considerations, evacuation procedures, system restart, equipment and software availability, safety inspections, consequences of vandalism and trespassing, etc. The central control facility will log all operations and communications for subsequent analysis in the event of a failure. Consideration must be given to safe use of materials and construction methods, and to the safety of other users of the ROW. This has a high priority. We checked the following:

- Hazard analysis for reasonableness.
- Control system response to hazards.
- Access to failed components.

Table 10. Actual assessments of controls.

System	*Evaluation comments*	*Rating*
TGV	Little reliance on micro-processor based controls Fail-safe design with more traditional electromechanical equipment Consistent with modern European practice Automatic supervision, not automatic control In-cab signals generated by coded track signals Voice communication with operators Control system can stop train if needed Newest versions use solid-state devices, can provide near automatic control	1
TR07	FRA safety analysis indicates that control system is adequate for U.S. use Control software does not meet guidelines developed under Broad Agency Announcement Don't know and can't evaluate whether TR07 software meets Federal Aviation Administration regulation reliability level Does meet DG (central control), has LSM Designed to German standards	1
Bechtel	Central control, LSM Good control-system expertise, good approach	1
Foster-Miller	Central control, LSM Good control-system expertise, good approach	1
Grumman	Central control, LSM Good control-system expertise, good approach	1
Magneplane	Central control, LSM Good description of hardware, good expertise More demanding, flexible vehicle scheduling at very high system capacities, but they have considered how to do this	1

Table 11. Actual assessments of safety.

System	*Evaluation comments*	*Rating*
TGV	Examined by FRA safety team Fundamentally safe as built and used in France Some incompatibility with FRA specifications FRA issuing Rules of Special Applicability Sharing of track with freight and other trains could be a problem	1
TR07	TSC published three safety reports—no serious problems encountered	1
Bechtel	Have recognized hazards and developed safety strategy	1
Foster-Miller	Have recognized hazards and developed safety strategy	1
Grumman	Have recognized hazards and developed safety strategy	1
Magneplane	Have recognized hazards and developed safety strategy	1

In addition, we reviewed BAA work, and the Transrapid hazard analysis. This criterion was not very helpful for evaluation (it calls for a safety plan only—estimates of actual levels of safety beyond SCD scope). Table 11 gives the evaluation comments and ratings for safety.

Station operation (DG). Provision should be made for convenient and efficient intermodal and intramodal transfer and transport of passengers, baggage, and freight. This has a low priority and we omitted it as an evaluation parameter.

Availability and reliability (DG). The design should have high system availability and subsystem reliability, maintainability, and ease of inspection. This is a high priority item. We checked the following:

- Reliability plan.
- Failure mode analysis.
- Failure response plans, e.g., removing failed vehicles.
- Safety assurance plan.
- Redundancy, modularity.
- Diagnostics, maintenance on condition.
- Maintenance plan.
- Costs reflecting maintenance, availability.

We also reviewed the BAA on diagnostic sensors. Table 12 gives the evaluation comments and ratings for system availability and reliability.

Table 12. Actual assessments of system availability and reliability.

System	*Evaluation comments*	*Rating*
TGV	Good operating experience 93% probability of meeting its schedule within 5 minutes, average delay 40 seconds Fleet size dominated by peak demand, small (5%) surplus to ensure high availability Surplus may need to change with service pattern Must schedule routine maintenance for wheel reprofiling, bearing service, and other operations associated with wheel–rail systems Nontilting vehicle (less complex) Proven, conventional switch quite reliable	1
TR07	Potentially significant guideway maintenance owing to tight tolerances (small gap, passive secondary) Needs either adjustments for beams on piers or very conservative foundation design (geotechnical investigation for every pier) Earthquake sensitivity may seriously affect availability in certain corridors Three-phase, dual LSM windings and controls can tolerate a winding failure and still operate (degraded mode) Bending beam switch, reliability unproven	1
Bechtel	Complete fault-tolerant system design Relatively low takeoff speed (10 m/s) Contactless air cushion for low-speed support (unproven, 10 times higher speed than current applications of this technology), although they may use active coils instead Cable-in-conduit superconductor cooling (no sloshing or flashing) Has liquid helium reservoir, no refrigerator Nb_3Sn wire has higher transition temperature than NbTi but is more brittle Fluctuating loads from ladder will cause eddy current losses in dewars and magnets that will require cooling beyond that identified in final report Six-phase, dual LSM windings and controls can tolerate a winding failure and still provide operational capability (degraded mode) Bending beam switch, reliability unproven	1.2
Foster-Miller	Landing speed of 20–50 m/s moderately high, requires wheels Helium bath provides thermal reservoir, no refrigerator but sloshing and flashing possible NbTi wire has lower transition temperature than Nb_3Sn but is less brittle Fluctuating loads from discrete coils will cause eddy current losses in dewars and magnets that will require cooling beyond that identified in final report LCLSM requires an H-bridge for each coil, so many opportunities for failure of electronic components However, LCLSM coils are independently controlled, so motor can operate in degrade mode with individual coils disabled (also, repair or replacement need not shut system down) Electromagnetic switch potentially very reliable	1.2
Grumman	Zero-speed hover possible, no landing gear needed Helium bath provides thermal reservoir, no refrigerator but sloshing and flashing possible (daily recharge—recompress and store helium gas) Control coils interacting with SC magnets are key to reliable design (unproven concept) Three-phase, dual LSM windings and controls can tolerate a winding failure and still provide operational capability (degraded mode) Bending beam switch, reliability unproven	1.2
Magneplane	Concern over reliability of air-bag supports and low-friction landing skids High takeoff speed (50 m/s) places demands on low-friction skids Cable-in-conduit with 30-minute reserve of liquid helium, no sloshing or flashing Cryogenic refrigerator least reliable component Nb_3Sn wire has higher transition temperature than NbTi but is more brittle Significant guideway heating owing to sheet levitation scheme (about 95°C temperature rise for 20-second headways) and ambient air temperature and sun (additional 83°C rise) Continuous-sheet guideway avoids fluctuating forces produced by discrete coils, good for magnets Aluminum and concrete react so attachments may corrode or fatigue (more maintenance) Single three-phase LSM not as reliable as dual LSM concepts (no degraded mode for LSM failure) Nontilting vehicle is more reliable Electromagnetic switch potentially very reliable	1
All maglev	Noncontact for lift, guidance, propulsion, braking, and power transfer. Should allow “on-condition” maintenance, which is preferred to scheduled maintenance (inspections still done during down time) Repeated transient loads will accelerate settlement If suspension can smooth out ride (e.g., active control of primary or secondary) then magnet contact limits allowable guideway irregularities—large gap systems yield big advantage in this case	

Table 13. Actual assessments of vehicle capacity.

System	*Evaluation comments*	*Rating*
TGV	1.2 m^2 cabin-floor area / passenger Plenty of headroom Overhead luggage racks Car size variable (standard gauge) Freight car possible	1
TR07	0.83 m^2 cabin-floor area / passenger Multiple-vehicle consists possible, width variable	1
Bechtel	0.80 m^2 cabin-floor area / passenger Single vehicles, width variable Meets ADA requirements	1
Foster-Miller	0.74 m^2 cabin-floor area / passenger Multiple-vehicle consists possible, width fixed Meets ADA requirements	1
Grumman	0.93 m^2 cabin-floor area / passenger Multiple-vehicle consists possible, width variable Meets ADA requirements	1
Magneplane	0.61 m^2 cabin-floor area / passenger Limited headroom Single vehicles, length variable Meets ADA requirements	1

Aesthetics (DG). Attention to aesthetics should be evidenced in the design to increase public acceptance and ensure consideration of economic aspects. This is a low priority item (omitted.)

Communications (DG). The system will include provisions for nonvital voice, data, and video communication capability. This is a low priority item (omitted.)

Human factors (DG). Human factors should be considered in the design, including the operator, passengers, and maintenance personnel. This is a low priority item (omitted.)

Vehicle requirements

Capacity (DG). Vehicles of different sizes, configured to carry passengers or freight, or both, should be feasible with the same basic design. This item has a medium priority. We checked the following:

- Ergonomics (seat size, headroom, luggage space, etc.).
- Dimensions vs. aircraft cabins.
- Egress times.
- ADA (Americans with Disabilities Act) requirements.

Table 13 gives the evaluation comments and ratings for capacity.

Braking system (MR). Vehicles must have redundant braking systems that are fail-safe (DG). Normal braking of up to 0.2 g should be considered. This has a high priority. We checked the following:

- Controls.
- Levels of redundancy.
- For one system independent of wayside power (minimum).
- Cabin equipment and procedures (warnings, seat belts, airbags).
- Load distribution—vehicle and guideway (especially emergency).
- Impacts to power system.
- Use of frictional braking in rain, snow, ice.
- Skid design, heat buildup.
- Wheel–guideway traction.
- Asymmetrical magnetic braking.

Table 14 gives the evaluation comments and ratings for the breaking system.

Structural integrity (MR). Vehicles must safely withstand high-speed collisions with small objects such as birds, debris, snow, and ice. Vehicles must also have adequate fatigue life and low-speed crash worthiness and should sustain only minimum damage in a 2.2-m / s (5-mph) impact.

This has a low priority and has been omitted as an evaluation parameter.

Onboard power (DG). All power for normal hotel functions, controls, levitation, etc., should be transferred from the guideway (MR). The vehicle must be equipped with emergency power for

Table 14. Actual assessments of braking system.

System	*Evaluation comments*	*Rating*
TGV	All braking (except aerodynamic drag) traction limited Primary service braking via rheostats on powered axles Secondary braking via disc brakes on unpowered axles and tread brakes on powered axles Anti-skid control of each wheel set to prevent wheel lock Normal service braking at 0.03–0.06 g, emergency braking at 0.10 g Traction will limit emergency braking	1
TR07	Aerodynamic braking, eddy current braking and emergency skids are all independent of wayside power Aerodynamic and eddy current braking are independent of onboard power Normal braking as linear generator—power dissipated in resistors (rather than regenerative) Can also apply reverse thrust by reversing motor direction Control system deflates air bag in secondary suspension for asymmetric magnet loss to control braking direction Normal braking at 0.12 g Emergency braking at 0.30 g	1.2
Bechtel	Primary: regenerative Secondary: aerodynamic–electrodynamic Emergency: drogue Normal braking at 0.20 g Emergency braking at 0.25 g	1.2
Foster-Miller	Primary: regenerative Secondary: aerodynamic–wheels Emergency: skids Normal braking at 0.16 g Emergency braking at 0.25 g	1.2
Grumman	Primary: regenerative Secondary: electrodynamic–eddy Emergency: friction / skids Normal braking at 0.16 g Emergency braking at 0.20 g	1.2
Magneplane	Primary: regenerative Secondary: aerodynamic–sheet drag Emergency: skids Normal braking at 0.16 g Emergency braking at 0.50 g	1.2

operation, as appropriate within the system safety plan. This is a high priority item. We checked the following:

- System safety plan for failure contingencies.
- Emergency braking power requirements.
- Power to move failed vehicle to off-load locations.

Table 15 provides the evaluation comments and ratings for onboard power.

Emergency systems (MR). Vehicles must include emergency systems for fire fighting, lighting, HVAC, evacuation, communication, etc., as appropriate within the system safety plan. This was given a low priority and was omitted as an evaluation parameter.

Instrumentation and controls (MR). The system should include instruments that monitor the integrity of the guideway (presence of debris, snow, and ice, misalignment or deterioration of guideway, etc.) and the status of onboard systems (propulsion, levitation, guidance, power, safety, etc.). Data acquired should be recorded and fully integrated into vehicle and overall-system controls to allow appropriate response in emergency and normal operations. In normal operation, vehicles will be monitored or controlled from a central facility. However, vehicles will include manual controls for emergencies and maintenance.

Priority is high for this (debris being defined as extraneous matter that poses a hazard to the vehicle). We checked the following:

- Completeness of sensor system.
- Previous experience of contractor.
- Response of sensors to adverse weather.

Table 15. Actual assessments of onboard power.

System	*Evaluation comments*	*Rating*
TGV	No levitation power needed Onboard power (batteries) for commutation to use traction motors for braking Backup power for anti-lock braking and skid control	1
TR07	Dual battery systems for emergency hover Has rescue strategy to relevitate and move stranded vehicle	1
Bechtel	Onboard methanol-powered fuel cell requires fuel aboard vehicle	–1
Foster-Miller	LCLSM coils, when not in propulsion mode, function as the primary of an air-core transformer for inductive power transfer to vehicle Power transfer works provided LCLSM works Not speed dependent Emergency batteries for wheel deployment and braking	1
Grumman	High-frequency, single-phase excitation of LSM windings in conjunction with linear generator provides inductive power transfer Speed independent	1
Magneplane	Inductive power transfer by injection of high-frequency, three-phase current into LSM windings in direction opposite to LSM propulsion current Speed dependent	1

Table 16. Actual assessments of instruments and controls.

System	*Evaluation comments*	*Rating*
TGV	Normal daily operation begins with scout train at lower speed Have fragile-wire sensors to detect rock slides Extensive onboard controls and diagnostics (interlocked with central control)	1
TR07	Gap sensing permits monitoring of guideway degradation Good lightning protection	1
Bechtel		1
Foster-Miller		1
Grumman		1
Magneplane		1
All systems	Concern over reliability of forward obstacle detection in bad weather	
All maglev	Concepts include integrated sensors and control systems (details vary) LSM controls vehicle position well inherently	

- Block and central control hierarchy.
- Integration of instrumentation into maintenance plans.
- Interface between instrumentation and control facility.
- State-of-the-art of the sensors being proposed.

We also reviewed BAA information (Martin-Marietta 1992). Table 16 gives the evaluation comments and ratings for instrumentation and controls.

Sanitary facilities (MR). Space must be provided for sanitary facilities, including a retention system. This has been given a low priority (omitted).

Guideway requirements

Structural integrity (MR). A civil structure (foundation and structure supporting the guideway) should have a minimum 50-year life. Consideration should be given to structural integrity during earthquakes and in high winds.

The seismic criterion was later updated to require that the guideway structure be designed to the specifications for seismic zone 2 of the *Uniform Building Code* (International Conference of Building Officials 1992). Zone 2 covers most of the continental U.S. except for California, Nevada, and isolated regions near St. Louis and in the Rocky Mountains.

A common set of wind specifications was also later provided to the contractors (see Appendix B). Not all contractors were instructed to use these specifications, so we cannot apply them as minimum requirements. However, Table 17 reports design wind speeds for comparison. Note that the specification for guideway structural integrity called for use of a 38-m / s basic wind speed. Structural integrity has a high priority. We checked the following:

Table 17. Actual assessments of structural integrity.

System	*Evaluation comments*	*Rating*
TGV	Viaducts built to *L* / 4000 Ballast is relatively easy to realign and maintain	1
TR07	Designed for *L* / 4000 dynamic deflection ratio Although not considered in original design, California–Nevada proposal indicated that guideway would meet California codes for seismic design (more severe than zone 2 requirement) Low stress levels (all compressive) in concrete owing to deflection-limited design—very good for fatigue and durability behavior of concrete Attachments would have shorter lives Florida proposal indicates wind loads not a problem—should easily meet wind-load requirements Steel beam life comparable to steel bridges in Germany (about 80 years) California–Nevada proposal indicates that they have considered thermal stresses	1
Bechtel	Simple, conventional superstructure design Requires controversial FRP transverse reinforcing in upper half of girder to prevent magnetic effects. However, FRP is not used for prestressing (which is more controversial) Numerous attachments Girders designed for *L* / 2500 dynamic deflection ratio Structural analyses indicate low deflections and stresses in guideway, promoting good ride quality, fatigue life and durability. Should meet 50-year life requirement. Thermal stresses not a problem owing to support conditions. Differential thermal deflections not a problem given large magnet–guideway gap Designed for seismic zone 2 Guideway designed for 38-m / s crosswinds. Vehicle operation allowed at full speed with lateral gusts to 18 m / s; will reduce speed for 18- to 27-m / s range. These vehicular loadings controlled portions of guideway design	1
Foster-Miller	Innovative modular superstructure, possibly complex to construct Design dependent on viability of FRP post-tensioning Girders designed for *L* / 4500 dynamic deflection ratio Structural analyses indicate low deflections and stresses in the guideway, promoting good ride quality, fatigue life and durability. Should meet 50-year life requirement Thermal stresses not a problem owing to support conditions. Differential thermal deflections not a problem because of the large magnet–guideway gap Designed for seismic zone 2 Guideway designed for 38-m / s winds. Partial enclosure of vehicle by guideway provides some crosswind protection	1
Grumman	Innovative modular superstructure that has a single (spine girder) substructure EMS design does not require FRP reinforcing Structural analyses indicate total dynamic deflection ratio is *L* / 2400 as input to vehicle Structural analyses indicate low stresses in the guideway, promoting good fatigue life and durability. Should meet 50-year life requirement Thermal stresses not a problem owing to support conditions. Differential thermal deflections not a problem owing to large magnet–guideway gap. SPC-B seismic design comparable to zone 2 requirement Guideway designed for steady side wind of 44.7 m / s with no vehicles operating, and a steady 22.3-m / s wind with gusts up to 33 m / s while vehicles are traveling at 134 m / s	1
Magneplane	Superstructure requires nationally significant quantities of aluminum Structural analyses indicate very low deflections, well below *L* / 2000 design limit Stresses well below allowable fatigue limits for infinite number of cycles. Should meet 50-year life requirement Temperature differentials of 83°C considered in thermal analysis Designed for seismic zone 2 Guideway designed for 38-m / s crosswind. Vehicle designed to operate at 134 m / s in steady crosswinds of 13.4 m / s with 22.3-m / s gusts	1

- Earthquake analysis—should meet seismic zone 2 requirements.
- Design wind loads and structural response.
- Use of sensors to forecast winds, earthquakes.
- Discussion of fatigue, degradation.
- Measures to meet 50-year minimum life (e.g., cathodic protection).
- Effects of thermal stresses.
- Long-term serviceability.
- Magnetic effects.
- Methods for calculating vehicle loads.
- Possible aeroelastic loads.

Configuration (DG). Guideways will normally be elevated and have bi-directional capability, but must also accommodate near grade and underground situations. Single guideways must include provision for passing vehicles and future expansion. Dual guideways must include crossovers to sustain partial service during routine maintenance and repair of local failures. The central facility will control crossovers and bi-directional traffic.

This item has a medium priority. We checked the connection to the operation plan and control systems. Table 18 gives the evaluation comments and ratings for guideway configuration.

Structure (DG). To facilitate maintenance, repair of local failures, and eventual system upgrade, guideways should be of modular construction with an independent support structure. This support structure (foundations, piers, beams, and connectors) should be designed to accommodate growth in traffic (see *System Capacity*). The design should also include means for vertical and lateral adjustment of guiding elements to maintain required tolerances.

This is a high priority item. We checked the following:

Table 18. Actual assesments of guideway configuration.

System	*Evaluation comments*	*Rating*
TGV	Not normally elevated (heavy) Fully grade separated on high-speed sections No switching problems	–1
TR07	Normally elevated, can be at near-grade Switch proven	1
Bechtel	Normally elevated, can be at near-grade	1
Foster-Miller	Normally elevated, can be at near-grade	1
Grumman	Normally elevated, can be at near-grade	1
Magneplane	Normally elevated, can be at near-grade	1

Table 19. Actual assessments of guideway structure.

System	*Evaluation comments*	*Rating*
TGV	Ballast provides modularity, means for alignment	1
TR07	Can replace motor sections Guidance elements cannot be adjusted Single-span beams can be adjusted (with difficulty) on piers Foundation settlement would require lengthy repair	1
Bechtel	Single-span beams can be adjusted (with difficulty) on piers Levitation, guidance and propulsion package adjustable on beam using shims	1
Foster-Miller	Levitation, and guidance–propulsion coils separately adjustable on beam Two-span beams can be adjusted on piers, but with more difficulty than single-span beams	1
Grumman	Multiple adjustment points (rails, slab beams, spine girder seats) Innovative adjustable post-tensioning can compensate for concrete creep Short-span slab beams easily adjusted	1
Magneplane	Very simple girder layout, easily adjusted Two-span beams are short so shouldn't pose extra adjustment problems	1

- Realignment features.
- Modularity.
- Constructiblity.
- Integration with maintenance plan (50-year life).
- Features for capacity upgrade.

Table 19 provides the evaluation comments and ratings for guideway structure.

Vehicle entry and exit (DG). Entry and exit to off-line stations, feeder lines, and other main lines should require minimal vehicle headway and overall trip time. This item has high priority. We checked the following:

- Reasonableness of technique.
- Safety implications.
- References to controls, operation plan.
- Headway restrictions, implications for capacity.
- Hypothetical route costs for entry–exit.

Note that turnout speeds for all switches depend upon radius of curve and hence length of switch. Because switch radius is a design trade-off with cost, turnout speeds do not generally indicate the relative merits of each switch type. Turnout speeds in Table 20 are minimum achievable values for baseline switches.

Instrumentation and controls (MR). The system shall include instruments that monitor guideway integrity (presence of debris, snow, and ice, misalignment or deterioration of guideway, etc.), the status of its subsystems (propulsion, levitation, guidance, power, entries–exits, etc.), and the locations and velocities of all vehicles. Data acquired should be fully integrated into guideway and overall system controls to allow response in both emergency and normal operations.

This is a high priority item. We checked integration with central control and operation plan, and vehicle control issues (vehicle position and

Table 20. Actual assessments of vehicle entry and exit from the guideway.

System	*Evaluation comments*	*Rating*
TGV	No jerk at 61 m/s Full speed possible straight through switch Turnout possible at 95 m/s Standard rail switch, reasonably fast and reliable Minimum headway 81 seconds with emergency braking of 0.10 g (actually uses 4 minutes of headway)	1
TR07	Bendable steel beam is baseline switch (proven at Emsland) Has physical interlock to confirm switch status No superelevation possible, and vehicle does not tilt so turnout speed limited Large jerk (0.5 g/s) also limits turnout speed Turnout possible at 56 m/s Mechanical movement and interlock results in relatively slow switch cycle time	1
Bechtel	Baseline bending beam switch is all composite material (FRP) No superelevation of bending beam, but vehicle tilts Turnout possible at 32 m/s Mechanical movement and interlock results in relatively slow switch cycle time Electromagnetic switch studied as an alternative	1
Foster-Miller	Baseline high-speed switch is electromagnetic (vertical, switched null-flux coils with moving safety floor as interlock) Turnout possible at 50 m/s Vertical orientation for turnout should permit higher speeds Relatively fast cycle time should be possible (except for need to move safety floor) Two lower-speed switches developed: full 20 m/s segmented switch, 20–12 m/s switch for vehicle on wheels	1.2
Grumman	Baseline switch consists of a bending-beam section (similar to TR07) and a rotated section to allow superelevation Turnout possible at 65 m/s Mechanical movement and interlock results in relatively slow switch cycle time	1
Magneplane	Electromagnetic horizontal switch using null-flux coils Angling of coils permits banked turnouts for higher turnout speeds Turnout possible at 100 m/s Relatively fast cycle time should be possible Vehicle maintains self-banking capability, so switch on curve possible	1.2

Table 21. Actual assessments of guideway instrumentation and controls.

System	*Evaluation comments*	*Rating*
TGV	Misalignment a less severe issue—regular track and catenary diagnostics Can detect rail breakage	1
TR07	Guideway senses vehicle position and control system uses this information	1
Bechtel	Well-developed control system	1
Foster-Miller	Well-developed control system	1
Grumman	Well-developed control system	1
Magneplane	Well-developed control system Intelligent vehicle, so no sensors on guideway	1
All systems	Expect that all will probably use Japanese-style earthquake detection and response Sensors needed for forward obstacle detection, reliability in bad weather a concern	

Table 22. Actual assessments of guideway power systems.

System	*Evaluation comments*	*Rating*
TGV	Can't maintain full speed (83 m/s) up sustained 3.5:100 grade 82% overall efficiency from electrical source, 0.91 power factor	–1
TR07	83% overall efficiency from electrical source, 0.74 power factor A lot of redundancy, some fault tolerance Large land requirement for power system Larger capacity needed to meet grade and wind requirements Current design has residual acceleration of only 0.006 g at 134 m/s (0.6:100) so cannot maintain full speed up sustained 3.5:100 grade 10% grade climbing capability only at very low speeds (14 m/s) Increased thrust capability limited by stator current density–conductor life trade-off Stator slot width limits conductor size so upgrade not easy	–1
Bechtel	85% overall efficiency from electrical source, 0.98 power factor High-voltage DC distribution with inverters along wayside provides a continuous guideway distribution system Inverters adjacent to guideway avoids feeder cables but requires real estate for inverters High-voltage DC circuit breakers may be difficult and costly Can climb 10% grade at 134 m/s with some reserve acceleration (0.02 g)—excellent grade climbing capability Reserve acceleration at level 134 m/s is 0.12 g	1.2
Foster-Miller	91% overall efficiency from electrical source, 0.97 power factor DC distribution to individual H-bridges Locally commutated LSM—high risk, high benefit item Blocklengths are a consist length, so LCLSM has potential for very high efficiency (91%) Can climb 10% grade at 100 m/s Reserve acceleration at level 134 m/s is 0.044 g (can maintain full speed up 3.5% grade)	1
Grumman	78% overall efficiency from electrical source, 0.98 power factor Conventional LSM and inverters (as per TR07) Inverters at substations with feeder cables Typical LSM blocklengths of 500 m, in conjunction with feeder cables for 4-km inverter spacing 10% grade climbing capability only at very low speeds (5 m/s) for 60-kN baseline design Reserve acceleration at level 134 m/s is 0.048 g (can maintain full speed up 3.5% grade) Replacing aluminum LSM windings with copper enables 100-kN motor thrust (at extra cost)	1
Magneplane	83% overall efficiency from electrical source, 0.31 power factor if uncorrected Conventional LSM and inverters (as per TR07) Inverters at substations with feeder cables Typical LSM blocklengths of 2 km, longer blocks require power-factor correction 84% overall efficiency from electrical source, 0.99 power factor if corrected Can climb 10% grade at 90 m/s Reserve acceleration at level 134 m/s is 0.039 g (can maintain full speed up 3.5% grade)	1

velocity may be sensed by the vehicle, not the guideway). Table 21 gives the evaluation comments and ratings for instrumentation and controls.

Tunnels (MR). The design of tunnels should address issues of comfort, noise, and safety, with special attention to vehicle entry and passing vehicles. This has a low priority (omitted).

Power systems (DG). Power systems should be sized so that the vehicle can accelerate and brake at all operating conditions, and they should be capable of meeting requirements for system capacity. Guideway power systems should be capable of sustaining vehicles at full cruising speed up sustained grades of 3.5:100, and provide vehicle propulsion at reduced speeds up a maximum grade of 10:100. This item has a high priority. We checked the following:

- Parametric study.
- Redundancy, spacing of equipment.
- Interface with controls.
- Cyclic loading response.
- Nonlinear currents.
- Power factor, demand, upgrade potential.
- Diagnostics, maintenance plans.
- Design against existing IEEE (Institute of Electrical and Electronics Engineers) standards.
- Relationship to single and multiple vehicle configurations.
- Nature of transients to grid.
- Dynamic vs. regenerative braking.
- Total energy analysis.

Table 22 provides the evaluation comments and ratings for power systems.

Superelevation (MR). Superelevated (banked) guideways must allow safe operation of vehicles at all speeds from zero to the maximum design speed of the curve. Emergency evacuation must be possible from vehicles stopped in a curve. This has a medium priority. We checked the following:

- Stopping and restarting in curves.
- Guideway sidewall strength.
- Evacuation procedures in curves.
- Loads from coordinated* vs. noncoordinated turns.
- Transition designs (shape, cost, length, effect on modularity).

Table 23 presents evaluation comments and ratings for superelevation.

3.1.3 Results of system-criteria assessment

Table 24 shows a numerical summary of our use of the SCD system criteria to assess technical viability. Essentially, the concepts fall into three groups. The top one consists of the Foster-Miller, Grumman, and Magneplane concepts. They each exceed the requirements for five or six criteria and meet all other requirements.

The middle group consists of TR07 and the Bechtel concept. Despite exceeding the requirements for a few criteria, these systems each fail to meet a high-priority criterion: TR07 cannot climb a 3.5% grade at 134 m / s, and Bechtel's vehicle includes a methane fuel cell to meet onboard power needs. The Bechtel concept suffers further

* Means that all loads are normal to the guideway top.

Table 23. Actual assessments of guideway superelevation.

System	*Evaluation comments*	*Rating*
TGV	Can evacuate at-grade easily	1
TR07	Beams designed for maximum lateral loads Guideway can support vehicle stopped in curve Can evacuate vehicle stopped in curves (chutes, walkways) Can coast to safe-stopping location	1
Bechtel	Have considered loads in structural analysis Tilting vehicle cabin returns to horizontal if stopped	1
Foster-Miller	Has considered loads in structural analysis Tilting vehicle body returns to horizontal if stopped	1
Grumman	Has central box girder for evacuation Tilting vehicle body returns to horizontal if stopped	1
Magneplane	Vehicle rolls to horizontal position if stopped in curve Walk on LSM to evacuate Guideway may be hot Has considered loads in structural analysis	1

Table 24. Summary of system criteria assessment.

Parameter	*Weight*	*TGV-A*	*TR07*	*Bechtel*	*Foster-Miller*	*Grumman*	*Magneplane*
System							
Speed	3	–1	1	1.2	1.2	1.2	1.2
Capacity	3	1.2	1.2	1	1.2	1.2	1.2
Ride comfort	3	1	1	0	1	1	1
Noise / vibration	0	—	—	—	—	—	—
Magnetic fields	3	1	1	1	1	1	1
Weather	2	1	1	1	1.2	1.2	1.2
Controls	3	1	1	1	1	1	1
Safety	3	1	1	1	1	1	1
Station operation	0	—	—	—	—	—	—
Availability / reliability	3	1	1	1.2	1.2	1.2	1
Aesthetics	0	—	—	—	—	—	—
Communications	0	—	—	—	—	—	—
Human factors	0	—	—	—	—	—	—
Subtotal	23	18	24	21	25	25	25
Vehicle							
Capacity	2	1	1	1	1	1	1
Braking	3	1	1.2	1.2	1.2	1.2	1.2
Structural integrity	0	—	—	—	—	—	—
Onboard power	3	1	1	-1	1	1	1
Emergency syst.	0	—	—	—	—	—	—
Instr. / controls	3	1	1	1	1	1	1
Sanitary facilities	0	—	—	—	—	—	—
Subtotal	11	11	12	6	12	12	12
Guideway							
Structural integrity	3	1	1	1	1	1	1
Configuration	2	–1	1	1	1	1	1
Structure	3	1	1	1	1	1	1
Entry / exit	3	1	1	1	1.2	1	1.2
Instr. / controls	3	1	1	1	1	1	1
Tunnels	0	—	—	—	—	—	—
Power systems	3	–1	–1	1.2	1	1	1
Superelevation	2	1	1	1	1	1	1
Subtotal	19	9	13	20	20	19	20
Total	53	38	48	46	56	56	56

because the final report did not provide sufficient information for us to determine whether the vehicle would satisfy ride-comfort requirements. The importance of these shortcomings differ for the two systems, however.

As discussed in the text, stator slot width limits the LSM thrust capability of TR07. While some additional thrust is possible with further work, the system will not easily provide the thrust needed to climb a 3.5% grade at 134 m / s. Conversely, Bechtel's choice of a fuel cell vs. batteries to provide onboard power reflected a cost–weight tradeoff. Substitution of batteries for the fuel cell would not be difficult or involve major changes in the concept. Also, further work would likely yield details of a suspension that could be shown to meet ride-comfort requirements. These improvements are straightforward and would move the Bechtel concept into the upper grouping.

TGV received the lowest assessment results here. This is not surprising, given that the SCD system criteria were established to guide U.S. maglev concepts towards performance superior to current high-speed rail systems. In particular, TGV-A cannot achieve a level cruise speed 134 m / s and cannot climb a 10% grade. It is also not normally an elevated system. Failing to meet these three criteria produced its low assessment result.

Use of the SCD system criteria for assessment served as a key step in our evaluation of technical viability. Essentially, it summarized the performance of each concept against requirements thought to be important to maglev's viability in the U.S. market. It also provided a focus for our analytical efforts by identifying specific performance questions that required data from our models to answer. Indeed, we found that we could not complete this evaluation step until our models had yielded the required data. Overall, this step tells us that U.S. maglev concepts should perform slightly better than TR07 and substantially better than TGV-A.

It is worth emphasizing that neither TGV nor TR07 were designed to meet the SCD system criteria, and both systems will undoubtedly improve with further development. However, it is beyond our scope to assess the likely outcome of such development in terms of the time, costs, and risks associated with specific performance improvements. We chose TGV-A and TR07 as baselines for evaluation because their perceived lack of development costs and risks are critical in the debate of whether these systems represent preferred alternatives to developing a U.S.-designed maglev system. Thus, we believe this is a fair assessment.

3.2 SUBSYSTEM VERIFICATION

As noted, one aspect of maglev's technical viability is technical feasibility: the soundness of the physical principles and engineering sciences upon which the concept is based. To assess this, the GMSA identified several critical subsystems that warranted direct verification. In general, these subsystems represented high-risk or high-cost items: guideway structure, linear synchronous motor, magnetic suspension (including stray fields), and vehicle suspension (including guideway interactions). We developed our own numerical models to assess the technical feasibility of these subsystems for TR07 and the SCD concepts. Because of the enormous scope of this undertaking, we focused most analysis effort on those items deemed critical to each concept.

The following four sections present the results our subsystem verification work. Each section describes specific objectives for the study, methodology used, critical issues examined for each concept, results obtained, and brief conclusions regarding each concept's technical feasibility.

3.2.1 Guideway structure*

Objectives

The supporting guideway of a Maglev system is generally the most expensive subsystem. As such, it represents the greatest potential for cost savings through good design. The objectives of this section were to identify key issues affecting the viability and economy of the TR07 and SCD guideway designs and to analyze their structures to address the key issues.

Methodology

To evaluate each guideway design, we did the following: reviewed all structural details; identified key issues that were deemed to have a direct effect on the viability and economy of the guideway design; and applied structural analysis "tools" to address the key issues for each design.

The following steps were taken to study the guideway structural designs:

- Identify the most appropriate and efficient analytical tools for the desired structural calculations.
- Test the analytical tools in a baseline evaluation of the German TR07 guideway.
- Use these tools to evaluate the four SCD guideway designs.

All analytical work was concentrated on the superstructure (girder) elements since the substructure elements (piers and footings) were all conventional designs with little or no innovations that required special consideration.

A vast array of "tools" exists for structural analysis and design, ranging from conventional hand calculations to complex, three-dimensional finite-element computer programs. For our analyses here, we used a combination of hand calculations (as discussed in Nilson 1978) and two different finite-element programs, ADINA (ADINA R&D, Inc. 1987) and ABAQUS (HKS, Inc. 1988). Hand calculations were used for the design and verification of reinforcing requirements within the concrete cross sections and for a cross-check of the finite-element analytical results. The finite-element analyses were used for the more complex studies involving static and dynamic response and resulting stress distributions from vehicular loadings.

German TR07 guideway

Key Issues. Since the TR07 guideway is currently in prototype operation and has performed successfully, the key issues for this design are mainly economic. The only structural question regards their use of pseudo-static loadings for their designs in place of actual dynamic vehicle–guideway interaction analyses. The economics of the guideway may be addressed by a study of the

*Written by Dr. James Ray, U.S. Army Waterways Experiment Station.

design to verify that it is as structurally efficient as possible.

In addition to structural efficiency, the construction requirements will also directly affect the cost of the guideway. The construction tolerance requirements for this guideway are far greater than current construction practice in the U.S. These tolerances will have a significant effect on the construction time and, thus, cost requirements. The sloping sides and rounded bottom of the TR07 superstructure girder are very aesthetically pleasing and possibly serve a minimal purpose in reducing wind loadings on the structure. However, these features also add to the complexity and cost of the structure.

Approach. During the initial stages of the GMSA work, sufficient details for a structural analysis of the TR07 guideway were sparse. To fill in the information gaps, the team members conducted an extensive literature search. Most of the useful design information obtained on the TR07 guideway came initially from five sources (see *Bauingenieur* 1983; City of Las Vegas 1987; *L'Industrial Italiana del Cemento* 1989; Maglev Transit, Inc. 1989; *The Indian Concrete Journal* 1991). The initial guideway analyses (using the pseudo-static loads) were based on this information. Missing details were filled in as necessary by assuming that the German designs corresponded closely to the U.S. specifications outlined in the design code published by the American Concrete Institute (1989).

The design details used in the analyses are as follows. All girders are single span and simply supported. Three different span lengths and, thus, three different girder cross-sections are used in the TR07 guideway (see Fig. 7). The 24.82-m span is the most common and is used in all straight portions of the guideway. The other two span lengths, 31.05 and 37.24 m, are used in curved sections of the guideway. A combination of straight and parabolically draped Dywidag post-tensioning bars reinforce each girder as shown in Figure 8. A German class B45 concrete is used in the girders, which corresponds to a concrete test cube strength of 45 N / mm^2 (approx. 5530-lb / in.^{2} test cylinder strength by U.S. standards). The girders have been constructed and post-tensioned in such a way as to practically eliminate long-term deflection changes attributable to concrete creep.

Maglev Transit, Inc. (1989) provides a complete set of pseudo-static load cases that reportedly were used for the design of the guideway in place of rigorous dynamic analyses. Seismic loadings were not considered in the design of these girders, although it has been reported to the GMSA team that the design is sufficient to resist seismic loadings. The girders were designed for a live load deflection ratio of 1:4000, which for the 24.82-m span corresponds to a mid-span downward deflection of approximately 6.2 mm. A permanent upward camber (under dead load only) of approximately 3.6 mm is induced in the beams by the post-tensioning to improve the total deflection characteristics under live loading.

All of the information discussed above was used for the initial analytical effort, with the pseudo-static loads provided in Maglev Transit, Inc. (1989). These analyses checked the longitudinal post-tensioning steel and the transverse reinforcing steel used in the three different TR07 guideway cross sections shown in Figure 7.

To verify the German pseudo-static loads and to validate the finite-element tools, we conducted a series of dynamic analyses of the TR07 girder. A comparative set of analyses, using both a beam-element and a solid-element model, confirmed the use of the simpler beam element model for most of the vehicle–guideway interaction studies. Vehicle speeds ranging from 100 to 500 km / hr (28 to 139 m / s) were considered. Dynamic vehicle

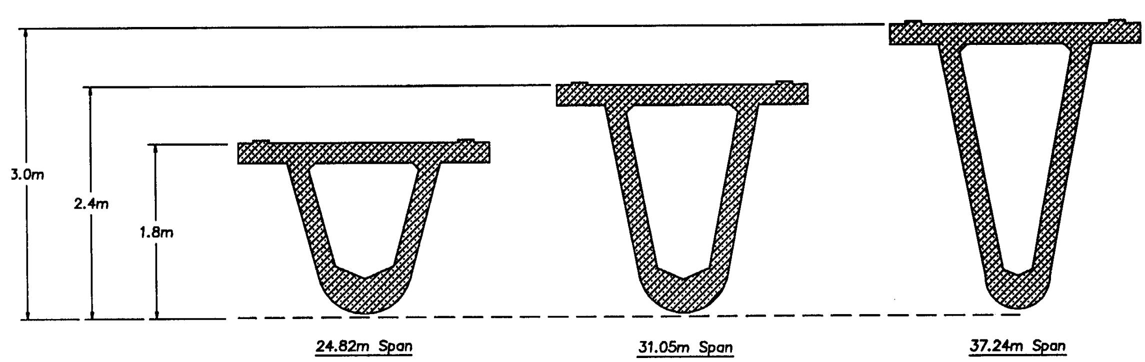


Figure 7. Cross sections of TR07 guideway girders.

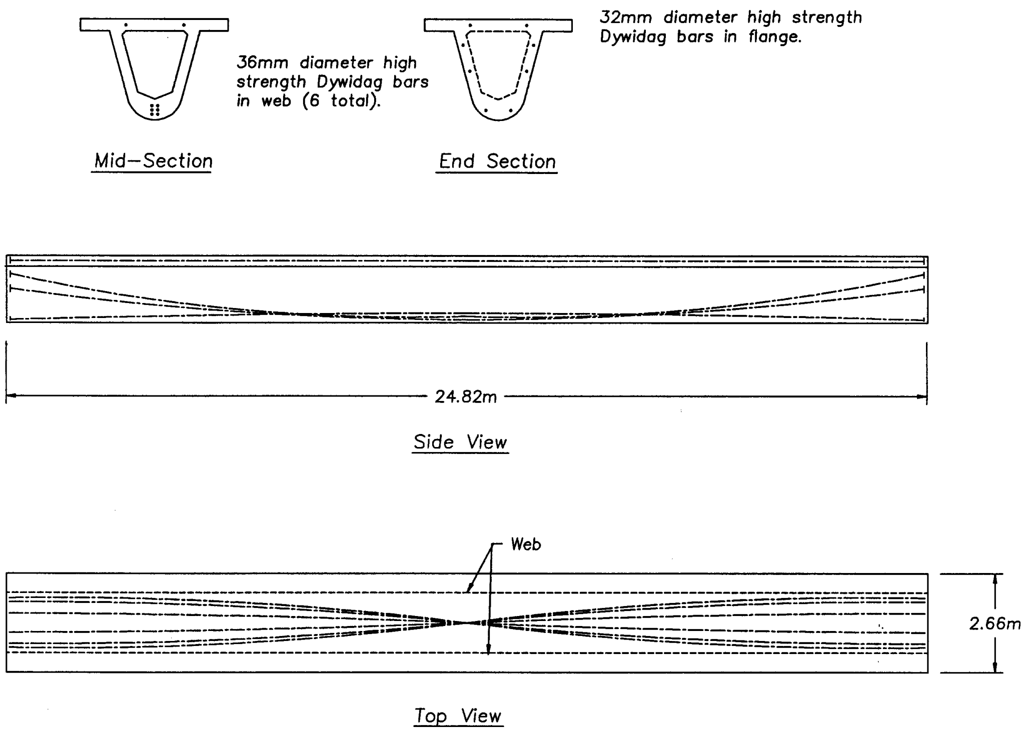


Figure 8. Post-tensioned steel arrangements in the TR07 girder.

loads were supplied by the Transportation Systems Center (TSC) of the Department of Transportation. Their vehicle model, discussed in section 3.2.4, provides load-time functions that represent the dynamic guideway loadings from the vehicle, attributable to both its "sweeping" passage across the guideway and its mass response (a function of vehicle mass and bogie suspension characteristics) to guideway roughness and deflection.

Before analyzing the solid-element finite-element model, and after completing the work with the beam-element finite-element model, we obtained an actual set of design drawings for the TR07 guideway from the Canadian Institute of Guided Ground Transport. These drawings provided more complete and accurate details of the 24.82-m girder. A comparison of the details in these drawings with those previously deduced from earlier documents revealed that the cross-sectional dimensions were slightly different. The new details gave the section a slightly lower moment of inertia than had previously been calculated. Since the new drawings were considered more accurate, the analyses using the solid-element model were made with these drawings.

Results. Longitudinal post-tensioning requirements were determined for the three different guideway span lengths and their corresponding cross sections using conventional prestress design procedures (discussed in Nilson 1978). These requirements were determined using the pseudo-static loads provided in Maglev Transit, Inc. (1989). For the design of longitudinal post-tensioning, the worst-case loading was for the case of the vehicle in a "trough," which produced a maximum downward load of 32.62 kN / m. The post-tensioning requirements were the same for the both the 1.8- and 2.4-m-deep sections, consisting of a combination of 32- and 36-mm-diameter high-strength Dywidag bars, as shown for the 1.8-m-deep section in Figure 8. The post-tensioning for the 3.0-m-deep section was approximately the same, except that two additional 36-mm-diameter draped bars were required.

As seen in Table 25, the resulting maximum stresses in the sections were well within the allowable limits defined by the American Concrete Institute (1989). In fact, the bottom portion of the section only had 1.10 MPa of tensile stress under its maximum downward loading, which is well below the allowable stress of 3.10 MPa. These low tensile stresses are very desirable for a concrete beam, since they will improve its long-term durability (weather resistance) and fatigue life. Because of the low stresses, the post-tensioning designs discussed above were apparently completely

Table 25. Analysis and design results for TR07 girder with 24.82-m span.

Deflections (mm)

*Load case**	*Hand calcs.*	*ABAQUS*	*Criteria**
IPS + DL†	–3.6	–3.55	NA
EPS + DL	–2.5**	—	–3.6
PS+DL+LL (trough)	6.1	—	6.2
PS*+DL+LL (curve)	—	5.25	NA

Stresses (MPa)

Load case	*Location*	*Hand calcs.*	*ABAQUS*	*Criteria*
IPS + DL†	Top	—	–3.20	–22.88
	Bottom	—	–5.20	+1.54
EPS + DL	Top	–2.90	—	–17.17
	Bottom	–3.31	—	+3.10
PS+DL+LL (trough)	Top	–5.52	—	–17.17
	Bottom	+1.10	—	+3.10
PS*+DL+LL (curve)	Top	—	–4.5	–17.17
	Bottom	—	–0.80	+3.10

* IPS = initial prestress, DL = dead load, EPS = effective prestress, LL = live load, NA = not applicable.

† Dead load of beam only

** Concrete creep neglected; creep increases camber

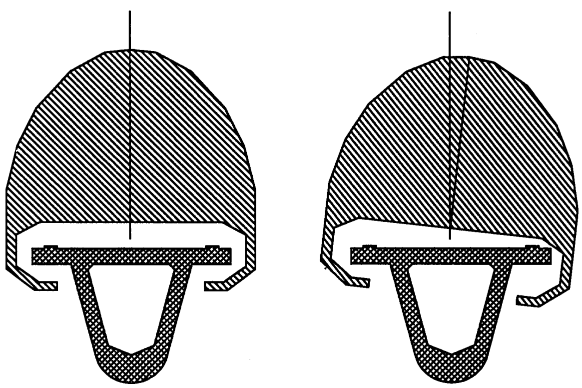


Figure 9. Roll motion of TR07 vehicle.

driven by the strict deflection limitations at the midspan (previously discussed).

Transverse reinforcing requirements were determined for the 24.82-m span subjected to the Maglev Transit, Inc. (1989) pseudo-static loadings. The worst-case shear and torsion loadings were for the vehicle in a circular curve, which induced a downward shear force of 31.2 kN / m and a torsional moment of 7.1 kN-m / m. The worst case loading for transverse bending within the box section was not discussed in Maglev Transit, Inc. (1989) and was thus assumed to be caused by a vehicle rolling completely to one side of the guideway, as demonstrated in an exaggerated form in Figure 9. This would cause the total vehicle loading to be transferred through the magnets on one side of the guideway only, thus inducing a large transverse bending moment into the section.

The design of reinforcing for the combined effects of transverse bending, shear, and torsion is very complex. The hand calculation procedure (Nilson 1978) is only an approximation and should be used with considerable conservatism. For an important design such as a maglev guideway, a three-dimensional finite-element analysis should be used to accurately define the maximum design stresses and thus reduce the required design conservatism.

The hand calculations showed that the shear and torsional stresses in the girder were quite low and could actually be carried by the concrete alone, without transverse reinforcing steel. The transverse bending stresses from the vehicle roll to one side were found to govern the design, which resulted in a maximum transverse steel requirement of 13-mm-diameter bars at 20 cm on center. This is fairly close to the more conservative TR07 design of 14-mm-diameter bars at 17 cm on center (considering the approximate nature of our calculations and the understandable conservatism of the TR07 design).

The midspan deflection–time histories resulting from the beam-element model are compared in Figure 10. From these plots, we can see that the girder has a natural frequency of approximately 6.0 Hz, which is the same as the hand-calculated value. The maximum deflections increase with vehicle passage speed because of the dynamic effect, with the largest deflection increase between 400 and 500 km / hr. The maximum dynamic deflection at 500 km / hr was approximately 3.6 mm. Note that this value was much less than the maximum allowable deflection for the TR07 girder (governed by ride quality and magnetic gap) of 6.2 mm. This should be the case since the loadings used for this model were not the worst case loadings, which result from the vehicle passing through a trough.

The ratio of the maximum dynamic deflection and the deflection of the span under the same statically applied loading is called the dynamic load factor (DLF). This value is used as a static load amplification factor in the conventional static design of structures. Based upon the 3.6-mm dynamic deflection of the girder at a vehicle speed of 500 km / hr and the hand-calculated static deflection of 2.3 mm, the DLF for the TR07 girder was calculated to be 1.56. This corresponds very closely to the DLF value of 1.40 reported in

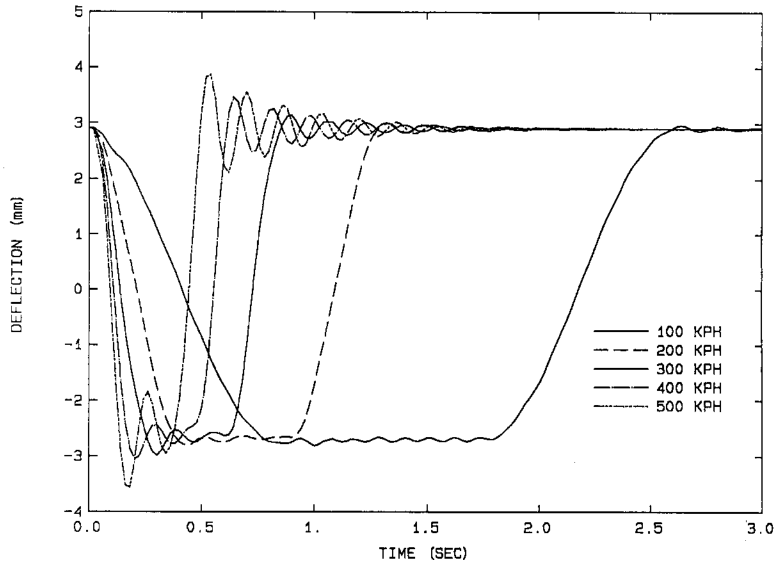


Figure 10. Midspan deflection–time histories for beam-element model of TR07 girder (KPH = kilometers per hour).

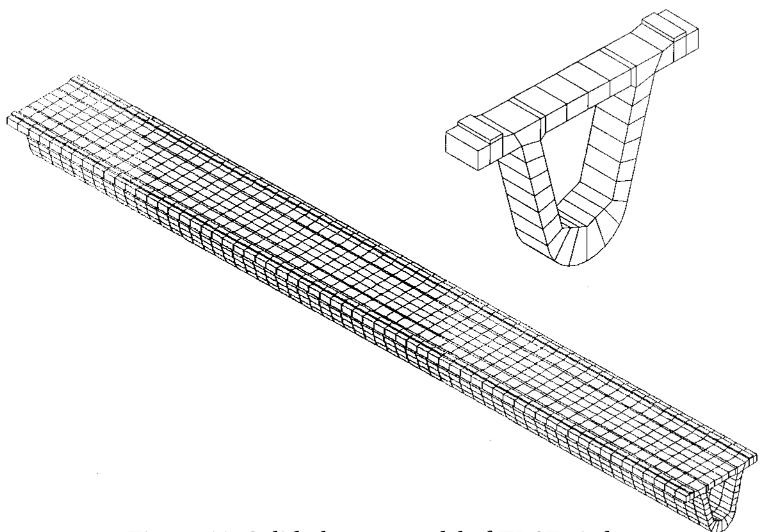


Figure 11. Solid-element model of TR07 girder.

Maglev Transit, Inc. (1989), which was used to determine the pseudo-static loadings reported therein.

The solid-element model is shown in Figure 11. The midspan dynamic deflections from this model are compared to those for the beam-element model in Figure 12. We attribute the small differences in stiffnesses and deflections between the plots to the soild-element model using the more accurate, less stiff cross section from the Canadian Institute of Guided Ground Transport drawings and the beam-element model using the section extracted from literature prior to receipt of those drawings, as previously discussed. The stress distributions and magnitudes obtained from this model also agreed well with the hand-calculated values.

Conclusions. Our analyses showed that the superstructure of the TR07 guideway is an efficient design and meets all of the stated requirements relating to allowable deflections and stresses. The Germans appear to have designed both an aesthetically pleasing and economical structure, a combination that is sometimes difficult to achieve. However, it should again be emphasized that the aesthetics add to the construction cost and the benefit to cost ratio of this combination must be carefully weighed. It should also be reemphasized that the required construction tolerances for this guideway will have a significant effect on its construction cost. In addition, continued maintenance of these tolerances on a structure in the U.S. could be very difficult and costly because of the highly varied soil conditions and seismic activity throughout the country.

The analytical tools provided an effective means of assessing the TR07 guideway and provided good agreement with the published data on the TR07. These tools should also prove sufficient for evaluating the SCD designs.

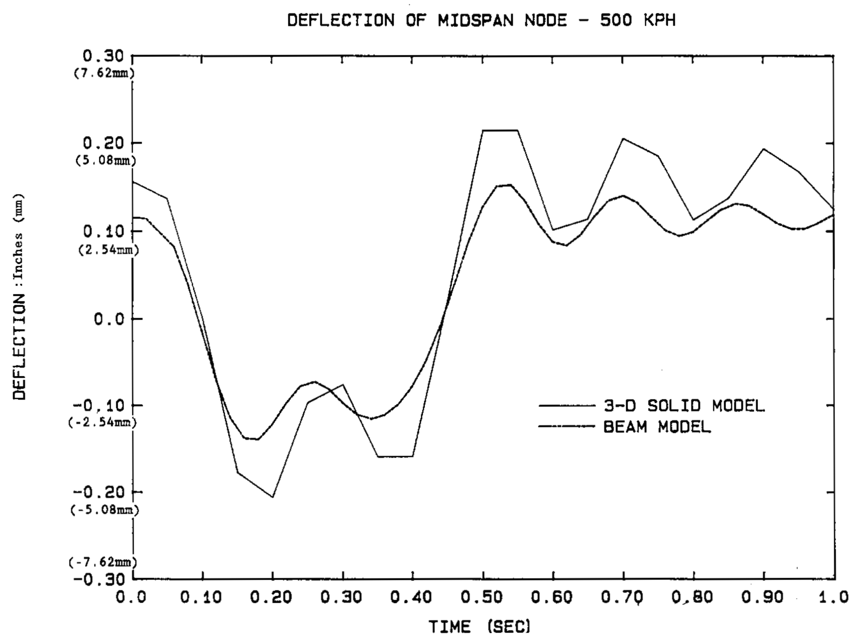


Figure 12. Comparison of results from beam- and solid-element models of TR07 girder.

Bechtel guideway

General. Bechtel's final SCD guideway concept is shown in Figure 13. It is a single-cell box girder made of prestressed concrete with both straight and parabolically draped post-tensioned reinforcement in the longitudinal direction. The post-tensioning details shown in Figure 13 are for curved sections of guideway. Slightly less post-tensioning is used in straight guideway sections. A combination of conventional steel reinforcing and FRP reinforcing is used in the transverse direction to resist shear and torsional stresses. The FRP reinforcing is used in the upper half of the girder to prevent magnetic interaction with the levitation–guidance system.

The baseline design calls for simply supported spans over the entire guideway. It also shows that multiple continuous spans (up to eight-span continuous) can be built in a future design if desired. In fact, Bechtel's earlier baseline design called for an eight-span continuous guideway with simple spans in the curves when necessary. Because a portion of the analytical work reported here was done prior to the completion of the final baseline design, some of it was based on an eight-span continuous guideway and the final portion was based on a simply supported guideway. This is differentiated throughout the discussion.

Key issues.

- As with all guideway designs, the dynamic interaction between the passing consist and the guideway (vehicle–guideway interaction) must be carefully studied to ensure desired ride quality and to give us a complete understanding of the loads applied to the guideway.
- The width of the guideway girder is relatively small. As a result, its torsional stability could be insufficient, especially for the guideway sections in curves and the vehicle consist in crosswinds.
- FRP reinforcing is a very new technology. Many important factors, such as long-term durability and end anchorage, have yet to be studied in sufficient detail. This technology is very promising as an alternative to steel reinforcing, but is currently a technological risk that must be considered.
- As discussed in Bechtel's final report, the cost benefits of using a large number of continuous spans must be carefully weighed. The use of continuous spans will allow more efficient piers and girders, but the construction complexity, and thus cost, will be greater. Maintenance of continuous span girders may also be more difficult.

Approach. The dynamic response of the girder to vehicle passage was studied using a beam-type finite-element model and the ADINA code. Speeds ranging from 100 to 500 km / hr (28 to 139 m / s) were considered. The required properties for the beam model (mass, stiffness, and moments

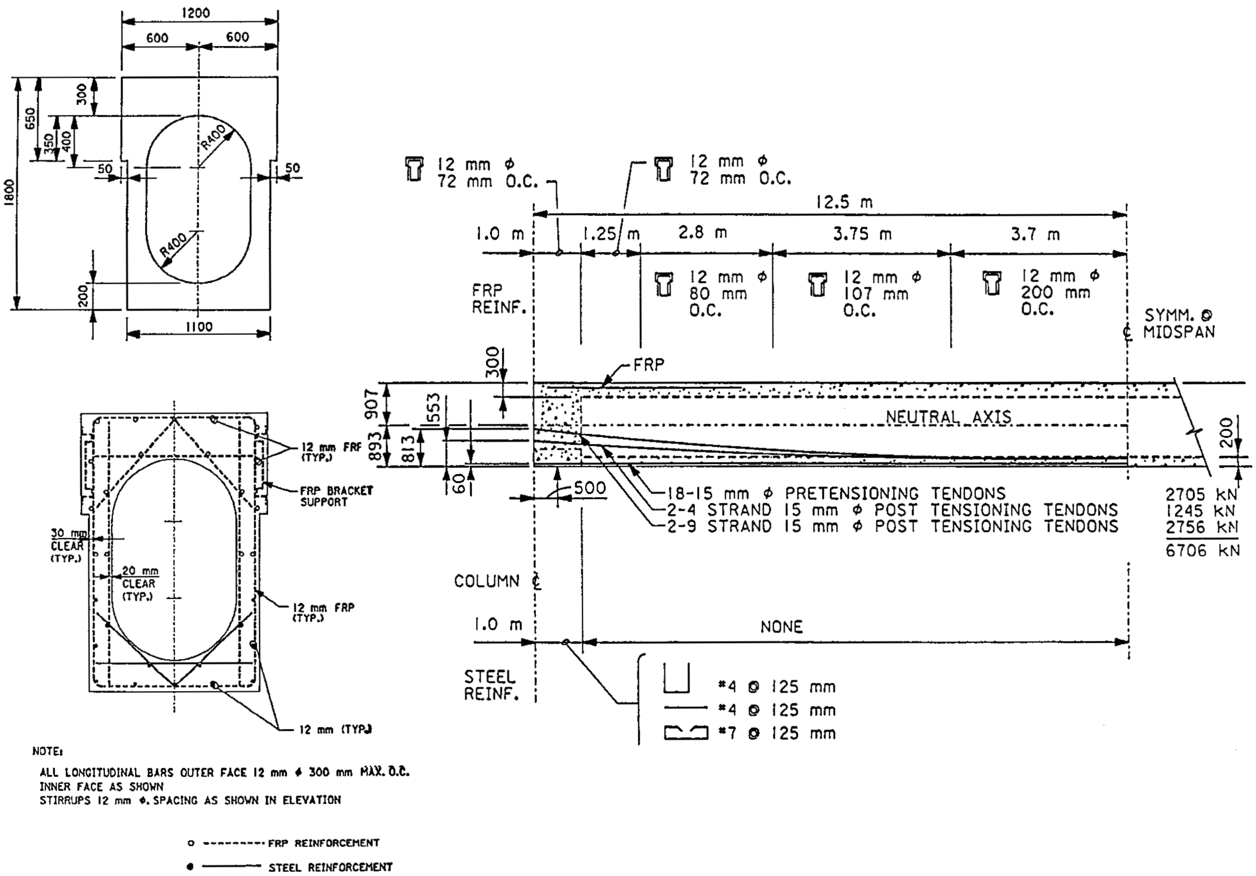


Figure 13. Bechtel girder design.

of inertia about the principal axes) were determined by conventional hand calculations. These calculations were made prior to the final baseline design and were thus based on an eight-span continuous structure over a flat surface.

The dynamic loadings were produced by distributing the vehicle weight out to each of the vehicle bogies and over the length of each bogie. Through use of a computer program, these loadings were then "swept" across an assumed straight and flat guideway and a load–time history was calculated for each loaded node. These loadings were simplified and are by no means a "worst-case" loading scenario. These calculations were only done to study the DLF associated with the specific combination of girder stiffness and bogie passage frequency. A more in-depth dynamic analysis would include more accurate vehicle loadings, accounting for vehicle suspension characteristics, guideway irregularity and curvature, and pre-camber and flexure of the guideway. If time had allowed on this project, these loadings would have been obtained from the vehicle–guideway interaction model produced by the Transportation Services Center (TSC), as described in section 3.2.4 of this report.

A three-dimensional finite-element model using 20-node solid elements is shown in Figure 14. It was employed along with the ABAQUS

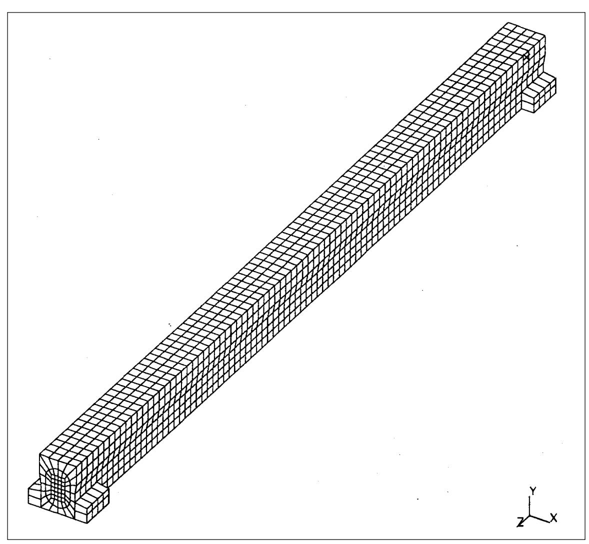
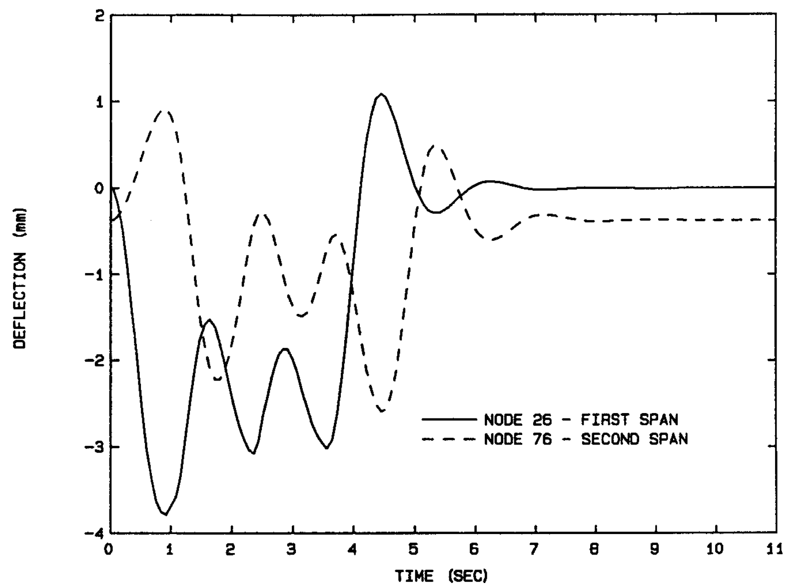
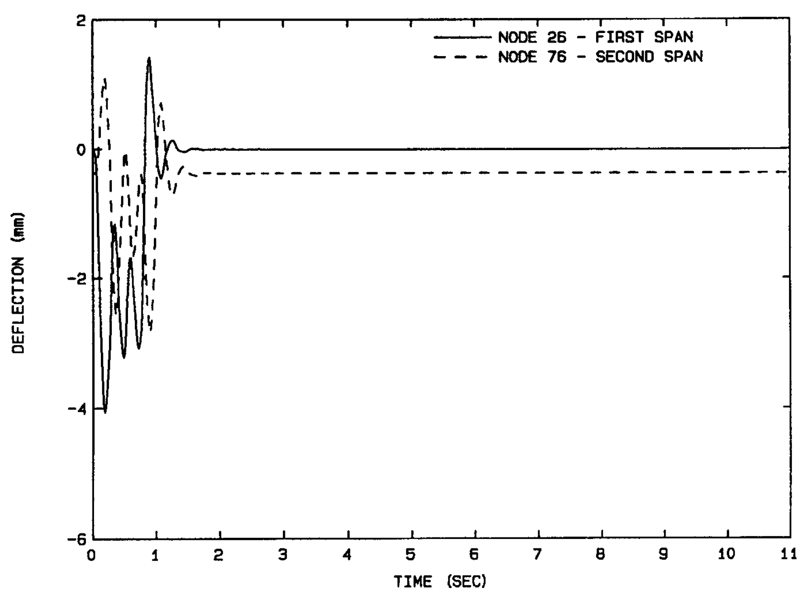


Figure 14. Solid-element model of Bechtel girder.

finite-element program to study the complex shear and torsional stresses within the girder and to determine its dynamic flexural characteristics. While reinforcing designs were provided by Bechtel for both straight and curved guideway sections, only the reinforcing for curved sections was modeled. The effect of the parabolically draped post-tensioning was modeled by applying an equivalent upward uniform load along the length of the girder and centered axial loads at the girder ends (as discussed in Nilson 1978). The straight post-tensioning was modeled by applying axial loads at the appropriate eccentricities at the ends of the girder. For expediency, the transverse reinforcing was not modeled and the concrete was assumed to be a linearly elastic isotropic material. These assumptions were reasonable since the deflections were known to be small and thus stresses would likely be low. More in-depth modeling would need a nonlinear concrete model that, upon cracking, would transfer all stresses to the reinforcing.



a. 100-km/hr vehicle passage.



b. 500-km/hr vehicle passage.

Figure 15. Dynamic analysis results from Bechtel beam-element model.

The design loadings for the propulsion–levitation–guidance system defined in section C2 of the Bechtel (1992a) SCD report were applied to the soild-element model. These loadings result from the vehicle in a curve at full speed and tilt with a 40-mph (18 m / s) crosswind, and with the larger fraction of wind force concentrated near the nose of the vehicle. These forces were assumed transferred to the guideway girder in the form of vertical and horizontal forces (levitation and guidance) at the attachment points for the levitation and guidance hardware.

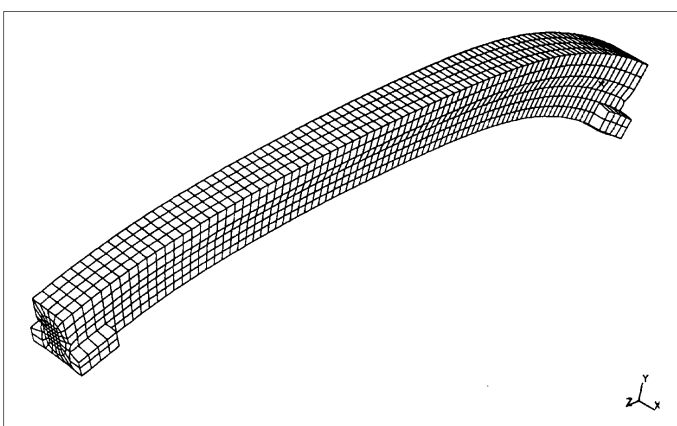
An eigenvalue analysis was also performed on the solid-element model using the ABAQUS program. This type of analysis is used to study the varied mode shapes and natural frequencies that make up the total dynamic response of the girder. It is very useful for understanding the manner in which a structure will respond to actual dynamic loadings.

Results. The results of the dynamic analyses with the beam element model are summarized in Figure 15 for the 100- and 500-km / hr vehicle passes. Both plots show deflection–time histories for the maximum response nodes of both spans 1 and 2 of an eight-span continuous structural system. We can see that, since span 1 was pinned at one end, its response to loading was greater than that of span 2, which was continuous across both of its supports. This demonstrates the effectiveness of continuous spans in reducing deflections. The response of span 1 is most similar to that which would be expected from a simply supported span, as called for in the final baseline design.

The maximum dynamic deflections varied from approximately 3.8 mm for the 100-km / hr vehicle passage to 4.2 mm for the 500-km / hr passage. If we assume that the 100-km / hr passage is equivalent to a static loading, this corresponds to a very low DLF of 1.10. The Bechtel report indicates that they conservatively used a DLF of 1.4 to design the girder. The low DLF shows the value of closely spaced bogies on the vehicle.

Please note that the loadings applied to the beam model were not the worst case and thus the deflections calculated were less than can be expected under more severe loadings. In addition, the post-tensioning for the beam element model was based on approximate values, since the Bechtel design was not complete at the time of these analyses. The results of these calculations should only be used to study the dynamic amplification effects of the bogie spacing and beam stiffness combination.

The displaced shape of the solid-element model resulting from the applied static loads discussed above is shown in Figure 16. Note that the girder bent about both the *x*- and *y*-axes as well as twisted about the *z*-axis. This was expected because of the way that the loads were applied. The deflected



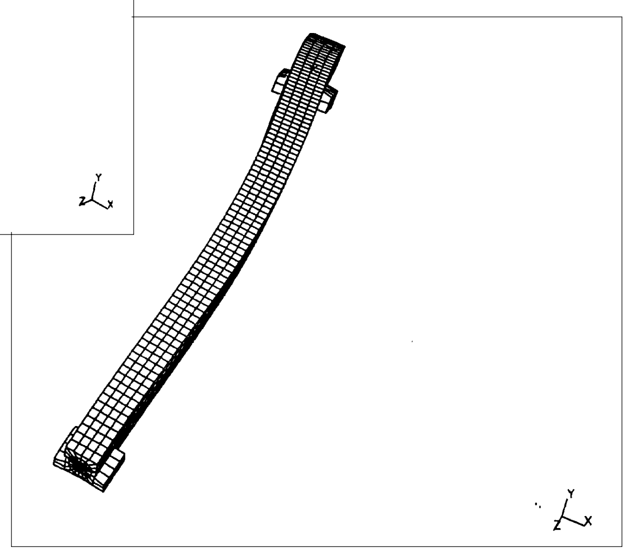


Figure 16. Displaced shape for Bechtel solid-element model.

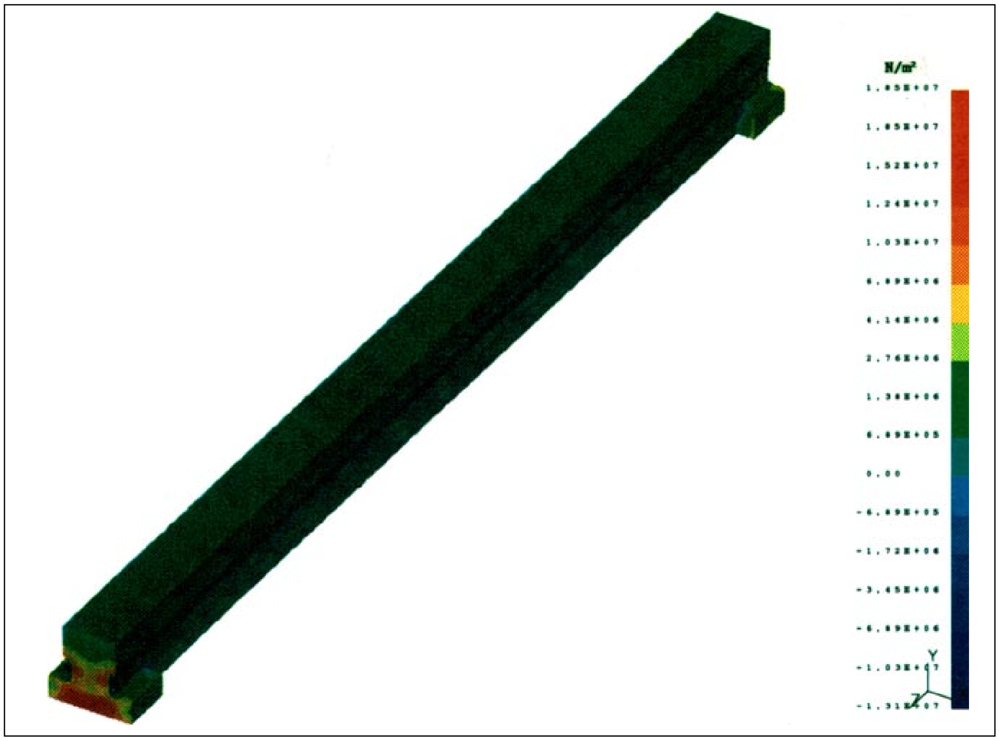


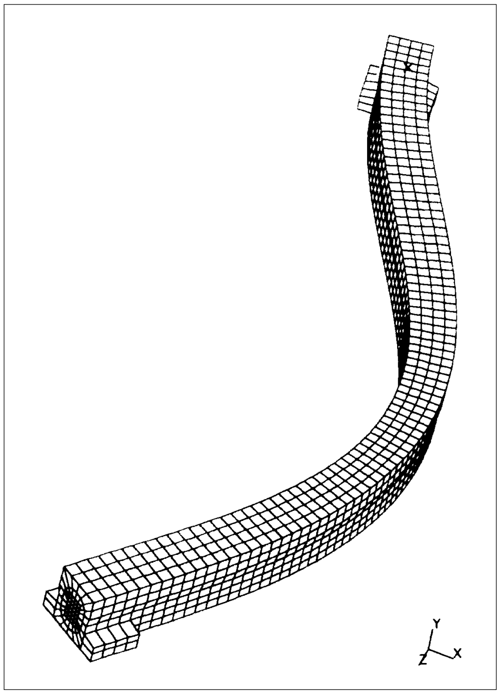
Figure 17. Maximum principal stress contours for Bechtel girder.

shapes are magnified several hundred times to show more detail. The actual deflections were quite small. The maximum (*y*-axis) deflection was only approximately 1 mm downward from its original 7.8-mm upward cambered position. The 7.8-mm upward camber may appear extreme at first. However, Bechtel designed their girder for a dynamic span:deflection ratio of 2500, which means they allowed for a 10-mm deflection response to a worst-case dynamic loading. Under this loading, the guideway would only deflect approximately 2 mm past its flat position if it had an initial 7.8-mm upward camber. A similar philosophy was used by the TR07 designers.

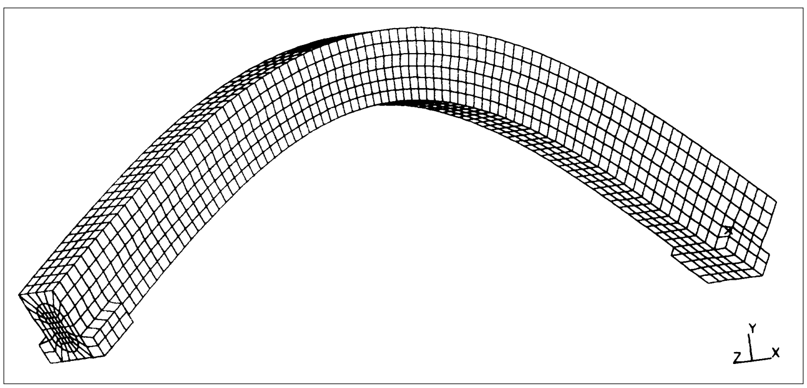
The maximum horizontal displacement (*x*-axis) was 3 mm. We expect that the load case used for this analysis was close to the worst case for horizontal guideway deflections. Therefore, little problem should result from a 3-mm horizontal displacement, since the physical lateral gap between the magnets in this direction is 50 mm. The maximum difference between *x*-displacements at the top and bottom of the girder, representing the degree of twist, was a negligible 0.4 mm. Therefore, even though the girder originally appeared torsionally weak, we may conclude that it is torsionally sufficient. This statement is also supported by the low stresses discussed in the following paragraph.

As seen in Figure 17, the principal stresses ascribable to the applied loads were low. The maximum principal tensile stresses were about 18.5 MPa, but these were at the ends where the prestressing forces were applied. In reality, these stresses would be more spread out owing to the normal methods of post-tensioning. The other principal stresses were quite uniform along the length and depth of the girder and were in the ±0.689-MPa range. Nilson (1978) says that principal tensile stresses in the concrete in the range of 2.5% of compressive strength are acceptable. This limit for a 69-MPa compressive strength concrete (Bechtel's design) is 1.73 MPa. The applied stresses (excluding those at the prestress anchor points) are below this value, without even allowing for the transverse reinforcing. However, the loading combination used to produce these stresses was not necessarily a worst-case combination for stress.

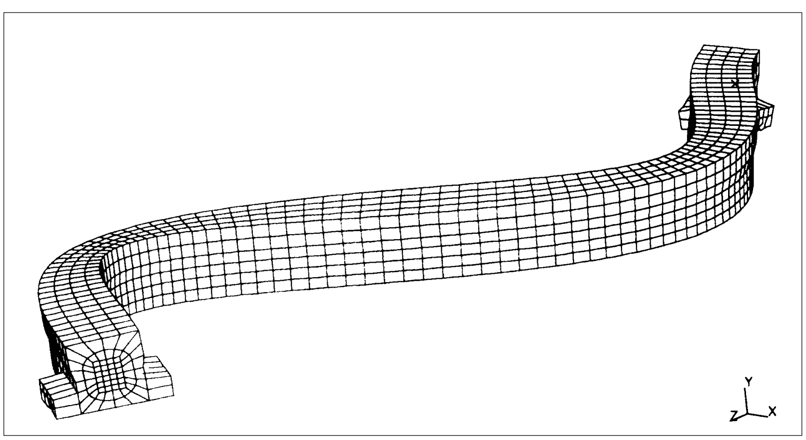
The first three dynamic bending modes are shown in Figure 18. These were as expected, showing the girder being weakest in bending about the *y*-axis, and then about the *x*-axis. The frequencies for the first through third bending modes were 6.3, 6.7, and 20.0 Hz, respectively.



a. First.



b. Second.



c. Third.

Figure 18. Dynamic flexural modes for Bechtel girder.

Since the vehicle bogies are closely spaced, these beam frequencies should not cause problems by resonance in any direction. This was also shown in the beam element analyses for bending about the *x*-axis only.

To address the viability of FRP reinforcing, we conducted a literature search to determine the state-of-the-art in FRP reinforcing. Little information was found on its use in major structures, especially pertaining to long-term durability and overall structural performance. However, this type of reinforcing has captured the interest of many researchers and much more information can be expected in the future. The advent of maglev promises to spur further interest and development in this area. Some basic information on different types of FRP reinforcing was assembled and is summarized in Table 26.

Conclusions. Although a complete range of static and dynamic loadings was not considered, the analyses told us that the girder should perform within its required limits. The variations of stresses (stress cycles) were not studied since a dynamic analysis was not made with the solid-element model. However, the low stresses and small deflections observed for the static load case show that the fatigue life of the structure should not be a problem.

Further study of this girder should include dynamic analyses with the solid-element model using more realistic and worst-case vehicular loadings, as provided from a dynamic vehicle model. These analyses would allow a study of stress cycles within the girder, which would give a better look at of its durability and the amount of transverse reinforcement actually required. Reducing the amount of transverse reinforcing would be beneficial since much of it is FRP reinforcing, the viability of which is yet to be proven.

Insufficient information exists at this time to allow strong conclusions about the viability of FRP reinforcing. The technology does appear to be evolving rapidly and holds promise. In the Bechtel girder, FRP is only used

Table 26. Characteristics of fiber-reinforced plastic (FRP) composite reinforcing.

Type	*Longitudinal tensile strength (MPa)*[a]	*Transverse tensile strength*	*Young's Modulus*	*Anchorage*			*Fatigue resistance*	*Chemical resistance*	*Durability*
				Expense	*Problems*[d]	*Creep*			
Prestressing steel	1600–1800	Same as longitude	200 GPa	Least	No	—	Susceptable to salt	Good	Good
Carbon fiber	Up to 2800[c]	Low	129 GPa[c]	Most[c]	Yes	—[e]	O.K.	Good[g]	—[h]
Aramid fiber	1200–1400	Low	41–65 MPa	Medium	Yes	—[e]	O.K.	Good[g]	—[h]
Glass fiber[b]	700–1500	Low	41–65 MPa	Least of FRP	Yes	—[e]	Least[f]	Good[g]	—[h]

[a] Strength increases with smaller diameter fibers because of less surface area for defects. FRP has no yield point prior to failure (straight line to failure).
[b] Most research data thus far. Most susceptible to surface flaws that affect strength.
[c] Depends upon purity of carbon fibers.
[d] Some successful methods exist but are expensive and difficult to use effectively. Post-tensioning presents most problems because of localized end anchorage. More research needed.
[e] No data on creep of FRP, except for small amount of conflicting data on GFRP. However, low modulus of FRP means concrete creep will cause less prestress loss.
[f] Alkali sensitive. Concrete is a strong alkali, so careful protection necessary.
[g] FRP not susceptible to fatigue-producing longitudinal magnetic forces from train passage. Fatigue from beam flexure dependent upon applied stresses, same as steel.
[h] No data on FRP. Research needed to study effects of water, oxygen, heat, light, etc., on creep, strength, polymer solubility, alkali resistance, etc.

for the top portion of the transverse reinforcing and it is not prestressed. This is considerably less risky than when it is used as main longitudinal reinforcing, especially when prestressed.

Foster-Miller guideway

General. The concept for the Foster-Miller guideway is shown in Figure 19. The guideway girder is a unique structure with an open-cell, integral sidewall constructed from modular units. Two symmetrical halves are coupled together by a series of intermittently spaced truss-type diaphragms. The modular system is designed to be lightweight enough that each half can be built at a central off-line facility and easily transported to the construction site.

The system is held together by post-tensioning tendons that run horizontally through the section. It is reinforced in the longitudinal direction by a combination of pre- and post-tensioned steel tendons in the lower half and FRP tendons in the upper half. While there is no bonded shear reinforcing, a combination of FRP post-tensioning and polypropylene-fiber-reinforced concrete is used to keep tensile stresses in the concrete within allowable limits. The girders will be placed on the pier supports as simple-span units. Then every other support will be made continuous through the application of external FRP post-tensioning, making a two-span continuous system.

Key issues.

- The Foster-Miller vehicle has bogies only at its ends, at spacings of 24.7 m. At these large spacings, the passage frequency of the bogies is very close to the primary flexural mode frequencies of the guideway, meaning that there are potential resonance problems. This interaction can greatly increase the dynamic flexural response and resulting stresses within the guideway.
- Since the cross section is quite complex and is loaded horizontally, vertically, and longitudinally through its sidewalls, conventional analytical methods for the prediction of local shear and bending stresses will not apply.
- The unique guideway design heavily depends upon the viability of FRP reinforcing as a nonmagnetic substitute for conventional steel reinforcing.
- Bending stresses within the cross section must be kept low enough through use of FRP prestressing and wall thickness adjustments to alleviate the need for bonded transverse shear reinforcing.
- The size and construction complexity of this guideway are a concern. The modular girders will be easy to transport, but this approach could have a significant effect on the complexity of construction.

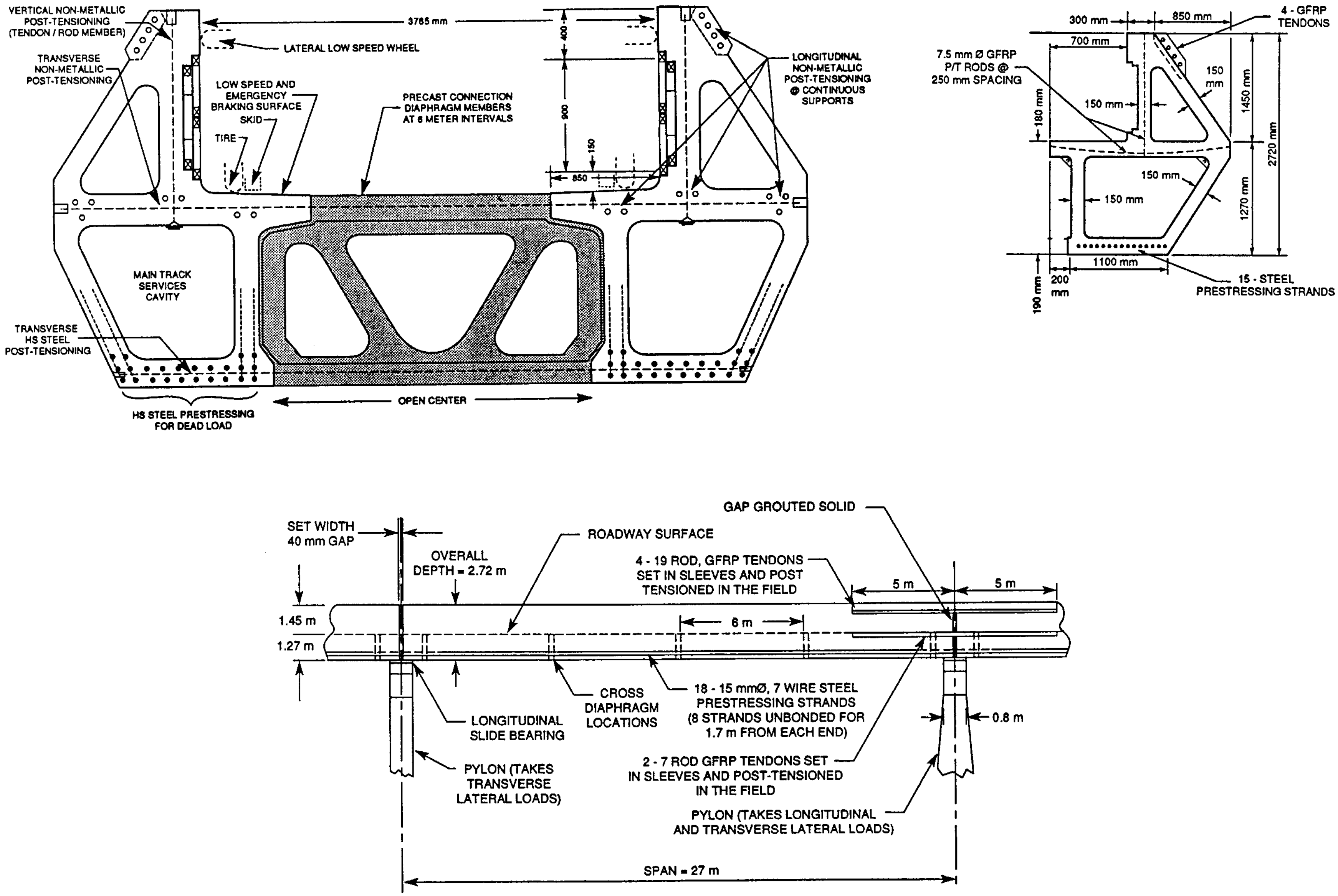


Figure 19. Foster-Miller guideway superstructure.

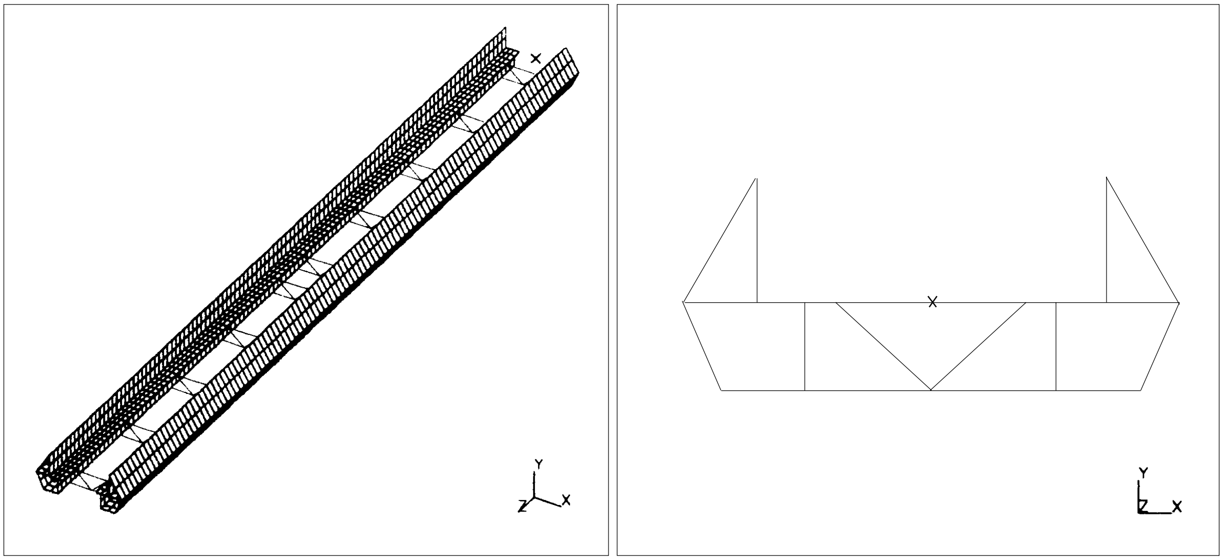


Figure 20. Shell-element model for Foster-Miller superstructure.

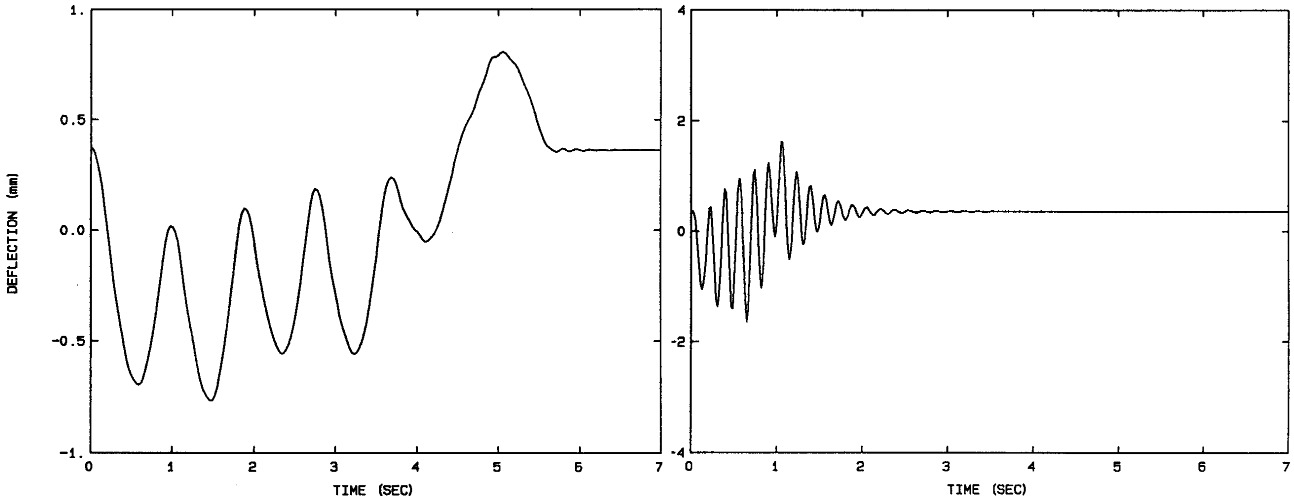
Approach. We studied the dynamic response of the girder to vehicle passage in the same way that we used for the Bechtel guideway. These calculations were made prior to the final baseline design and were thus based on a slightly different cross section than the final recommended design shown in Figure 19. However, the differences were small and should have little effect on the analytical results.

A three-dimensional finite-element model of the Foster-Miller guideway, using eight-node thin-shell elements, is shown in Figure 20. A two-span continuous structure was modeled. The ABAQUS code was used with this model to study the complex stress combinations within the girder and to study its dynamic flexural characteristics. All pre- and post-tensioning bars were modeled within the shell elements as rebar elements with initial stress conditions. The concrete was assumed to be a linearly elastic isotropic material.

The vertical and horizontal vehicular loadings discussed in section 3.4.4 of the Foster-Miller (1992a) final report were statically applied to the model. The vertical loadings were 51 kN / m and the horizontal loadings were 31 kN / m, both distributed over the 5-m bogie lengths. The horizontal loads were only applied to one side of the guideway at each bogie location. Since the structure is continuous over a support, two different load cases were considered. Load case 1 had only one bogie set in the middle of the first span, representing a vehicle halfway across. Load case 2 represented a vehicle with its midpoint at the middle (continuous) support and thus had a bogie set near the middle of each span. For load case 2, the horizontal portion of the loadings were applied in opposite directions from each other.

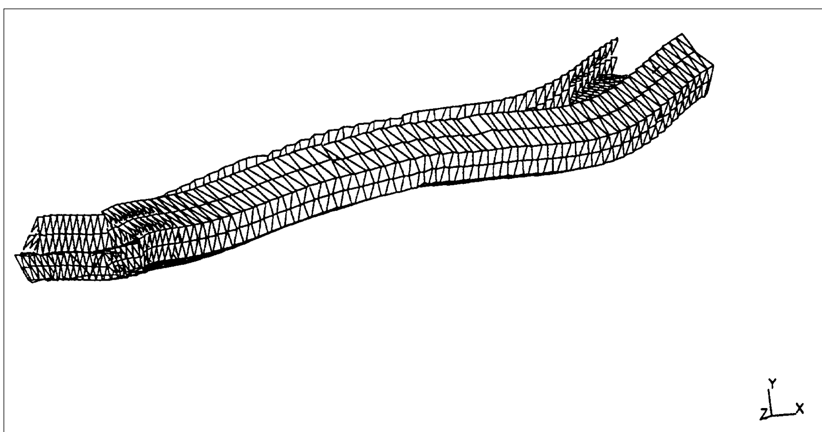
Results. The results of the dynamic analyses with the beam element model are summarized in Figure 21 for the 100- and 500-km / hr (28- and 139-m / s) vehicle passes. Both plots are for the maximum response nodes of span 1 only. The response of the second span was always identical to that of the first, indicating no dynamic coupling between the two spans. The maximum dynamic deflections varied from approximately 0.8 mm for the 100-km / hr vehicle passage to 1.7 mm for the 500-km / hr passage. If we assume that the 100-km / hr passage is equivalent to a static loading, this corresponds to a significant DLF of 2.10. The high DLF compared to that of the Bechtel design shows the trade-off associated with larger bogie spacings. Again, please note that the loadings applied to the beam element model were not a worst case and, thus, the deflections calculated were less than can be expected under more severe loadings.

The displaced shape of the shell element model resulting from load case 2 is shown in Figure 22. Of the two load cases, this one caused the greatest deflections and stresses. Bending occurred about both the *x*- and *y*-axes. The maximum downward (*y*-axis) deflection was 2.6 mm from its original 0.3-mm upward cambered position, ending up at 2.3 mm down from a flat position.



a. 100-km/hr vehicle passage. *b. 500-km/hr vehicle passage.*

Figure 21. Dynamic analysis results from beam-element model of Foster-Miller guideway.



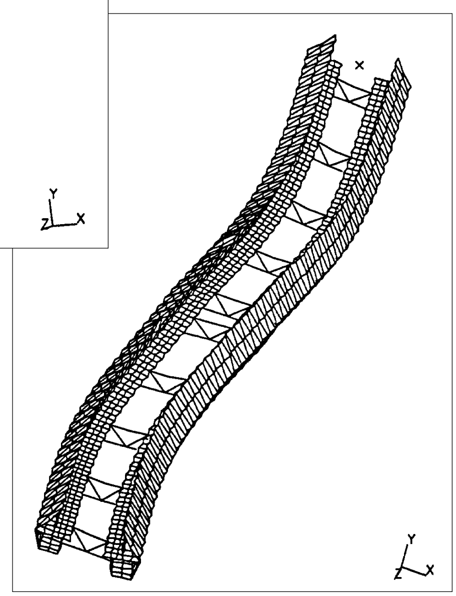
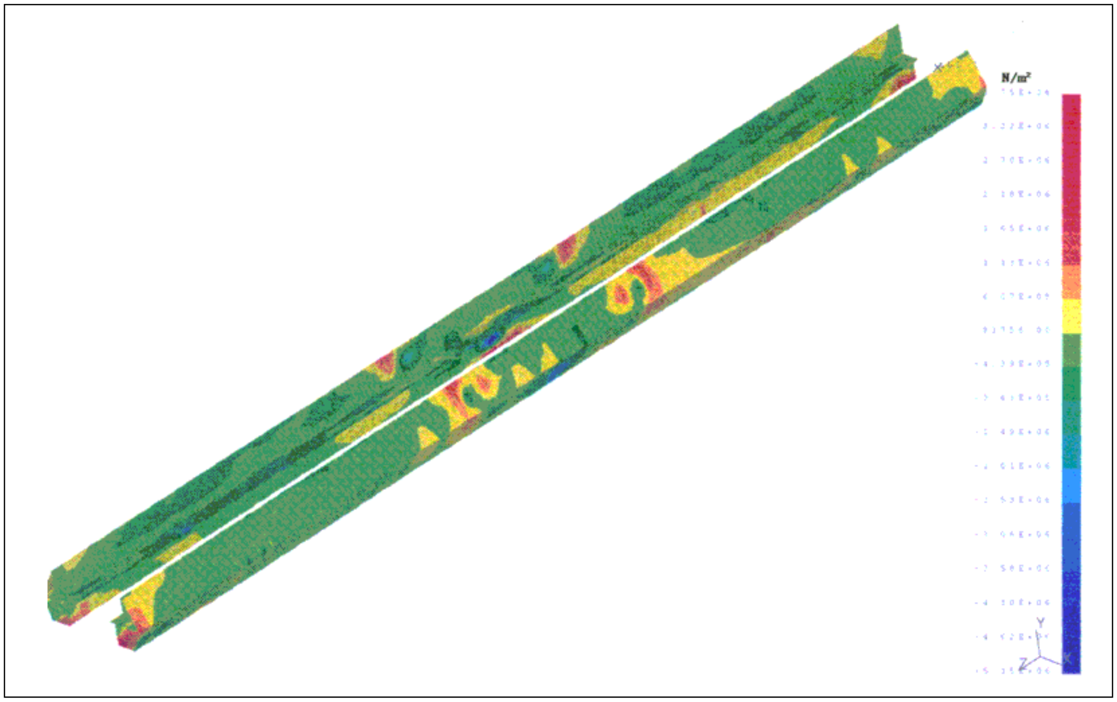


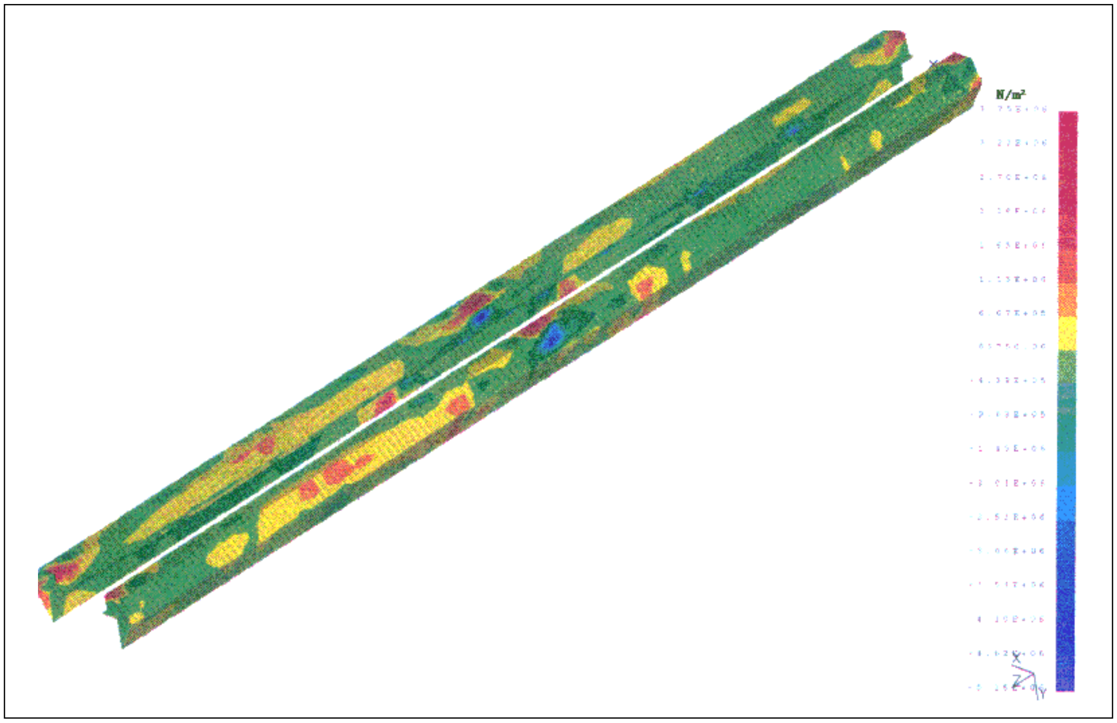
Figure 22. Displaced shape for Foster-Miller shell-element model.

The maximum horizontal (x-axis) displacement was 6.7 mm. The design horizontal gap between the magnets is 75 mm. Obviously, the lateral displacements would have been smaller if the lateral loadings had not been acting in opposite directions from each other. These were all static deflections and, according to the previously discussed dynamic analyses, would have been approximately twice as much if applied as sweeping dynamic vehicular loadings. The same applies to the stresses discussed below.

Although they resulted from the greatest of the two load cases considered, the principal stresses for load case 2 (Fig. 23) were low. The majority of the girder experienced compressive stresses below 0.96 MPa. If we neglect stress concentrations

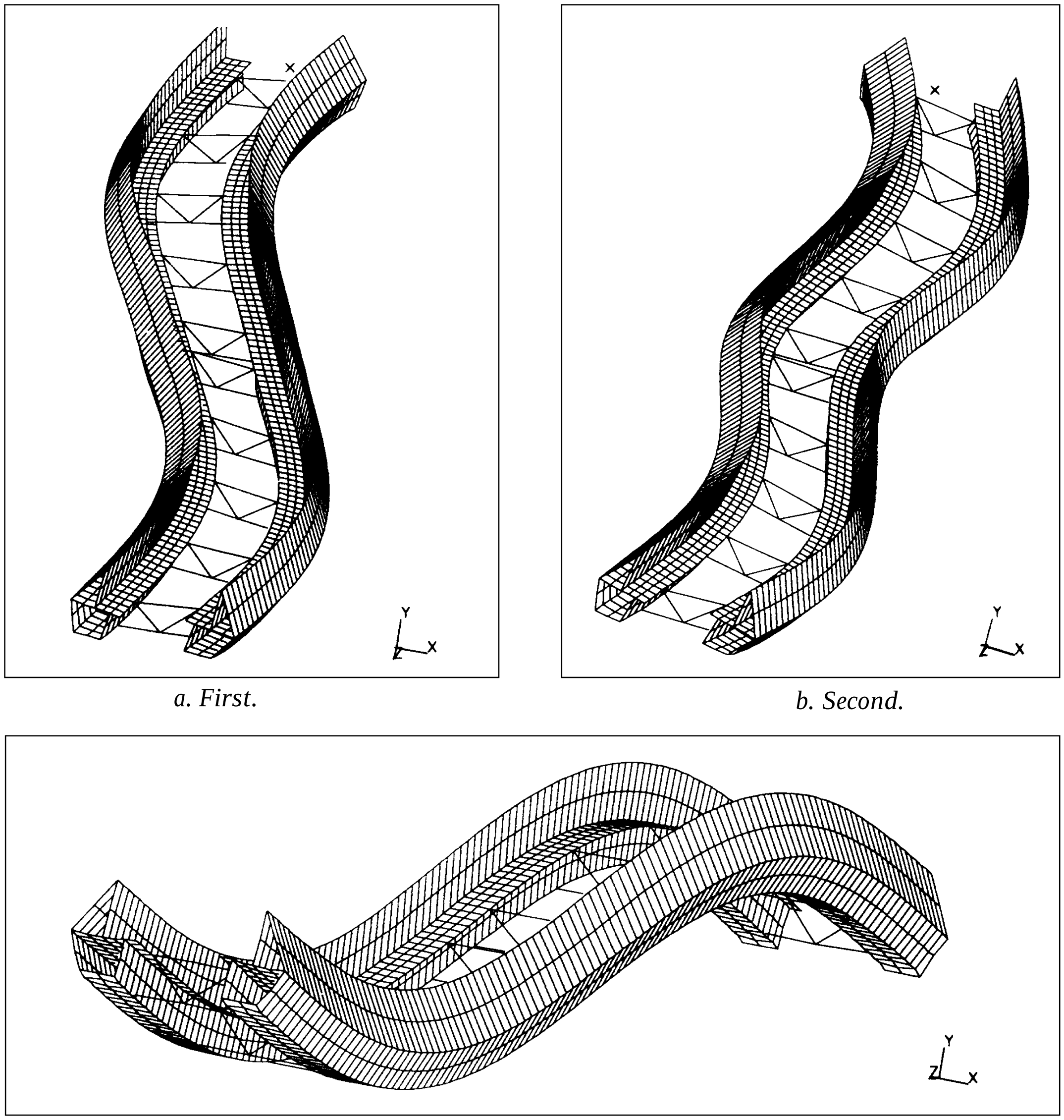


a. Top view.



b. Bottom view.

Figure 23. Maximum principal stresses for load case 2, Foster-Miller.



a. First.

b. Second.

c. Third.

Figure 24. Dynamic flexural mode for Foster-Miller superstructure.

ascribable to prestress anchoring and support conditions, the majority of maximum principal tensile stresses were below 0.61 MPa. These tensile stresses were well below commonly accepted allowable limits for pre-stressed concrete, which are in the 1.4-MPa range (Nilson 1978). Low stresses are desirable for the static case since the dynamic case could cause as much as a factor of 2 increase.

The first three dynamic bending modes are shown in Figure 24. These were somewhat surprising, since the first two modes were for bending about the vertical *y*-axis, indicating the structure to be weakest in this direction. However, upon closer study, it is understandable. The connecting diaphragms (between the beam units) are parallel to each other and perpendicular to the beam units, and thus add no stiffness in the horizontal bending direction. The frequencies for the first through third bending modes were 4.4, 5.2, and 5.7 Hz, respectively. These frequencies are of concern since the bogie passage frequency for the vehicle (with 24.7-m bogie spacings and traveling at 500 km / hr) is very close at 5.4 Hz. A complete set of dynamic analyses considering simultaneous vertical and horizontal loadings should be conducted.

Conclusions. The Foster-Miller guideway is a very innovative design that apparently meets all of their stated objectives. However, because of the complexity of the structure and the limited scope of this and the SCD analytical work, much more in-depth analyses should be conducted before its actual construction. Specifically, a more thorough study, possibly with a more refined finite-element grid, should be made of localized shear and bending stresses resulting from worst-case dynamic vehicle passages inducing three-dimensional loadings. Note that these dynamic vehicle loads may well result from resonance conditions. This study is particularly important since the current design employs no bonded shear reinforcing in the precompressed zones, mandating that tensile stresses be kept very low for safety and durability.

The analyses showed that the principal stresses within the structure were low for the load cases considered. Principal stresses are useful in visualizing the flow of stresses in uncracked beams. They also provide useful information on the location and orientation of diagonal tension cracking and the load at which these cracks might occur. However, because small increases in load beyond this point can cause disproportionate increases in diagonal tensile stresses, principal stresses do not give us a good indication of the inherent safety of the structure. A strength analysis, based on direct tensile and shear stresses, is necessary for this. The shell element model used here can provide this information.

The heavy dependence of this guideway on nonmagnetic FRP reinforcing is a concern because the longevity of this material is not currently well known. In particular, the durability of the attachments of post-tensioning rods is an issue requiring further study. Also, the consequences of using conventional steel reinforcing in this guideway warrant investigation to determine whether FRP is enabling technology or enhancing technology. Despite these issues, FRP appears headed for use in high-performance civil structures, so that practical experience with it will soon begin to accumulate. This experience will undoubtedly address its durability and hence its desirability for use in maglev guideways.

Grumman guideway

General. The concept for the Grumman superstructure is shown in Figures 25. The superstructure design is very innovative in that it allows for two guideways to use the same substructure system. The relatively small hat-type slab elements that are actually traversed by the vehicles are each supported on closely spaced (4.6-m centers) outrigger elements, which are connected to a central simply supported “spine” box girder.

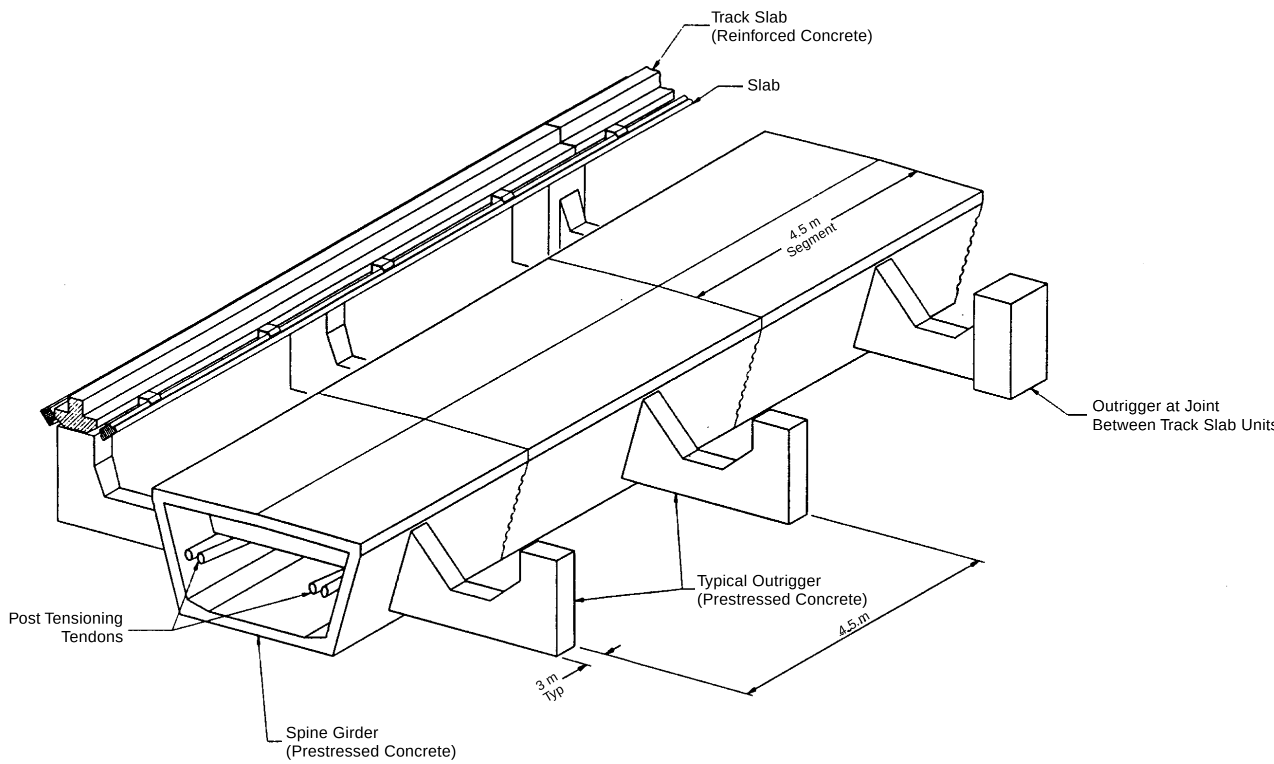
The slab elements are precast reinforced concrete units, continuous over the outriggers and simply supported only at 27-m centers to match the spine girder. To reduce deflections further, part of each levitation rail is designed to act compositely with the slab elements.

The spine girder is constructed from 4.5-m-long precast segments that are post-tensioned together. The post-tensioning has been equally divided between adjustable and nonadjustable profiles. The adjustable tendons allow periodic changes in the span deflections to cancel the effects of concrete creep.

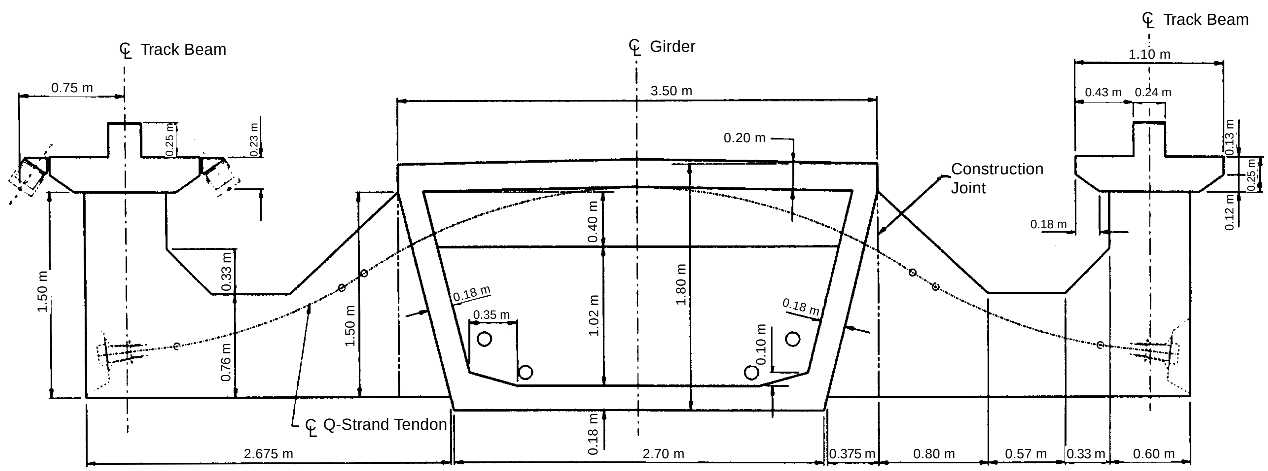
Key issues.

- Since two vehicles may pass simultaneously on opposite sides of the spine girder, complex deflections and stresses may be induced, both of which will affect the total movement and thus ride quality experienced by the passing vehicles.
- The combined bending and torsional stresses within the central spine girder cannot be accurately predicted with conventional analytical methods.

Approach. The three-dimensional finite-element model used for the analyses of the Grumman guideway is shown in Figure 26. The spine girder and outriggers were modeled with combinations of four- and eight-node thin shell elements, and the guideway slab elements were modeled with beam elements. The composite-acting levitation hardware on the slab elements was not modeled. The ABAQUS code calculated both static and dynamic responses. We modeled the post-tensioning effect in the spine girder by applying an equivalent upward uniform load along the length of the girder and central axial loads at the girder ends (Nilson 1978). We modeled the post-tensioning effect in the outriggers by applying axial loads at the anchor points for the tendons. This method did not accurately account for the draping of the outrigger tendons through the cross section; future modeling should account for this. The transverse reinforcing in the spine girder was not modeled and the concrete was assumed to be a linearly elastic isotropic material. These assumptions were reasonable since the deflections were known to be small, likely keeping stresses low. More in-depth modeling would employ a nonlinear concrete model that, upon cracking,



a. Detail view.



b. Cross-sectional detail.

Figure 25. Grumman's spine-girder superstructure.

would transfer all stresses to the reinforcing. This will be especially important for ultimate strength and earthquake response calculations.

Because of time limitations, only two load cases were considered. The first was the static application of vehicle loads on one side of the guideway only, and the second was the dynamic application of the same vehicle loads moving across the span at 500 km/hr (139 m/s). The dynamic loadings were produced by distributing the vehicle weight out to and over the length of each of the vehicle bogies. Through use of a computer program, these loadings were then swept across an assumed straight and flat guideway and a load–time history was calculated for each loaded node. Note that these loadings were simplified and by no means were a worst-case loading scenario.

Results. The magnified displaced shape of the finite-element model resulting from the dynamic load case is shown in Figure 27. The deflected

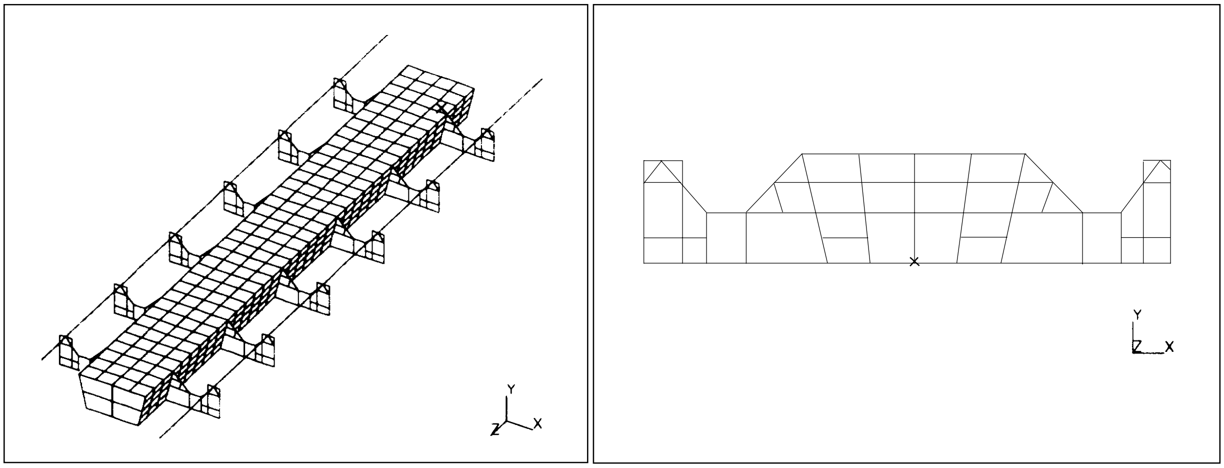


Figure 26. Finite-element model for Grumman superstructure.

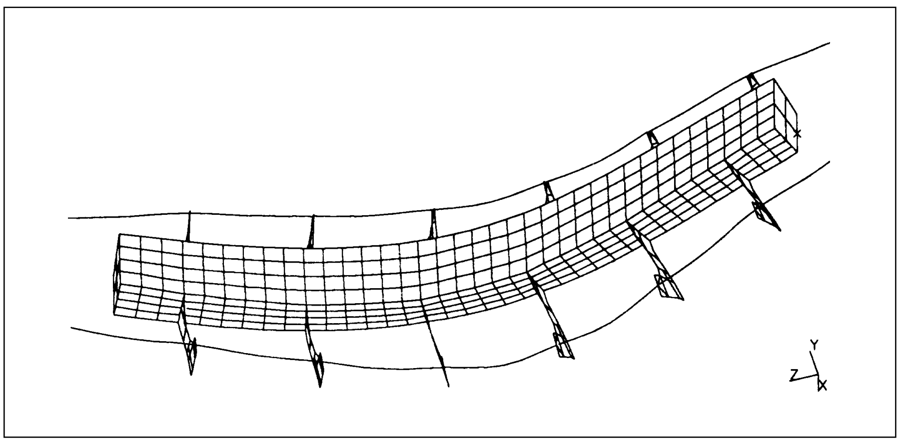


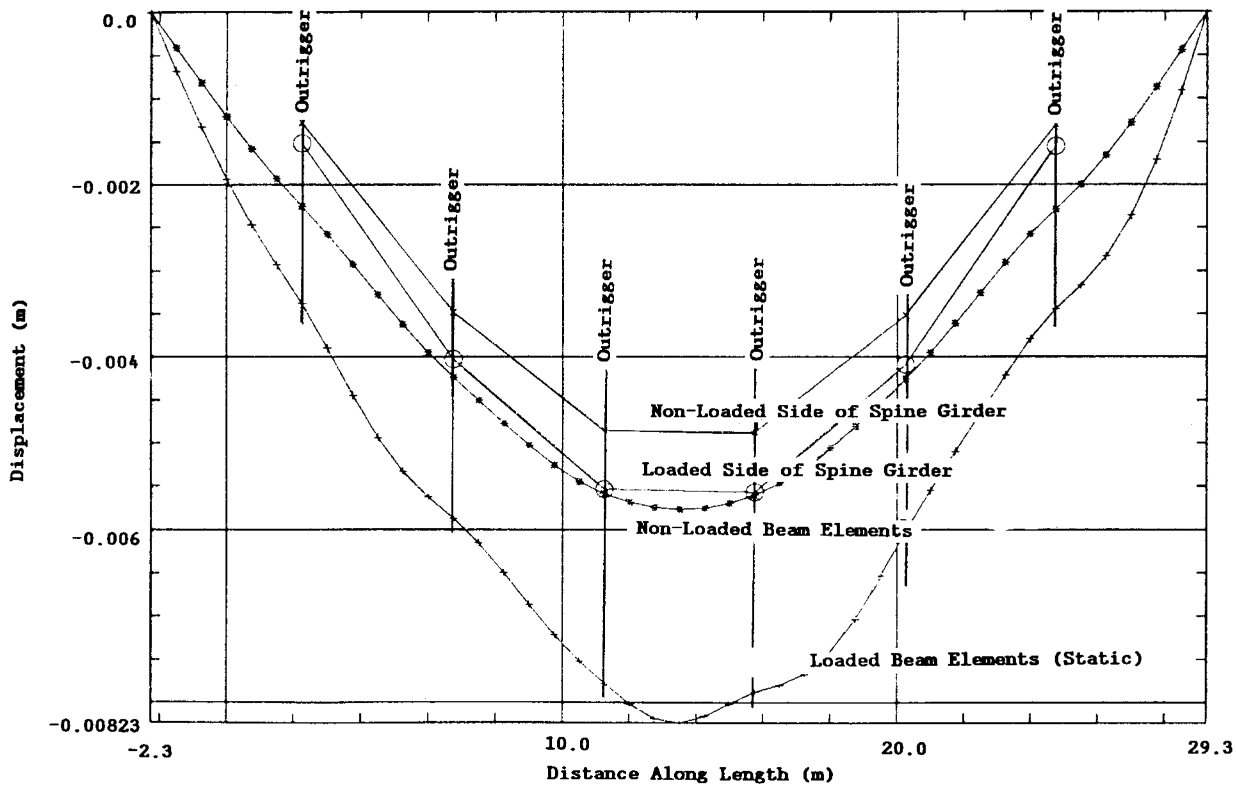
Figure 27. Displaced shape of Grumman finite-element model at t *= 0.22 s.*

shape for the static load case was the same, except that no deflection was seen in the unloaded slab elements on the opposite side of the guideway. These elements experienced deflections for the dynamic case because of their inertial response to motion.

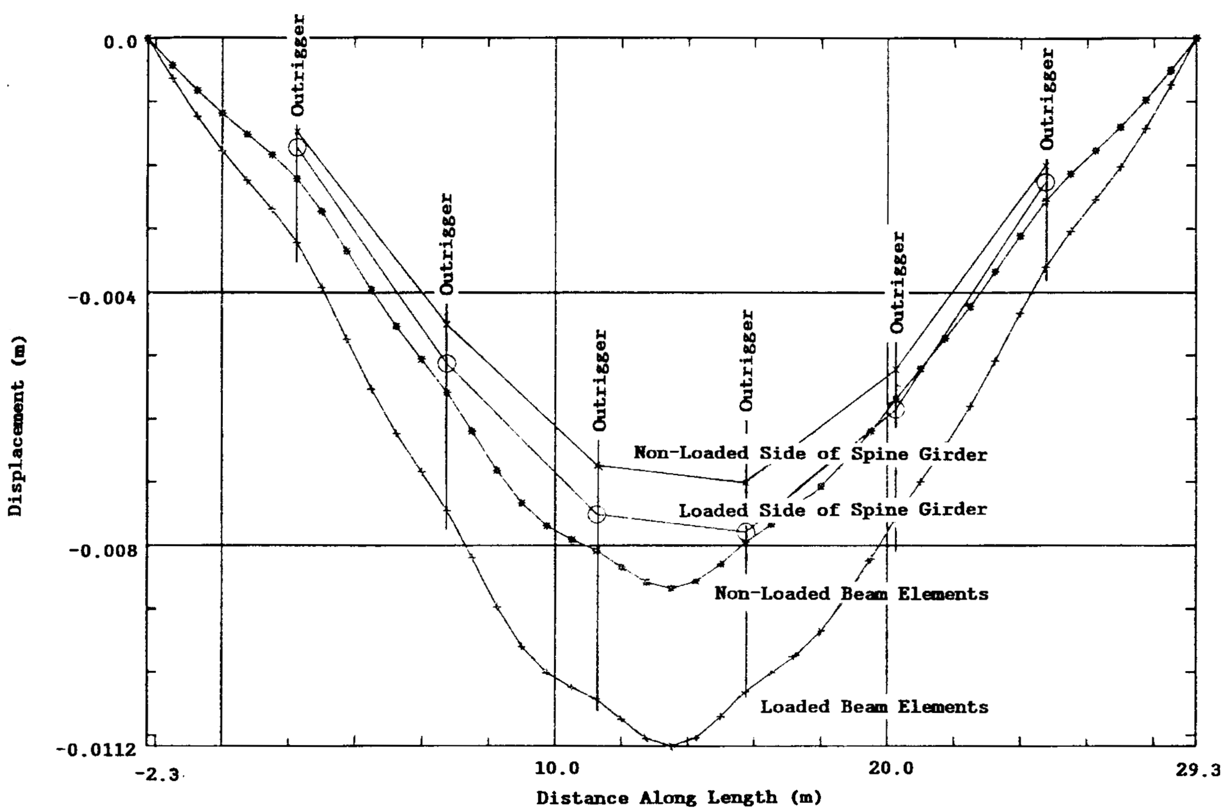
Figure 28 compares nodal deflections along the length of the structure for both the static and dynamic cases. The deflections of both the loaded and unloaded beam elements (track slab) are shown, together with both the loaded and unloaded side of the spine girder. Comparing these deflections shows the amount of torsional twist experienced by the spine girder and the local and total deflections experienced by the beam elements.

For the dynamic case (Fig. 28b), the maximum local deflection of the loaded beam elements between outrigger supports was only about 1 mm. However, the total deflection, accounting for spine girder twist and vertical deflection and outrigger flexure, was 11 mm. The vehicle bogies should respond mainly to the local deflection of 1 mm and thus minimum gap requirements should easily be met. However, the vehicle as a whole will be affected by the total 11-mm movement of the guideway and ride quality may be affected. Note that the outrigger flexure accounted for much of the total movement. The outriggers could be stiffened by a redesign of their shape or of the post-tensioning. It is also possible that the way in which the outrigger post-tensioning was modeled was too simplified and showed more deflection than would actually be the case. Future analytical work should address this possibility.

Comparing the static and dynamic deflections in Figure 28 gives a DLF of approximately 1.6 for the slab elements and 1.4 for the spine girder. These values are a bit higher than the 1.2 value that Grumman used in their design calculations.



a. Static vehicular loading.



b. Dynamic vehicular passage.

Figure 28. Displacement along length of Grumman superstructure.

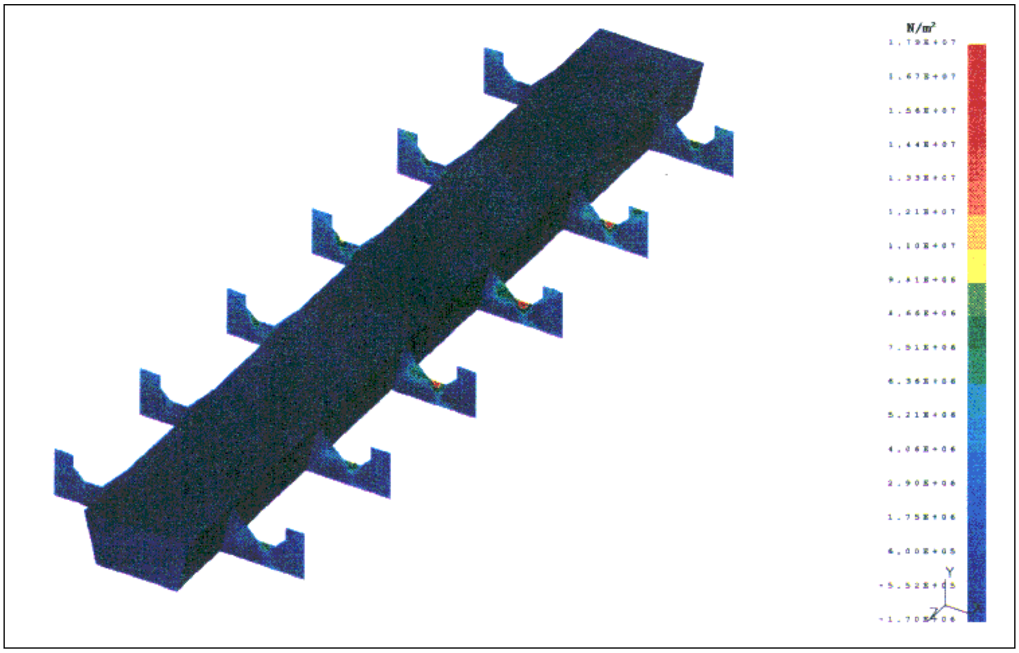


Figure 29. Maximum principal stresses from Grumman analysis at t *= 0.22 s.*

The reason for the relatively high DLF for the slab elements is not readily clear because the Grumman vehicle has closely spaced bogies that would normally load the guideway at a high enough frequency to avoid large dynamic increase effects. However, the slab elements may be of short enough span and stiff enough that their natural frequencies are close to the loading frequency. Also, the loading frequency that the spine girder actually experiences may be considerably lower than the bogie passage frequency since it is transmitted to the spine girder through the 4.6-m center to center outriggers. Further study should be made of the dynamic response of the guideway, especially with simultaneous vehicle passages on both sides.

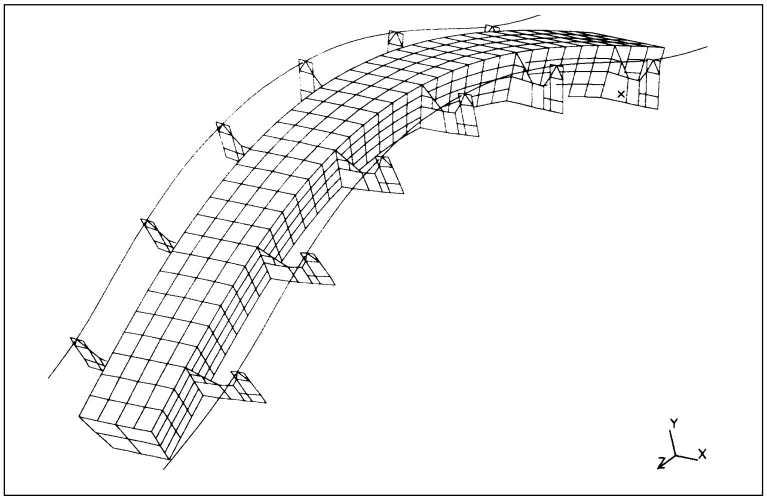
The maximum principal stresses for the dynamic load case at the time of maximum deflection are shown in Figure 29. Most of the guideway experienced compressive stresses around 1.7 MPa. We saw very little principal tensile stresses throughout most of the structure. The exception is at the tops of the outriggers, where the principal tensile stresses were approximately 17.9 MPa. Such stresses would likely cause cracking of the concrete and hence could affect its durability. Nevertheless, the problem is easily rectified by adjusting the drape or the degree of post-tensioning in these areas or by changing the overall dimensions of the outriggers. We do not see this as a critical issue.

The first three dynamic bending modes are shown in Figure 30. The first mode had a frequency of 4.4 Hz and represented overall bending of the entire structure. The next two modes had basically identical frequencies of around 4.9 Hz and represented flexure of the outrigger elements.

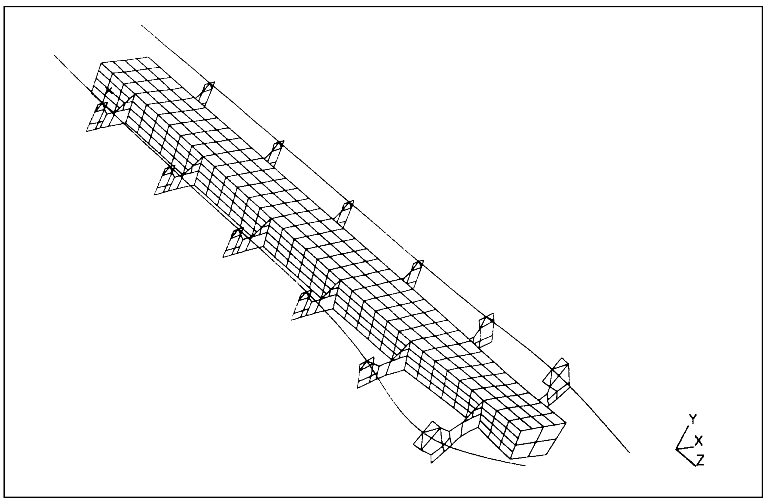
Conclusions. The Grumman guideway appears to be very efficient—it allows two guideways to use the same substructure. The analyses tell us that it will perform this function within allowable limits. However, a much more dynamic analysis would be required before it is actually built. These analyses should include more accurate vehicle loadings accounting for vehicle suspension characteristics, guideway irregularity and curvature, pre-camber and flexure of the guideway, and unbalanced loadings on the vehicle. In addition, various combinations of simultaneous vehicle loadings (i.e., one on each side of the guideway) must be considered.

Magneplane guideway

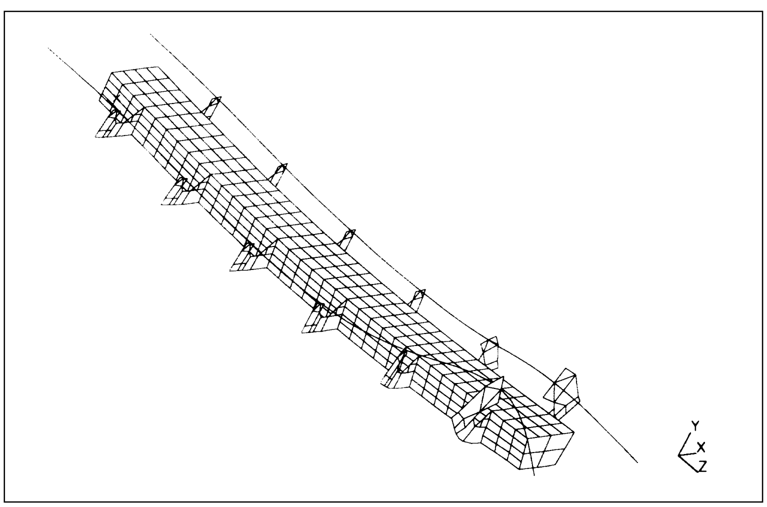
General. The Magneplane guideway, called a "Magway," consists of a trough and its supporting substructure (Fig. 31). The trough is composed of two aluminum levitation plate box beams connected by an LSM winding. The design varies, depending upon the required span length and guideway curvature–superelevation requirements. The design discussed here had a 9.14-m



a. First.

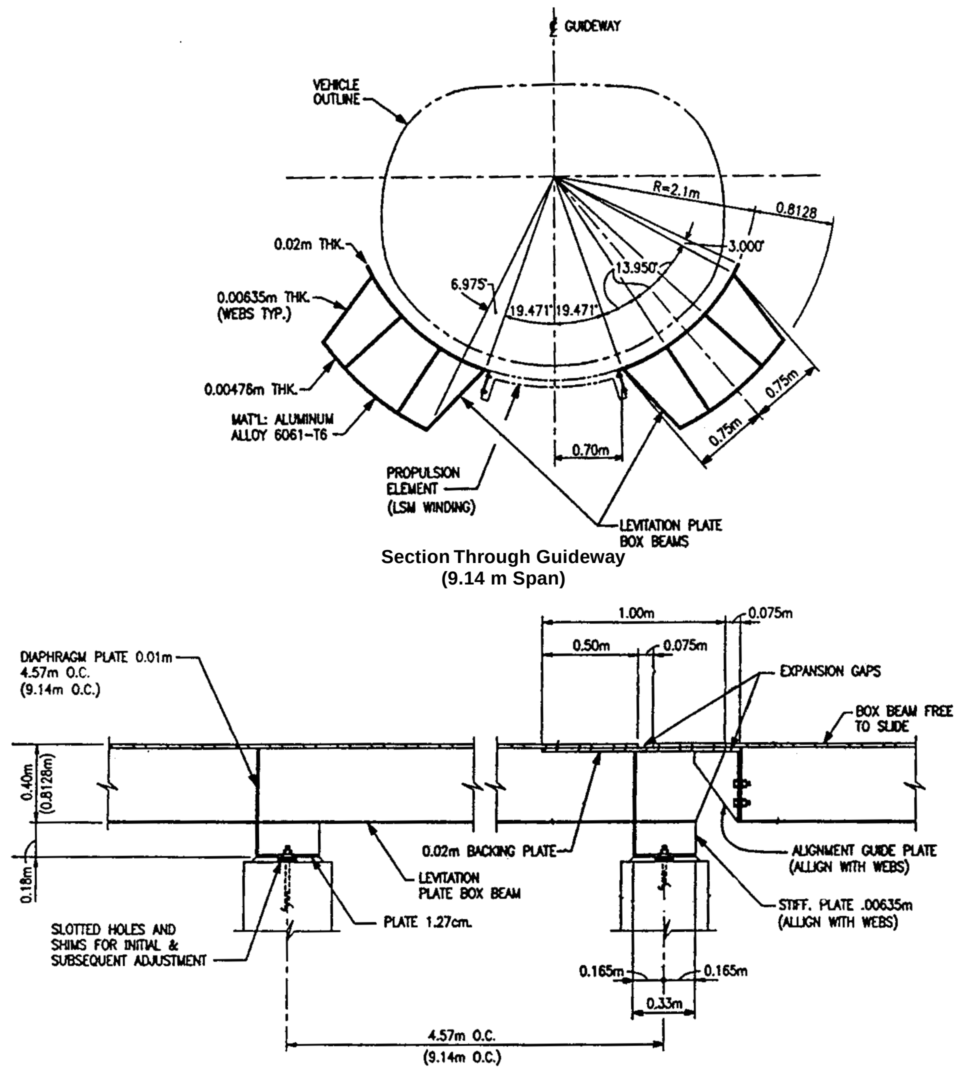


b. Second.



c. Third.

Figure 30. Dynamic flexural modes for Grumman superstructure.



Section Through Guideway
(9.14 m Span)

( ) Dimensions are for 9.14 m Spans
Longitudinal Section

Figure 31. Magneplane guideway superstructure.

span and the levitation box beams were 0.81 m deep. These beams are two-span continuous and connected to adjacent beams, as shown in Figure 31.

Key Issues.

- Aluminum structures are very susceptible to fatigue failure, and as a result have a short life expectancy unless the applied cyclic stresses are within durability limits. Because of the structure's complexity, conventional analytical methods may not reliably predict the actual stress states experienced by the structure.
- Aluminum also experiences a high degree of movement with temperature variations. This property will require careful and innovative designs for expansion joints within the trough and the connections of the aluminum trough to its supporting structure and LSM winding.
- Because of the vehicle's high banking angles in curves, large tangential and torsional loadings will be applied to both the superstructure and substructure and must be carefully considered in the design.

Approach. The three-dimensional finite-element model used for the analyses of the guideway is shown in Figure 32. The ABAQUS code was used to calculate static response and to study dynamic flexural characteristics. All parts of the guideway, including the diaphragms, were modeled with eight-node thin shell elements. The aluminum 6061-T6 material was modeled as an isotropic