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ADVANCED LOW-COST, HIGH-PERFORMANCE GUIDEWAY CONCEPTS

Office of Research and Development
Washington, D.C. 20590

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FINAL REPORT
VOLUME 1

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16. Abstract

This report presents the results of a program to develop a high-performance, low -cost guideway configuration to meet the requirements of a United States Maglev system. This work initially involved research to identify and quantify the guideway design requirements specific to such a U.S. system. Based on the defined requirements and the general configuration options identified by this research, four alternative guideway concepts were developed which are primarily applicable to electrodynamic systems.

From the results of previous research in this area, a U-section guideway was chosen for the general configuration. The design options and enhancements developed by Foster-Miller, which include open floor, nonmetallic post-tensioning, and high strength, polypropelene reinforced concrete, further supported this selection. Extensive dynamic analyses were conducted to design and size each of the four candidate configurations. Further analyses evaluated the effects of span length and supporting pylon attachment with respect to both static and dynamic loading. Design and analyses of pylon and footing structures were also conducted. Fabrication and erection procedures were identified.

A cost analysis was developed which included all aspects of the guideway structure. This cost analysis and all other design aspects were included a tradeoff analysis which identified a dual cell, integral sidewall U-section with a partially open floor and alternating continuous span construction as the most favorable concept. Detail design is presented and recommendations are made for further development.

A second volume of this report, entitled "Design Calculations for Prestressed Guideway Beams (Girder Elements)" contains the supporting data and calculations in tabular form.

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PREFACE

The work in this report was sponsored by the United States Department of Transportation (DOT), Federal Railway Administration (FRA), through the National Maglev Initiative (NMI). The COTR for this program was Mr. A. Sluz of the Volpe National Transportation Systems Center.

Foster-Miller acknowledges the significant contributions of several individuals toward this program: Mr. Adam Purple and Dr. David Wormley, who conducted numerous dynamic analyses to evaluate the performance of the various guideway designs; Mr. Robert O. Fowler, P.E., who supported the design calculations and made the cost estimations; and Mr. Douglas Thomson who contributed to this report.

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1. INTRODUCTION

The development and selection of the guideway configuration is a central element in the overall design of a maglev system. All the fundamental system-wide technical and operating issues, such as those involving the vehicles, suspensions, capacity and power requirements, are interrelated with the guideway design in some manner, as are such requirements as high levels of safety, environmentally acceptable operation, and long life. Since the majority of the acquisition cost for intercity and longer-distance systems is attributable to the guideway and station network, the guideway design is naturally looked at closely for the best balance of low life-cycle cost versus meeting or exceeding system requirements. Some of the latter would certainly include safe, stable high-speed operation, achieving basic requirements of speed and capacity, and compatibility with the available route alignments and infrastructure.

The goals of this Phase I study can be summarized:

- Identify and quantify key guideway design elements for the United States maglev system requirements.

- Develop concepts for alternate guideway structural configurations that can yield high performance with low cost, incorporating recent technological improvements in high strength materials and advanced fabrication methods.

- Perform structural analyses for optimized stiffness and strength of candidate configurations, cost evaluations (both initial construction and life cycle maintenance cost) and tradeoff studies to determine most suitable configurations for United States maglev applications.

- Develop requirements for further study to substantiate the selected configurations, materials, and construction procedures.

The study addresses these goals through a sequence of task areas described in detail in the following sections. These include:

- Development of requirements for a U.S. maglev guideway system, based upon evaluation of essential features, operational and cost goals, including the accommodation of capacity growth.

- Development of candidate guideway concepts and configurations that address these requirements. These will include compatible switching and adaptability for tube-enclosed concepts.

- Structural and cost analyses for these configurations to a degree sufficient to evaluate them in tradeoff studies. An important part of this analysis includes the structural limits resulting from the projected dynamic behavior of the guideway with vehicle consists operating at revenue speeds.

- Tradeoff studies to select the candidate which best addresses the system requirements at acceptable cost.

- Further engineering development of the selected configuration.

- Recommendation of programs which could provide needed research or further technologies utilized in the guideway design.

The goal is to develop an advanced, innovative guideway which meets all safety and operational requirements, while minimizing manufacturing and erection cost and complexity.

2. REQUIREMENTS FOR U.S. MAGLEV

After detailed study of the needs for a U.S. intercity maglev network, we see that several major objectives will drive the design and development of the maglev guideway. The designs which will be addressed in this study are primarily applicable to a superconducting electrodynamic levitation system. These designs should:

- Accommodate a range of superconducting (SC/EDS) maglev schemes
- Accommodate vehicles sized for the U.S. market
- Provide for a primarily elevated system
- Support all operating and emergency loads
- Favor high capacity operation
- Provide for growth and technological advances
- Be built and operated at low life-cycle cost
- Provide high ride quality.

Maglev Layouts

The guideway should accommodate high capacity superconducting electrodynamic levitation and guidance/propulsion schemes (EDS). At present, these provide the greatest promise for high capacity, high speed maglev with manageable guideway tolerances. Here, these can include a conventional ground coil levitation layout with active sidewall propulsion coils, and null-flux sidewall layout, in which propulsion, guidance and levitation coils are overlaid in the vertical sidewall. After early experiments with inverted T-shaped SC/EDS layouts over a decade ago, Japan Railways (then JNR) has developed third-generation U-shaped ground-coil maglev configurations using full-scale vehicles and guideways in intensive long-term development programs. The null-flux approach is also entering major full-scale test and evaluation by JR and Japan's RTRI, using the same full-scale vehicles.

Vehicle Size

The minimum practical vehicle cross section for United States ridership acceptance and safety is based on a four-abreast configuration with modern airline type seating as a minimum guideline. Cross-sectional area is the major driver for aerodynamic power consumption, which dominates in speed ranges of 134 m/sec (300 mph) or greater. This also strongly favors a longer consist to minimize energy costs per passenger. Single-vehicle type systems pay a heavy aerodynamic energy penalty even if capacities are achieved through very tight headways, since large frontal drag forces are repeated for each vehicle. The guideway, therefore, is sized to accommodate vehicle widths of approximately 3.0 to 3.1m (9 ft - 10 in. to 10 ft - 2 in.), operating in two- to eight-car consists.

Elevated System

The system is primarily an elevated system which should use clear spans in the 24 to 30m range for minimal disruption in United States metro-corridor areas. Although even longer spans are feasible, fabrication and transportation costs rise quickly beyond this range. For unobstructed or sparsely populated areas, short span "low-rise" light guideway or even at-grade construction might be favored for cost reasons, but overriding concerns for safety and the reduction of potential obstruction hazards may make these approaches undesirable. Fewer areas will require tunnel or long-span bridge crossings.

Load Combinations

Guideway operating load combinations include the effects of vehicle interaction, aerodynamics, propulsion, guidance, levitation, speed, guideway curvature, and environment. Further, provision must be made for all potential emergency loads, balanced against their probability of occurrence. Both "working stress" analyses for operating conditions and "ultimate stress" analyses using accepted "factored" loads should be used. Factoring of all these various load conditions will be done using accepted civil-transportation practice.

High Capacity Operation

Any new transportation network in the United States, including maglev, requires sound economic cost-benefit justification. Based on goals provided in the National maglev Initiative, the system must have the potential of safely accommodating both passenger traffic levels in the 4,000 to 12,000 pph range, and also substantial priority freight service, with intermodal connections via airports and feeder networks. Considering practical system safety benefits such as minimum headways in the 2 min range, and performance drivers like aerodynamic forces, we foresee as a practical design point the use of moderately sized vehicles in the 70 to 80 passenger, 250 kN range joined in varying consists of two to eight vehicles.

Provision for Growth

The guideway network must be designed to accommodate growth, especially here in the United States. This includes both *capacity* growth in the form of larger payloads and higher operating speeds, and *technological* growth, as in the capability to incorporate new, more efficient maglev configurations, such as new versions of the SC/EDS null-flux sidewall scheme now entering the test phase in Japan. A modular-type guideway cross section could be designed for adaptability to a range of future maglev operating schemes with minimum modification.

Low Cost

Low life cycle cost (LCC), including construction, operation and maintenance, is a major driver since it is estimated that for a metro corridor-type system, guideway and station construction plus the associated power distribution and control network could constitute up to 85 percent of total system acquisition costs, with 70 percent in the guideway structures alone. A modular design approach using the manufacturing economy and precision attainable with high volume factory production will minimize capital costs. Equally important is a clear need for low maintenance activity (costs and downtime) in varied U.S. environments, and for a durable design that will allow these costs to be amortized over a long service life. A detailed study of life cycle costs is a universal requirement in the planning of all transportation systems. In the case of maglev, which has construction and operational requirements still being formulated, while it will be difficult to assign exact cost-benefit value to many of the design features, it is worthwhile to favor configurations that will minimize operating costs while providing desirable features from a system point of view.

3. DEVELOPMENT OF GUIDEWAY SYSTEM CONFIGURATIONS

3.1 Overall Approach for Selection of Initial Main Beam Configurations

The guideway primarily performs two basic functions - first, it must accommodate the required maglev components, with proper provisions for vehicle stability and control; and it must provide structural support for combinations of operating, emergency and environmental loads. In addition, the guideway must provide protected space for track power, communication and signal cabling, and accommodate walkways, internal access, structural monitoring, etc. The Foster-Miller team evaluated many different configurations suitable for a SC/EDS, each combined with varying structural cross sections.

The important tradeoffs in the selection and integration of the electrical and structural configurations for the guideway are outlined in the following pages.

3.1.1 Guideway Stiffness Approach

The basic guideway design philosophy we adopted in this study was to provide sufficient flexural and torsional *stiffness* in the guideway primary beam structure to ensure that safety, stability and ride quality can be met with a low-risk approach. This means that primary dynamic frequencies of the combined vehicle-guideway system should be kept above a certain minimum in order to prevent large deflections and accelerations from occurring when the vehicle consists are moving at high speeds. This is especially true when the system must function safely and predictably with crosswind gusts, guideway irregularities, variable vehicle weights and CG, etc.

If a flexible guideway approach is used, several additional concerns arise. First, the guideway may be subjected to destructive fatigue loading via excessive stresses in multiple bending and torsional modes. This can be a major source of concern for long-term maintenance and safety, as has been demonstrated in the past with transportation structures. Also, the superconducting primary vehicle magnets can be forced into quench when the magnetic field supporting the vehicles is subjected to high transient loads due to excessive vehicle-guideway motion.

This is of particular significance when a small cross section guideway such as a monorail or single-beam type structure is proposed. Although it is tempting due to potentially lower cost relative to a more substantial configuration, the reduced "footprint" of the vehicle on the guideway can result in even more flexibility being added between the vehicle and guideway itself.

The inherently high CG location and narrower stance of monorail-type maglev vehicles allows greater overall flexibility in roll for the same magnetic gap stiffnesses, relative to a vehicle containing the same passenger area cross section but supported at the outside in a sidewall-levitation type arrangement. This is due directly to the significantly higher ratio of the vehicle CG height (above the levitation reference height) to the lateral spacing ("gauge") of the levitation elements of the guideway for the monorail-type system. The realities of packaging of a usable vehicle interior directly above the monorail guideway beam can result in this situation. This was seen in the Japan Railways R&D work a decade ago with their ML-500 vehicles on an inverted-tee guideway which also intrudes on the center of the passenger area.

Unless the magnetic stiffness of these designs is increased beyond that of the sidewall type, reduced stability in rolling or roll-coupled modes could result. Increases in this stiffness require either higher magnet size and strength, and/or more guideway conductor, both of which increase costs. Furthermore, this increased flexibility could also raise dynamic acceleration levels in the vehicle due to dynamic interaction effects with the guideway or vehicle torsional modes, compromising ride quality or requiring more elaborate secondary suspensions.

In summary, the reasons why a stiffness-driven design approach utilizing a relatively wide "gauge width" has been chosen are the following:

- To control undesirable interactions between loaded vehicles and guideway when travelling at high speeds

- To allow for variations in vehicle speed, weight and consist length to provide for capacity growth, future vehicle configurations, etc., without encountering rapidly rising dynamic load or deflection situations

- To provide a margin for guideway irregularities while not compromising vehicle stability or magnet quench margin

- To provide a stable, wide stance for the vehicle.

3.1.2 Maglev Configuration Selection

Several potential configurations for the guideway cross section were evaluated and will be discussed in this section. The family of configurations that we have selected is U-shaped with a partial horizontal floor and vertical sidewalls in the magnet area. These features provide the stability of positive location and guidance at the outer corners of the vehicle. Basically, the resulting configuration incorporates a U-shaped SC/EDS maglev layout, combined with a high stiffness multi-celled box-beam incorporating the functions of main beam and sidewall. The main beam structure uses advanced high strength fiber concrete with high-tensile, nonmetallic prestressing and post-tensioning tendons in the upper areas, close to the high magnetic fields from the passing superconducting vehicle magnets. It is designed for high-volume plant manufacture, plus efficient transportation, erection and alignment.

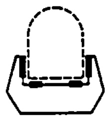
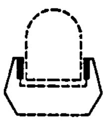
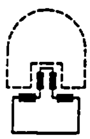
Other configurations have been investigated and are summarized in Table 3-1, but they were found to be inferior in one or more areas. These configurations include inverted tee, single vertical center rail (monorail type) and rounded U-channel.

The "inverted-T" or "monorail" type configurations shown in Table 3-1 offered the potential of allowing a somewhat lighter guideway structure and slightly lower aero drag. However, it places the guideway vertical members and vehicle magnets directly in the center of the car resulting in inefficient vehicle space allocation and limited capability for including any secondary suspension. Also, the stability and control of the vehicles is questionable with the short lever arm available between levitating elements in the transverse direction as discussed previously in subsection 3.1.1. The guideway layout must permit the vehicle to efficiently react all modes of loading and to retain multimode stability at high speeds and loads, especially in roll and roll-coupled modes.

The round-bottom shallow U-shape scheme with banking vehicles is interesting, but the lack of positive retention in the guideway and the potential stability and control difficulties with full-size vehicles operated at high speeds, make this, we believe, a high-risk choice.

One great advantage of the SC/EDS approach is the generous levitation and guidance air gaps - (~100 mm) that permit high speed operation with practical guideway alignment tolerances. With these gap sizes and associated spring rates, the wide stance of the U-type configuration is much preferred for vehicle stability and safety under all operating and emergency conditions. Much

Table 3-1. Summary of Alternative Maglev Configurations

	SC/EDS Configuration	Principal Characteristics	Development Status
	-shape with horizontal levitation surface sidewall guidance and propulsion	• Wider stance • Positive location • Wider guideway • Demonstrated full-scale	• Full-scale development and refinement for 10 years by JR/JNR/RTRI • Further refinement proceeding
	-shape with sidewall levitation, guidance and propulsion (null-flux layout)	• Wider stance • Positive location • Wider guideway • Potentially very high ground clearance	• Full-scale development and test now underway by JR/JNR/RTRI • Test tracks now operating with both null-flux and ground coil using same full-size vehicles
	-shape with horizontal levitation, center stem guidance and propulsion	• Narrower stance • Intrudes into center of vehicle • Potentially narrower guideway • Secondary suspension difficult to incorporate	• Tested in 1970s (LIMRV) on short track; not continued • Tested with coil-type layout in late 70s-early 80s by JNR (LR-500); development changed to U-shape layout
	Monorail-type beam containing levitation, guidance and propulsion	• Narrower stance • Intrudes into center of vehicle • Limited area for stiff beam cross section, esp. laterally and torsion • Secondary suspension difficult	• Smaller, non-maglev systems used for light, low-speed vehicles • Under consideration in the System Concept Design (SCD) program
	Round U-shape with propulsion, guidance levitation for banking vehicle	• Banking vehicle in guideway • Not positively located by physical restraint	• Subscale test on concept demo c. 1970 • Under consideration in the SCD program

valuable experience in this area has already been gained using full-scale vehicles and test tracks in Japan. Extensive further refinement of this approach for both the ground-coil and null-flux sidewall SC/EDS schemes will be underway soon at the Miyazaki maglev Test Center under the guidance of Japan Railways and the RTRI.

Many other important operational benefits can be seen with the U-type configuration:

- Lower sideload from wind gusts since the underside and one-third of the side is shielded by guideway

- "Track-type" surface available for emergency vehicles, maintenance vehicles and personnel, and passenger evacuation

- Guideway sidewalls provide inherently stable "capture" of vehicle, and "track bed" is available for emergency egress when stopped, including on banking

- More suitable for incorporating secondary suspension (vehicle with bogie) from a space allocation and multimode dynamic control point of view

- Simple adaptation to tube-enclosed system if warranted in future. Tube enclosed freight systems (Super Cargo System) are already under development in Japan.

3.2 Development of Candidate Main Beam Cross Section Layouts

3.2.1 Structural Configuration Development

Our proposed primary configuration for the elevated guideway uses an adaptation of an efficient, hollow, multicell box-beam shape integrated with the U-shaped electrical configuration. We anticipate that the structure will utilize advanced pre-stressed/post-tensioned high strength concrete beams, which have an extensive history of successful use in elevated transportation structures.

Several actual and planned guideway projects have used simple single-cell prestressed concrete box-beams, and there is also substantial bridge experience with these sections. Single and double tee sections, and slab-on-I beams have also been widely used in prestressed concrete highway bridges of moderate span. A few monorail systems for low-speed, light vehicles have also been constructed.

Development of the primary structural configuration for the elevated guideway elements started with the most promising box-beam and double-tee cross sections. We used multi-vehicle consists of two to eight vehicles, supported by a single bogie under each coupling area, and travelling in the

134 m/s (300 mph) speed range. Two vehicle configurations are incorporated as are typical for high speed rail consists. The "B" vehicle is the intermediate passenger car joined to other cars on both ends. The "A" vehicle essentially consists of the "B" vehicle with an aerodynamic nose and control cabin on one end and thus is joined to another car on only one end. Loaded vehicle weights assumed were approximately 320 kN (71,900 lb) for the "A" vehicle and 260 kN (58,400 lb) for the "B" vehicle.

The section had to provide enclosed space for trackside power, control and signal cabling, plus space for potential utility services, so this favored the box-beam approach. Also, a configuration was needed that would prevent accumulation of rain, ice, snow and debris for low maintenance, safe operation.

In the tradeoffs we evaluated the effects on structural performance and cost of structural cross section shape and area, materials, construction methods (manufacture and erection), and span lengths (pylon spacing) and continuity.

For the span and load ranges used here, some form of pre-stressed closed-cell box-beam, using high strength concrete to make efficient use of pre-stressing, and having constant nominal cross section for economical production is typically used for modern highway and light transit structures. This was confirmed in our initial studies which indicated that a one or two-celled closed configuration would be the most cost-effective solution meeting all the design and operational requirements.

Pre-stressed concrete box-beam configurations are widely used in transportation networks because of material efficiency, high multiplanar stiffness (including torsion) and suitability for high volume production and pre-stressing/post-tensioning. High torsional rigidity is important for control of vehicle roll dynamics and effects of crosswinds. Using this basic guideway beam element, therefore, related general pre-stressed configurations were created, each addressing the various guideway system requirements with a different balance.

An overview of these four configurations selected for evaluation is given in Table 3-2 and fully described in the following subsections.

Table 3-2. Candidate Guideway Configurations

	Main Beam	Sidewalls	Favored maglev Configuration
I	Modular two-cell	Separate shorter modules	Ground coil EDS
II	Modular two-cell	Integral with main beam	Ground coil EDS
III	Single cell	Integral, with modular alternative	Ground coil EDS
IV	Sidewalls form two main beams		Null-Flux EDS

3.2.2 Configuration I

Configuration I was designed with an open center floor between two interconnected trapezoidal box-beam elements, for use in severe weather conditions to minimize accumulation of ice, snow and debris. This is shown in Figure 3-1, with a more detailed layout of Configuration I shown in Figure 3-2.

The two box-beam elements would be erected and joined at intervals of 6 to 8m (20 to 26 ft) by premanufactured mating concrete flange spacers via transverse post-tensioning, resulting in one integral beam section. Alternatively, the two beams could be joined by vertical diaphragm elements, with thickened upper and lower areas matching the main beam upper and lower flanges. This would again accommodate the transverse post-tensioning which integrates the two main beams. Nonmetallic post-tensioning would be used within 0.8m of the vehicle magnets. This configuration also permits each box section to be manufactured in spans of 24 to 30m and still be easily transported to the site over roads, since individual beam weights will be in the range of 480 kN (108 kips) for a 27m (88 ft) span. The open floor spaces of approximately 1 x 5m could be covered with a nonmetallic composite grille to provide a continuous guideway floor for maintenance and emergency use. Also, the open floor may provide aero drag reduction via downward exhaust of air.

The solid guideway floor area just within the ground coils is used for wheels-down operation and emergency braking skids.

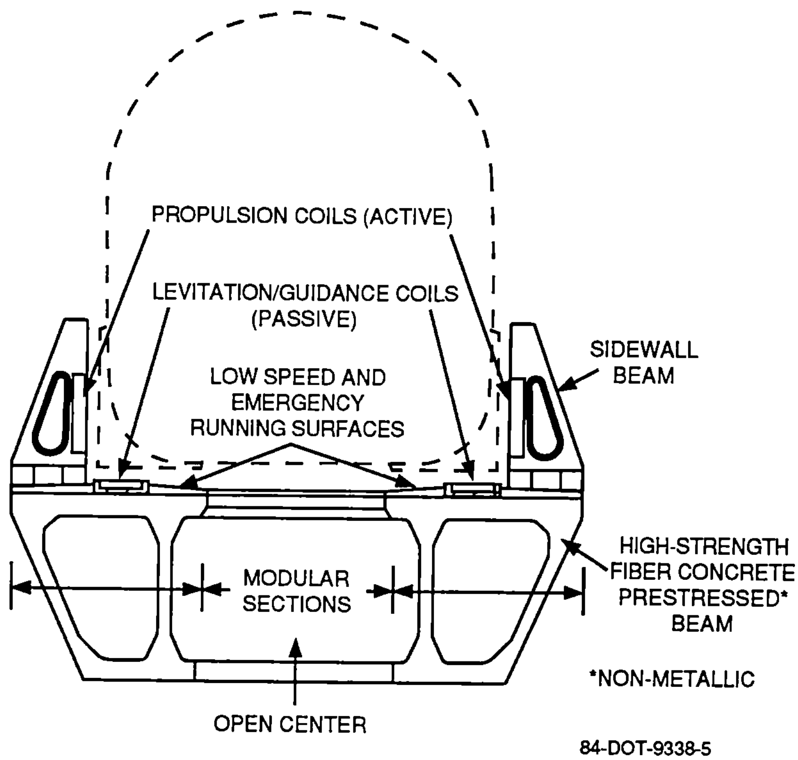


Figure 3-1. General Layout of Configuration I Guideway with Ground-Coil SC/ED Layout

Although a few individual situations might be served at lower cost by a lighter cross section, where closer pylon spacings are practical, the advantages of a standard shape for economical high-volume manufacture and span flexibility are considerable. The wall thicknesses, however, can be easily varied via core size changes for efficient use of material.

The U-shaped guideway running surfaces are formed using the top of the structural guideway beams. For the ground coil SC/EDS layout, coils could be prepackaged in strips to allow fastening and alignment in floor recesses. Sidewalls are formed using modular, hollow beam segments containing preassembled, prewired maglev coils. These replaceable beam segments would be elevated above the guideway floor on adjustable spacers. These sidewall elements, shown in Figure 3-3, would be 6 to 8m long, so there would be four sidewall beams per main beam span on each side.

The sidewalls can be strengthened considerably to react outward bending loads by incorporating a GFRP vertical tendon/bolt the full height of the inside face, performing the functions of both fastener and post-tensioning. A permanent head can be used on the lower

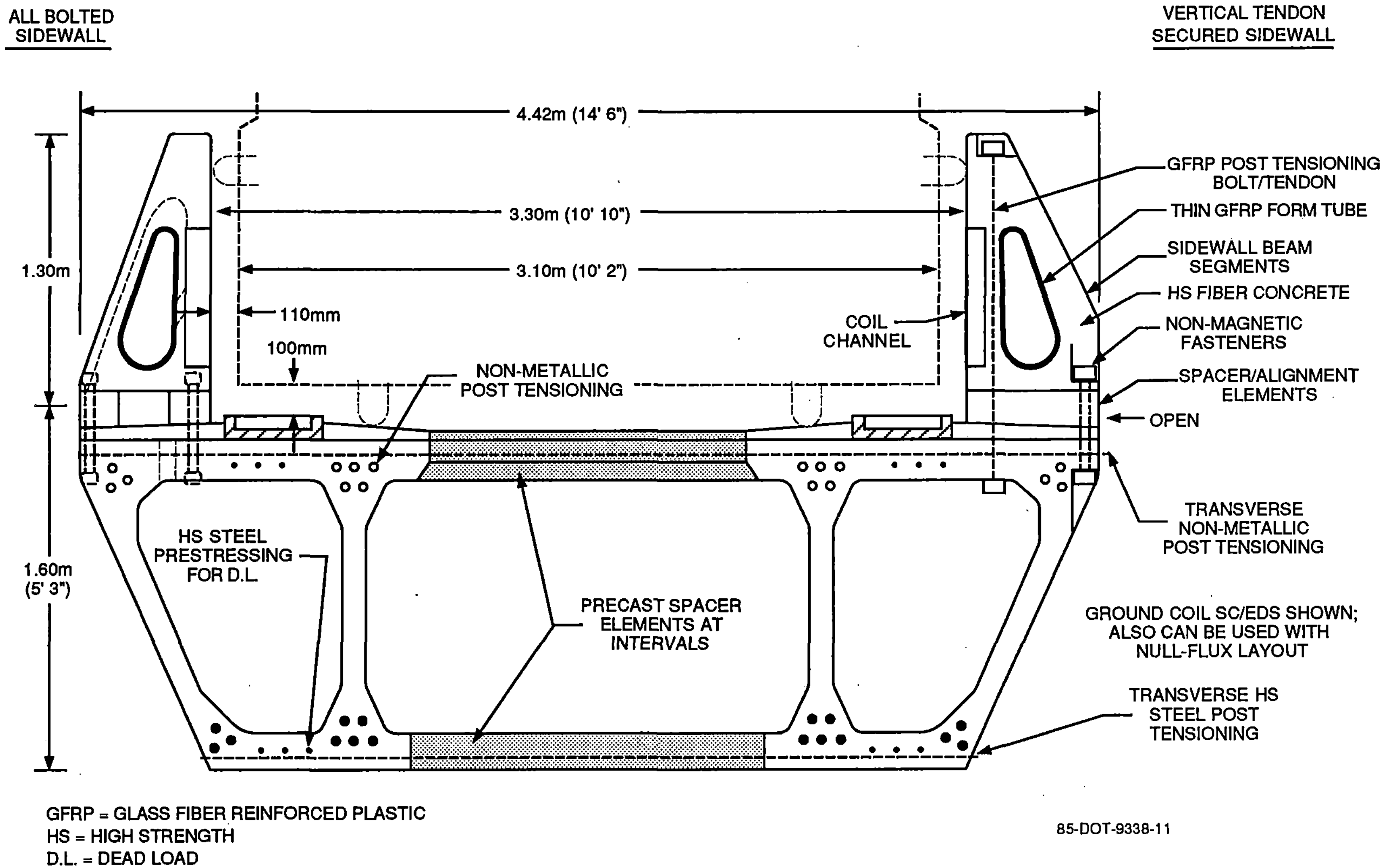


Figure 3-2. Open-Bottom, Modular Sidewall Guideway Configuration I

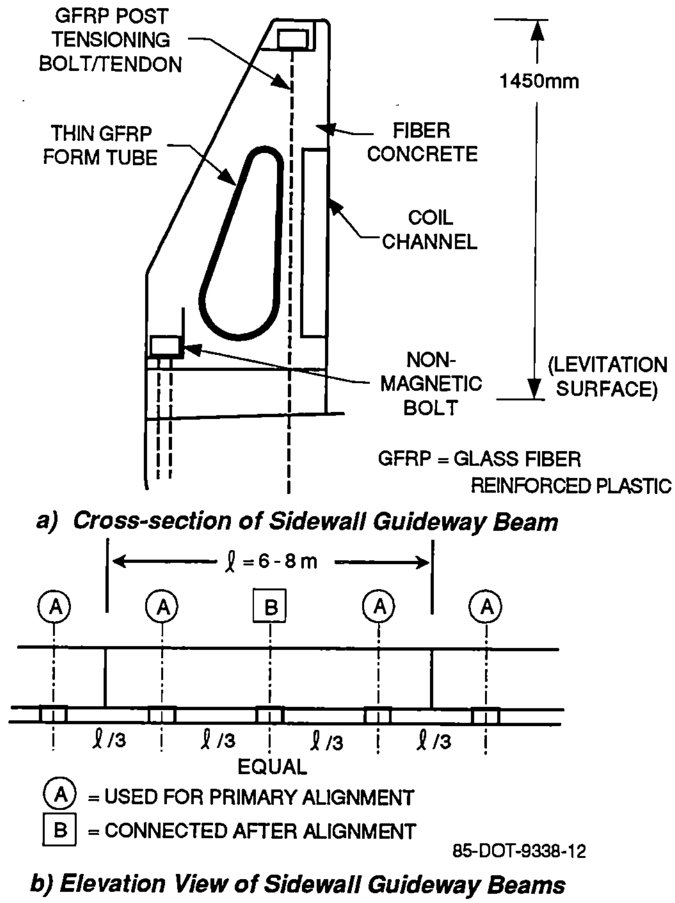


Figure 3-3. Elevation View of Sidewall Guideway Beams Configuration I

(guideway beam) end. The bolt could be installed, tensioned (or removed) by a tool, with permanent connection via a cone-compression anchorage.

This approach has several key advantages:

- The open center and the gap beneath sidewall beams allows direct runoff of rain, snow and debris at the guideway edges. Air pressure created by vehicle passage will assist this process.

- The main guideway structure can be manufactured and erected to larger tolerances more typical of existing bridge and low speed guideway practice, since these beam segments (and strips) will be capable of individual alignment in vertical, lateral and rotational directions.

- Rapid realignment in the event of long-term deflections, settlements, or damage is possible. This could be performed at beam supports (for pylon settlements) or on the individual sidewalls, as appropriate.

- Internal prewiring for each guideway beam segment will be connected to continuous main trackside power located in the main beam internal cavity.

- Separately mounted sidewall beams, spacers, and fasteners would furnish additional structural damping to minimize dynamic bending or torsional motions.

The sidewall beam segments would be designed to accommodate the U-shaped SC/EDS maglev. For the basic configuration using horizontal ground coils of levitation, the sidewalls would contain the active propulsion/guidance coils plus associated cabling.

The scheme for final alignment of guideway elements is shown in Figure 3-4 and a plan for internal space allocation and maintenance access is shown in Figure 3-5.

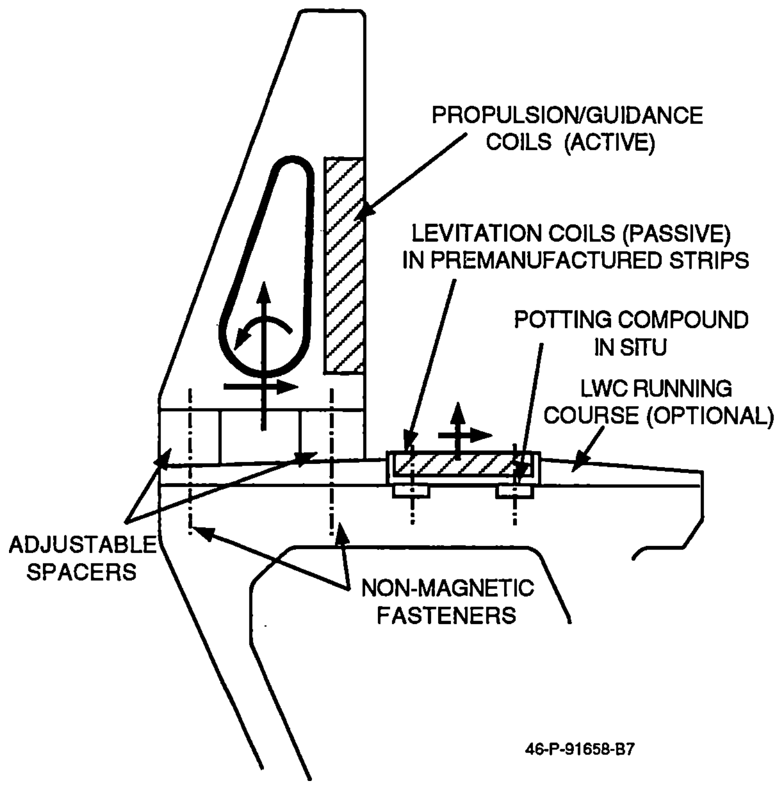


Figure 3-4. Alignment of Guideway Components (Ground Coil Scheme)

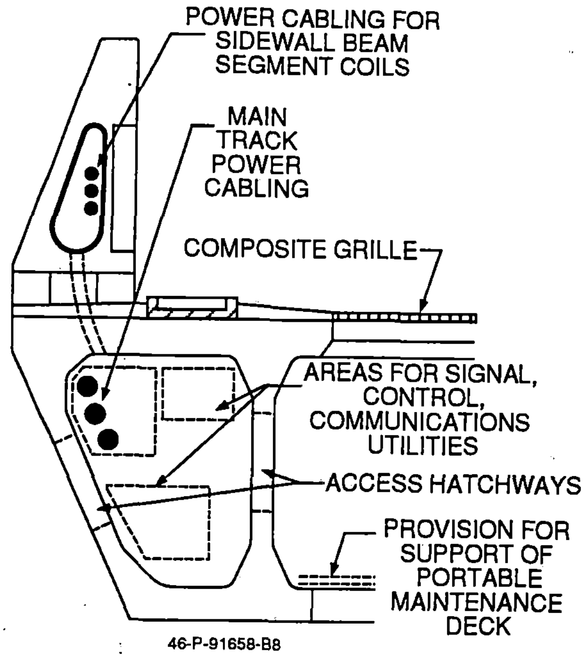


Figure 3-5. Service Spaces in Guideway

3.2.3 Configuration II

Configuration II utilizes the same type of double box beam modular layout as Configuration I, but integrates the sidewalls into the main beams. This is shown in Figure 3-6. Each main side girder is manufactured as a unit, with the two girders joined at intervals with spacer elements similar to Configuration I.

Here, the approach is to attempt to utilize the material of the sidewalls in contributing to the stiffness of the main beam, potentially reducing overall weight. An additional aim is the reduction in overall complexity and cost, with the hardware and local reinforcements needed to connect the modular Configuration I sidewall elements to the main girder no longer required.

There are, however, several design compromises relative to the Configuration I design:

1. The ability to premanufacture and prewire the powered sidewall coils in separate beam elements is lost, although the entire beam could have coils and wiring assembled before transport if they could be protected well enough during the transportation/erection process.

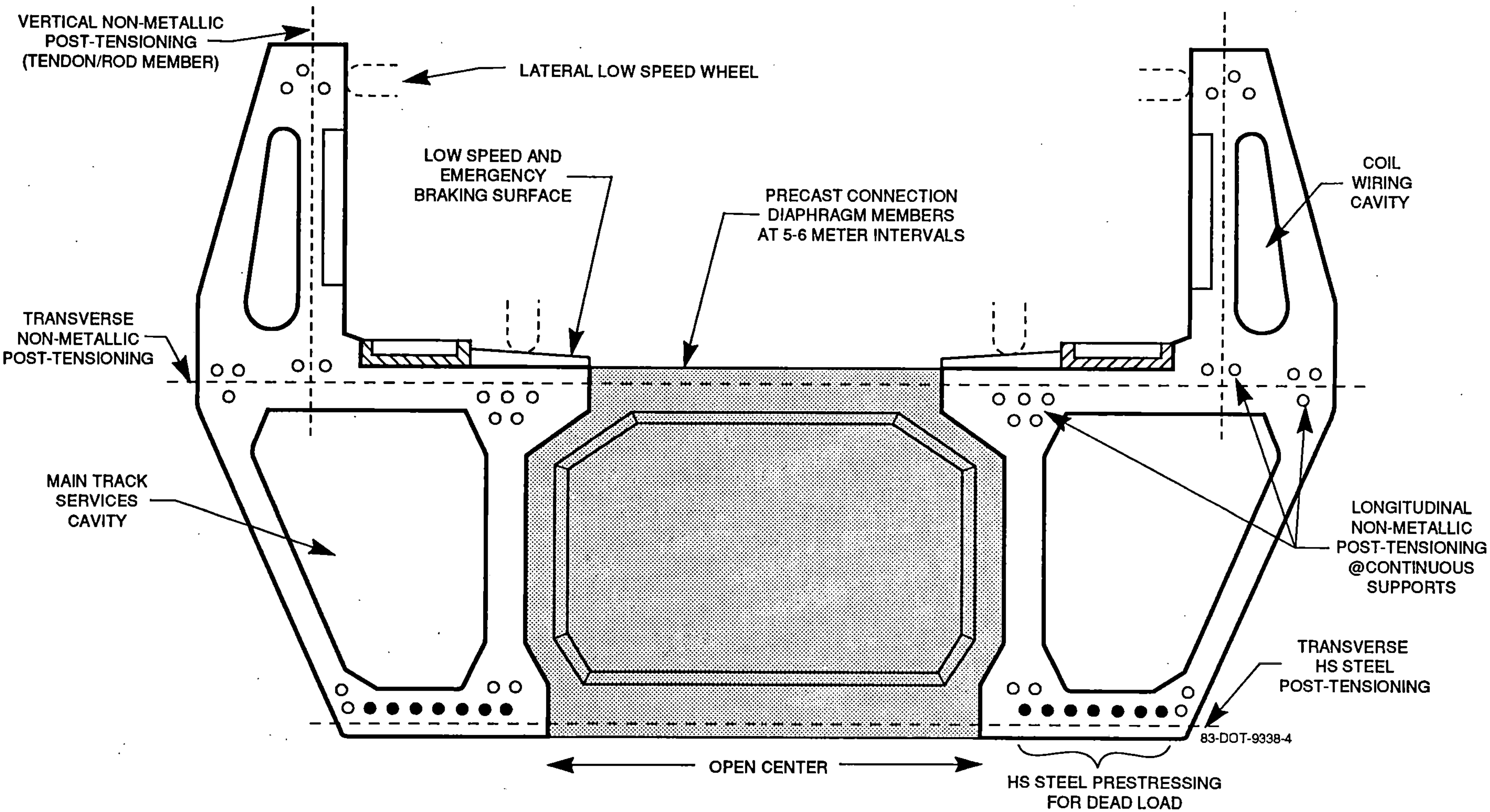


Figure 3-6. Open-Bottom, Integral Sidewall Guideway Configuration II

2. The sidewall alignment relative to the main beam portion is fixed, so that the overall tolerancing of the various portions of the integrated beam cross-section is more demanding and complex. Sidewall alignment therefore depends on maintaining overall beam straightness.

3. If any sidewall damage occurs in service, on-site repairs would have to be performed, rather than having the opportunity to simply replace a short, prewired sidewall beam element.

4. The weight of the integrated Configuration II beam will be at least 25 percent higher than the main beam element of Configuration I, making handling and transportation more difficult, and possibly more costly. However, it is likely overall weight of the completed beam, including sidewalls, will be less.

5. The gap under the sidewall, which contributes somewhat to the self-clearing capability of the Configuration I guideway is not present.

Nevertheless, the potential benefits of simplicity and the resulting effects on overall cost make it productive to consider in the assessment.

3.2.4 Configuration III

Configuration III, utilizing a large, single cell main beam centrally located under the guideway, is included because this is the familiar configuration seen in similar conventional transportation structures to date. In the case of bridge-like highway structures, there have been many examples erected in recent years using either single cells or "multiple single cells" arranged side by side below a continuous deck to form wide, multilane structures. For longer spans in the 50 to 100m range, or even greater, both segmental construction techniques and variable depth cross sections have been incorporated. However, since the objective for the maglev guideway has been to develop modular cross sections with a maximum of standardization, our approach for this version has been to retain a constant cross section with complete spans manufactured in the plant and then transported and erected without falsework (temporary supports). This avoids the prolonged on-site construction activity associated with the traditional "heavy" construction methods. Similarly, we did not use the cast-in-place (C-I-P) beam construction approach for beams, which would also have this similar shortcoming.

For the single-cell configuration, general factory manufacture of the entire cross section as one unit would probably preclude economical transportation to the right-of-way due to high beam weight. In the case of the Vancouver Advanced Light Rapid Transit (ALRT) project which was constructed in the mid-1980s, the total guideway width was approximately 3m (9 ft to 9 in.) and special multi-section vehicles had to be designed to carry the completed beams which weighed on the average over 100 tons (880 kN). This did not include the sidewall parapets, which were C-IP.

Therefore, we divided our single cell configuration into two sections (left and right) down the centerline, and joined them in the field with transverse post-tensioning after initial erection. The alternative of manufacturing a complete cross section but with only one-half span in each of two segments was dropped since this would have required the temporary midspan falsework referred to earlier, and also would have created a midspan joint at a high moment location which would not have allowed the final dead loads to be reacted by plant-installed prestressing. (Extra post-tensioning here would have been needed as for segmental construction.)

For the sidewalls, both the alternatives of either separate, modular construction or integral construction (analogous to Configurations I and II presented earlier) were considered. It was decided that since evaluation of the single cell configuration was still aimed at producing the most practical cross section from an operational point of view, we decided to incorporate the modular sidewall concept as in Configuration I. The elevated sidewalls with gap below would permit limited drainage and "track clearing" action on what otherwise would be a completely closed-floor configuration.

This resulting configuration is shown in the accompanying Figure 3-7. The principal advantages hoped for are, again, potentially lower cost due to simplicity and similarity to existing, familiar heavy construction techniques. There might be additional benefits in torsional stiffness, since the torsional input forces resulting from lateral wind or earthquake loads on the vehicle will be reacted in the closed portion of the cross section. Note that in the twin-beam configurations (I and II), most of the unbalanced lateral loads are transferred to one side only, with both sides then participating via the diaphragm interconnections.

The potential disadvantages of the Configuration III are:

- The closed floor, while furnishing a good "roadbed" surface, might restrict use of this guideway to areas of low snow and ice accumulation. While drains could be furnished, and the gaps beneath the sidewalls afford good water and debris runoff, these might be

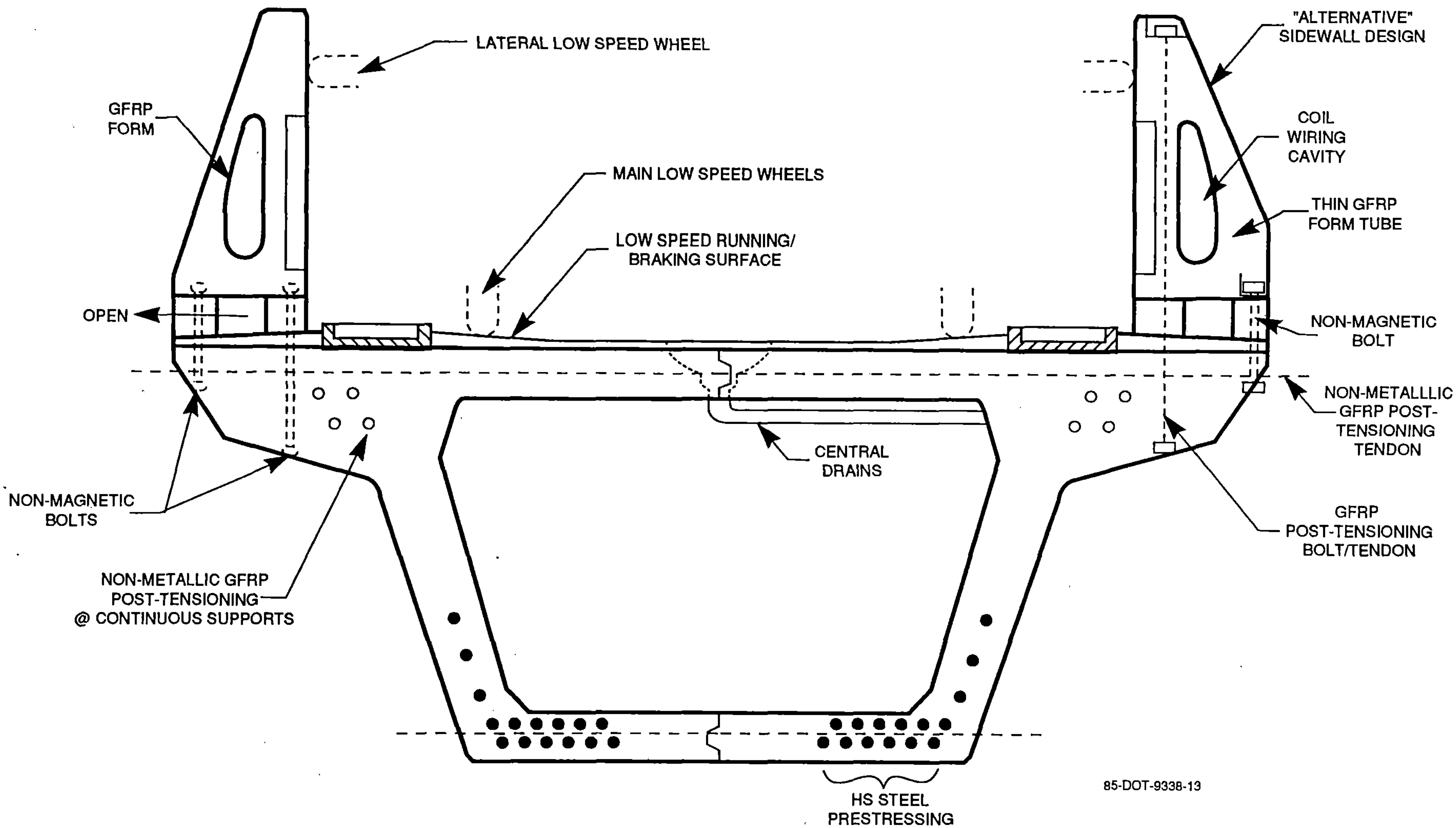


Figure 3-7. Configuration III - Single Cell Two-Piece Guideway

inadequate to prevent excessive accumulations in areas of high snowfall and icing. The result could be high snow clearing expense, and possible reduction in operating safety.

- The weight of the section might be excessive for efficient plant manufacture, transportation to the ROW, and erection.

- The mating edges of the two halves would have to be manufactured with enough precision such that the beam could be assembled accurately, with the internal cavity sealed sufficiently so as to provide the protected space for all wayside power, communications, signal, and other services.

- Not all of the lower flange areas can be effectively used for the factory prestressing of each beam half, due to distance from the vertical web. This reduces the efficiency of the beam half in supporting the beam dead load prior to assembly and erection.

3.2.5 Configuration IV

Configuration IV utilizes a different maglev operating concept than those of the previous configurations. In this Foster-Miller "null-flux" operation, the propulsion and guidance coils are in the vertical sidewall as before. These are overlaid with vertical figure-eight passive coils which interact with the vehicle magnets to provide levitation. Levitation occurs through lining up the crossing point of the figure eight coils with the vehicle magnets. This form of levitation is now entering full-scale test track operation in Japan. It is also utilized in the Foster-Miller vertical switching concepts covered later in this report.

This null-flux configuration, shown in the accompanying Figure 3-8, consists of two main beams which constitute the sidewalls, joined at intervals via post-tensioned spacer elements. This is a very efficient configuration, since all loads are applied directly to the main beams, and their simple design lends itself well to prestressing.

An important point is that the same vehicle could operate on both a ground-coil guideway and on a null-flux guideway, so that different sections of main line guideway could use either mode, as appropriate. This should be qualified by the realization that in configuration IV the low-speed running surfaces for the null-flux guideway are now on top of the sidewall. Thus, the landing gear would have to be configured to support full vehicle weight at that level, instead of at the bottom. If low-speed operation in both types of guideway is required, both sets of landing gear would have to

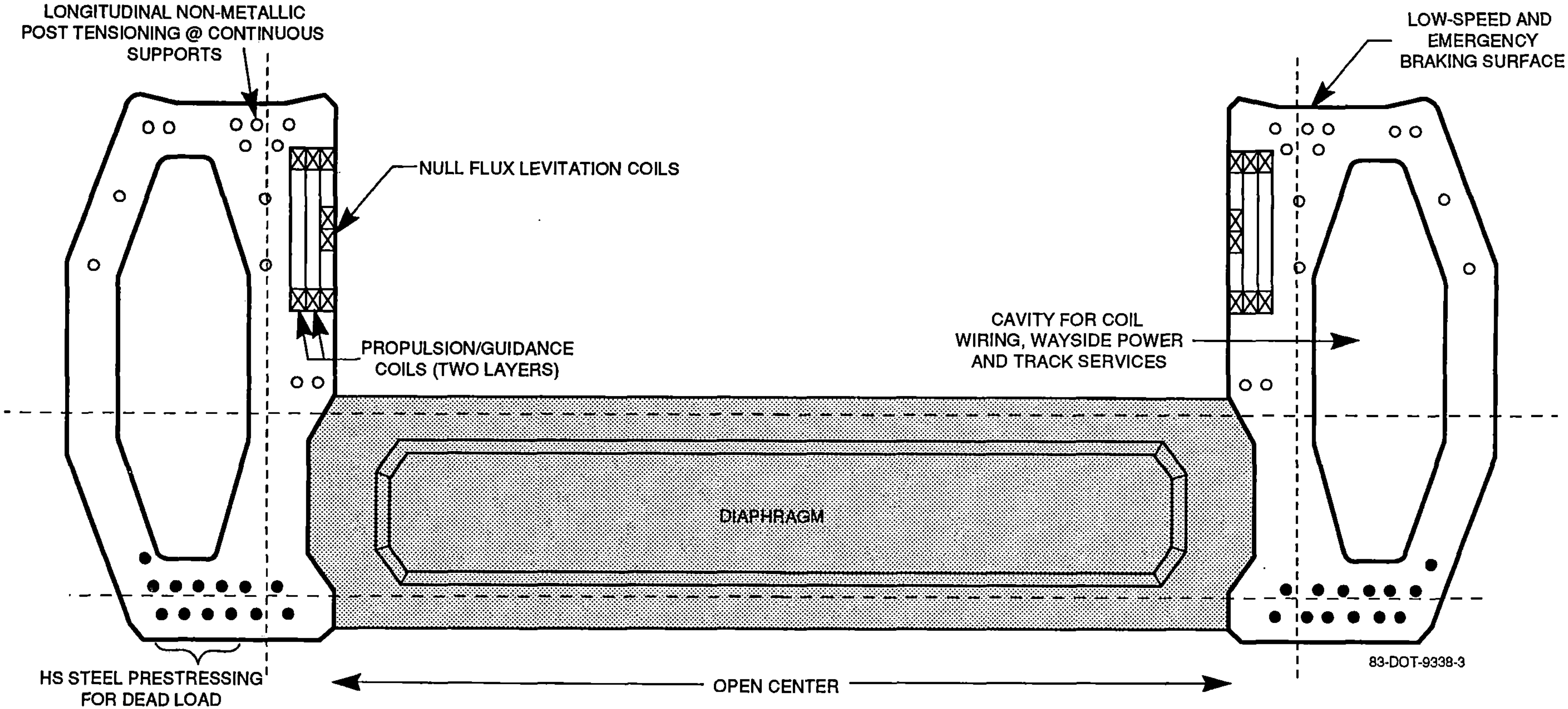


Figure 3-8. Open-Bottom, Null Flux Guideway Configuration IV

be provided. It should also be noted that the three previous configurations, could also accommodate the null-flux arrangement but the non-integral sidewall concepts (Configurations I and III) might have to be redesigned to support full vehicle weight in the sidewalls.

An important advantage of the open-bottom, null-flux guideway configuration is that it permits the use of an advanced vertical switching concept, described in more detail in a later section. This will permit full-speed "through" operation, with the switched direction dropping below the main line for transition to low-speed operation to the station "sidings." The side landing gear referred to above would retract during the switching.

The principal advantages of the null-flux Configuration IV guideway, therefore, include compactness and structural efficiency, with little excess material. Lower guideway costs could result from the fewer parts and the concentration of all required guideway structural support in the single sidewall members.

This design would certainly excel at resisting any accumulation of snow and ice, since there is no floor except what could be provided via an open grating for emergency egress and noise attenuation.

The new issues raised by this configuration are several:

- The vehicle would have to provide landing gear at the level of the top surface of the guideway as well as emergency landing skids. This is feasible, but the retraction mechanism is somewhat more elaborate. If the emergency skids are required to be deployed above this surface during all operations, there might be a slight increase in frontal area and drag.

- There is no floor to the guideway, as noted, so besides provision of a floor grating as noted above, there might be a simple reluctance to accept a "bottomless" guideway concept.

- The null-flux maglev configuration has not yet been verified as the best all-around choice for the primary network.

Nevertheless, the advantages of an advanced configuration such as this, especially when potential construction cost savings are considered, make it a valid candidate for evaluation.

3.3 Structural Continuity and Pylon Layout Issues

In general, beam continuity over supports provides desirable additional bending stiffness and deflection control provided the design is integrated with the system dynamic model. However, in United States climates with large seasonal temperature ranges of -35°C to +45°C (-30°F to +113°F) and daily ranges of up to 30°C (54°F), structural continuity in concrete bridge structures is generally limited to 100m (328 ft) or so, to provide the thermal expansion with reasonable joint geometry. In our preferred configuration, we propose that the spans be made continuous over every other span after initial erection. This is a practical compromise which provides significant reduction of structural and thermal gradient deflections while allowing thermal growths due to overall temperature changes. Some highway and railroad structures have been designed with as many as four or five continuous spans, having up to 150m (500 ft) between thermal expansion joints. In the two-span configuration, lateral and vertical loads will be reacted at each support, and longitudinal loads reacted at the continuous supports. This would dictate a stronger pylon and footing at these locations. Longer continuous runs might result in excessive gaps at the sliding joints for average spans in the 24 to 30m range, potentially affecting the smoothness of maglev operation.

Typical pylon configurations are shown in Figure 3-9. Since aerodynamic side forces during passing are a strong function of the spacing and train speed, configuration for dual lines would

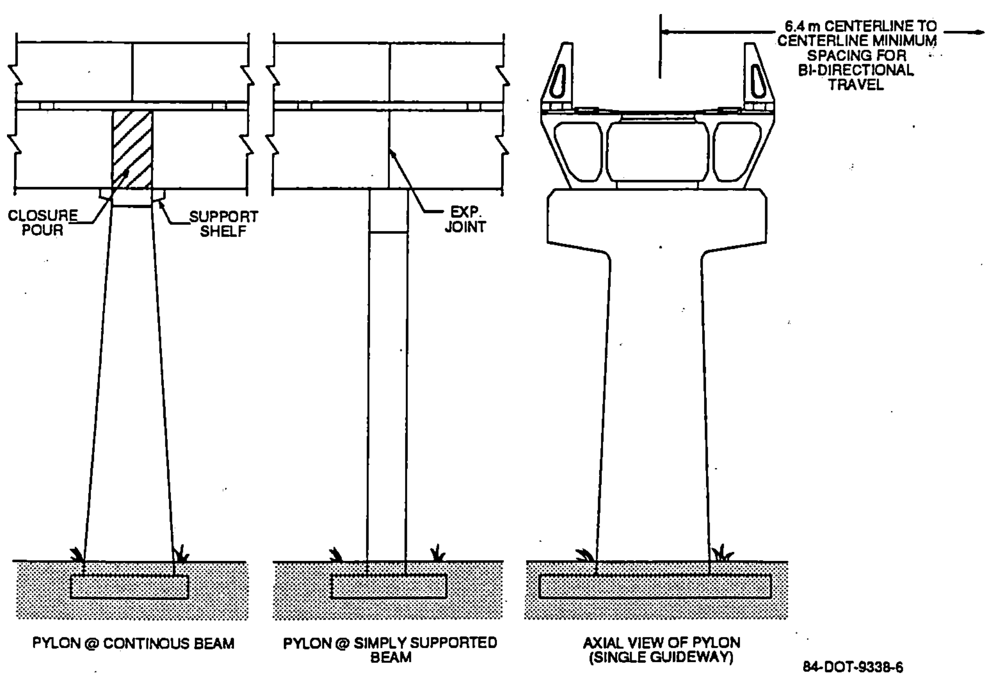


Figure 3-9. Typical Pylon Configurations

vary depending on these aspects. Japan Railway's commercial maglev will use 5.8m center-to-center for spacing speeds of 134 m/s (300 mph) with a slightly smaller vehicle; we project a value in the 6.2 to 6.4m range for the proposed vehicle size and speeds.

This minimum separation results in approximately 2m (6 ft-7 in.) of clear spacing between guideways for enroute safety (assuming travel in opposing directions). An assessment should be made of the feasibility of supporting both guideways on a single transverse beam and pylon versus use of independent pylons. Our conclusion to date is that for enroute speed sections where the full 3m separation must be maintained it is more practical to support each guideway on an individual pylon, due to the size of the connection required between the two guideways.

Use of this type of connected guideway with single pylon should be considered, however, when either of these two conditions are present:

- The required height of the guideway above the terrain is substantially greater than 3m.

- The maximum vehicle speeds in the section are substantially below 134 m/s (due, for example, to curve radius restrictions). When separations can be less than 1.5 to 2.0m, the integrated single pylon approach might be favored.

Long spans over 35m, required in special situations such as interstate highway crossings, can be more efficiently accomplished using a drop-in 20 to 25m section of standard guideway beam with shorter sections continuous over pylons, as is done in established bridge practice. Switching aloft in shorter, uneven spans could favor use of simply supported spans with joints at pylons.

3.4 Nonmetallic Concrete Reinforcement

The high magnetic fields of the SC/EDS maglev (~6 Telsa) can induce high voltages and currents in conductors, especially when interconnected or lengthy. This applies to pre-stressing tendons and other long reinforcing elements, although not necessarily to small mechanical parts (fasteners, inserts, etc.). Also, extensive use of ferromagnetic materials in the guideway can cause magnetic drag and permanent magnetization. The guideway structures must be designed to minimize the use of these materials, and three strategies can be used in the design:

Nonmetallic fiber pre-stressing tendons and anchorages will be incorporated in the main guideway box-beam elements along with optical sensing fibers to monitor stress/strain and fiber breakage. We anticipate that both embedded pre-stressing, to react dead load plus handling and erection, and in situ post-tensioning will be used. Post-tensioning may be used both in straight and deflected layouts, both for full span and continuity (over pylon) applications.

A carefully chosen fiber concrete mix can be used to raise the concrete tensile/shear capacity to the 5 MPa (830 psi) level, thereby reducing or eliminating the need for detail reinforcing. Much of this reinforcing is associated with local stresses at design details, areas of moderate web shear, transverse bending, anchorage areas, etc. For control of thermal/shrinkage cracking, moderate amounts (5 percent volume fraction of cement) of polypropelene, or other fibers can be used to help accomplish this in the mix design (Figure 3-10). This will also increase ductility and slightly increase tensile/shear strengths.

To raise the basic working concrete strength and modulus (E), moderate amounts of microsilica (plus superplasticizers/high range water reducing (HRWR) agents) in the 5 to 8 percent range can be used. Producibility of concretes having compressive strengths in the range of 60 MPa (9 Ksi) and stiffness moduli in the 35 GPa (5,000 Ksi) range is facilitated through the use of this material. This will also work with the fibers to further assure high tensile strength, and additionally reduces the moisture permeability of the concrete.

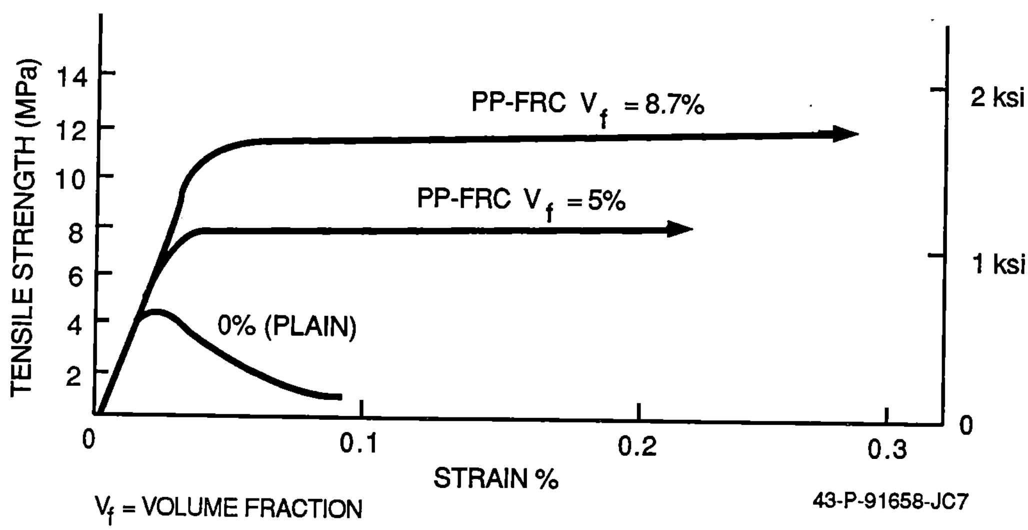


Figure 3-10. Typical Uniaxial Tensile Strengths for Polypropelene Fiber Reinforced Concrete (PP-FRC)

Nonmetallic Pre-Stressing and Post-Tensioning

A number of high strength nonmetallic fibers exist for possible use in composite pre-stressing/post-tensioning tendon. These include various forms of glass, aramids and carbon. (As a conductor, carbon may not be usable.) Glass and aramid fibers offer the potential of very high strengths but in general exhibit lower ductility than high strength (HS) steel (see Figure 3-11).

Particular material characteristics are required for effective use in pre-stressing applications. These include high tensile strength and low relaxation under high load. Once stressed, a low modulus of elasticity (E) reduces loss of pre-stress due to creep and shrinkage in the concrete; however, too low a modulus results in excessively long extension during the tensioning operation.

Some characteristics of GFRP (Glass Fiber Reinforced Plastic) or AFRP (Aramid Fiber Reinforced Plastic) tendon compared to HS steel must be considered in design. Modulus (E) is about 1/4 to 1/3 that of concrete, which results in lower loss of pre-stress.

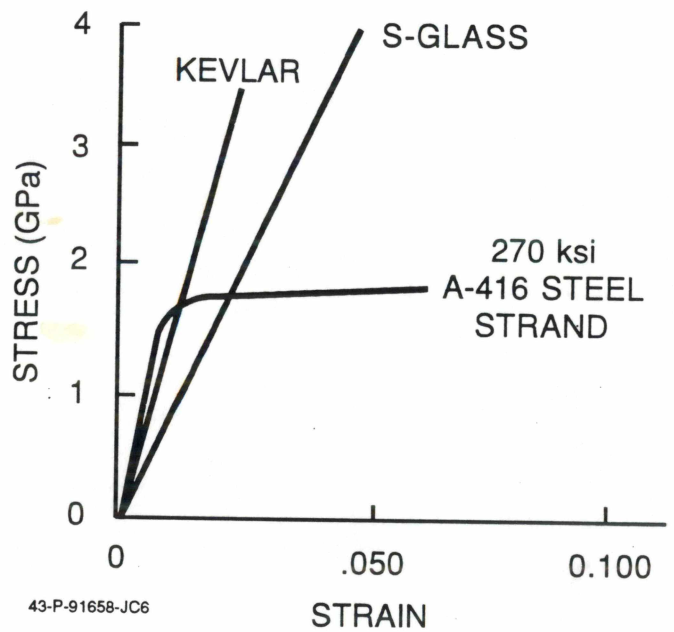


Figure 3-11. Stress-Strain Curves for Nonmetallic Fibers for Pre-Stressing

Strain to failure is below that of steel which requires careful allocation of the "strain budget" among pre-stress, beam flexure and safety reserve. This results in somewhat lower safe long-term stress levels in the FRP rods (0.50 times short-term ultimate) relative to steel tendon. Larger, longer anchorages and tensioning fixtures, usually relying on grouted embedment, must be used.

For composite fiber pre-stressing tendons, typical volume fractions of fiber are 60 to 70 percent. Since stress and modulus are conveniently applied to the gross tendon area, collective fiber stresses are 1.4 to 1.7 times nominal tendon stress. As an example, an AFRP rod with 70 percent fiber may fail at 1.7 GPa (250 Ksi) but collective fiber stress is nearer to 2.5 GPa (360 Ksi), compared in turn to an individual fiber strength of 2.9 GPa (425 Ksi). GFRP tendon exhibits similar relationships (1).

GFRP rods, in particular, are beginning to be used by the concrete industry and indeed have been incorporated into a highway bridge in Dusseldorf, Germany (2). This program also demonstrated the use of integral fiber optic monitoring sensors.

GFRP prestressing tendons using 7.5 mm unidirectional bars are laid up in a 19-strand tendon and used with an effective post-tensioning force of about 600 kN (135 kips) per tendon. The GFRP rods are covered with a polyamide coating and use alkalai resisting glass formulations to resist alkalai attack.

Aramid FRP pre-stressing tendons are now in development testing programs in Holland (Enka), Japan (Teijin, Sumitomo) and the U.S. The Japanese programs using Technora® fibers have been tested in post-tensioned T-beams but they are not yet available for commercial use.

Both GFRP and AFRP systems are suitable for the Foster-Miller guideway, with industry experience somewhat greater with GFRP. The GFRP systems, with raw material rod prices presently at \$4.40/kg (\$2.00/lb) would seem to have a strong advantage over AFRP rods, presently \$22.00 to \$26.00/kg (\$10.00 to 12.00/lb).

Also, GFRP rods in post-tensioning applications (in which the tendons do not come in direct contact with concrete) have a good performance record so far in over six bridges in Germany using the Polystal® system. Therefore, we selected GFRP as the nonmetallic post-tensioning material. In our configurations which include continuous beam connection at alternate pylons, the majority of the GFRP post-tensioning would be used in these areas, with some extending the full beam length at varying heights as appropriate.

3.5 Switching Capability

Switches of different types are required throughout the maglev network, and their configuration and operating principles depend principally on the type of maglev configuration used and the geometry of the basic guideway cross section. These switching configurations must also meet appropriate requirements for safe and reliable operation.

On the main line, one switch type must be capable of allowing full-speed vehicle operation in the through direction, while simpler versions would operate at lower speeds down to and including the non-levitated (wheels-down) mode necessary for station operations. Such a range of switching operations is shown in Table 3-3.

3.5.1 High Speed (Type I) Switching

In a Type I switch having a high-speed through direction, maglev guidance and propulsion must remain intact throughout the switch. The high enroute speeds in the range of 134 m/s (300 mph) do not permit any guideway contact. Since the guidance/propulsion principle in the maglev configurations being considered to date involves repulsion forces inward from the guideway sidewalls, both sides of the guideway must remain active in the through direction.

We have made a preliminary evaluation of two high-speed switching types, both of which meet the criteria above. The first, or Type I-A switch, uses a mechanically-switched configuration in

Table 3-3. Maglev Switching

Function	Application	Type	Train Speed	
			Through	Switched
Main line transfer	Multitrack lines	I	Cruise	20 m/s
Primary switch to station	Station areas, off-line sidings	I	Cruise	20 m/s
Add'l switches to stations; terminals; yard	Station areas, terminals; yard	II	20 m/s	12 m/s

which the switching section of guideway is divided into segments and traversed laterally for switching. The second, or Type I-B switch, is an advanced vertically-switched configuration which utilizes null-flux levitation for the vehicle, and has no moving parts.

The mechanically-switched Type I-A configuration is shown in Figure 3-12. This uses six precast high strength concrete segments 15m (50 ft) long which contain the complete electrical functions of the guideway. This is similar to a configuration now being tested on the Miyazaki test track in Japan by Japan Railways/RTRI. In the Foster-Miller version, the curve radius of the switched direction is 800m (2620 ft), resulting in an overall length of approximately 90m (295 ft) for the switch. The train will decelerate to the switching speed of 20 m/s (45 mph) before the

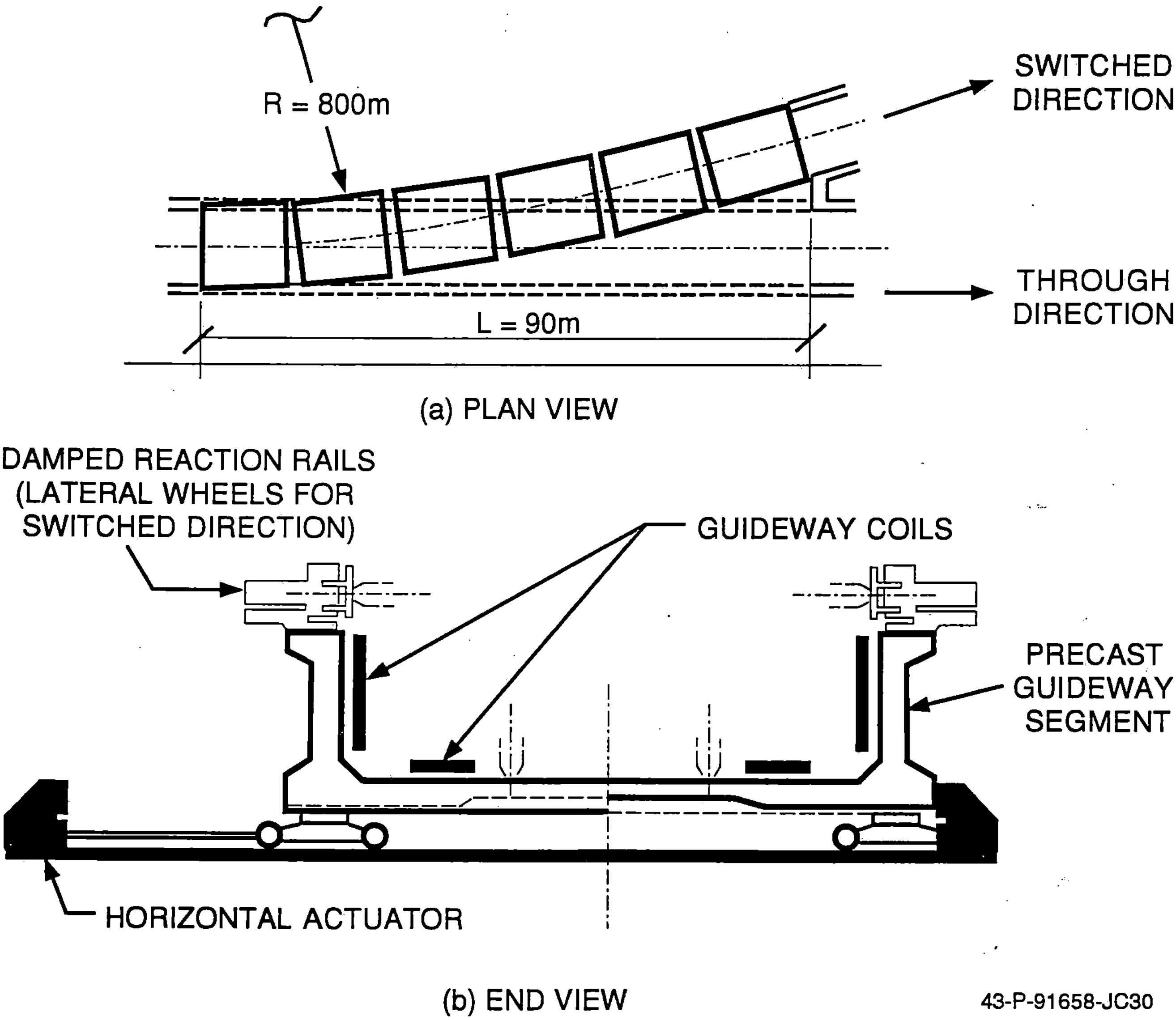


Figure 3-12. Type I-A High Speed

switch, with off-line operation non-levitated. When set to the through direction, the straight alignment of the segments permits full-speed, non-contact operation.

When this switch is used for transfer between two adjacent main lines, a switch pair of length equalling 190m (623 ft) would be required. In cases where switching is aloft on the guideway, approximately seven 24m main beam spans on each line could be used to support a continuous prestressed concrete deck forming the switch bed, thereby joining the two lines. If the enroute speeds in this section of the line are at the maximum of 134 m/s (300 mph), the deck would have to be at least 12m (40 ft) wide without allowing any extra for outside walkways, etc. This approach on a smaller scale was used for the elevated guideway switches in the Vancouver ALRT transportation system.

Switched speed can be raised by increasing curve radius, but since the required radius increases with the square of the speed, switch length and cost rapidly increase. (This is true, of course for any switch.)

Another switching concept permitting high through train speeds is the Type I-B vertical switching configuration utilizing null-flux levitation. This operates on the principle that the through direction can consist of open-bottom guideway, similar to Configuration IV shown previously, with the train completely supported by the sidewall null-flux levitating forces. The switched direction allows the train to descend out the bottom of the main guideway, using a second set of null-flux coils to direct the train along this path. This is shown in Figure 3-13.

Utilizing this guideway design, switching vehicles on guideways can be done with no moving parts. Overlaid sets of switched figure-eight null-flux coils allow the moving vehicle to be electrically switched smoothly and at speed to an upper or lower level of guideway which leads to a station or another route, as shown in Figure 3-13. The wheel/skids can be retracted during the switch when descending to the alternate guideway, at which point safety is provided by ledges at the bottom inner edge of the guideway. Eliminating mechanically switched sections of guideway greatly increases the safety, reliability, and throughput of the system while reducing maintenance and headway requirements of the system.

3.5.2 Low Speed (Type II) Switching

In Figure 3-14, a concept for Type II (terminal and yards) is shown which is shorter and less costly than Type I. All travel directions are wheels-down (non-levitated), but propulsion and

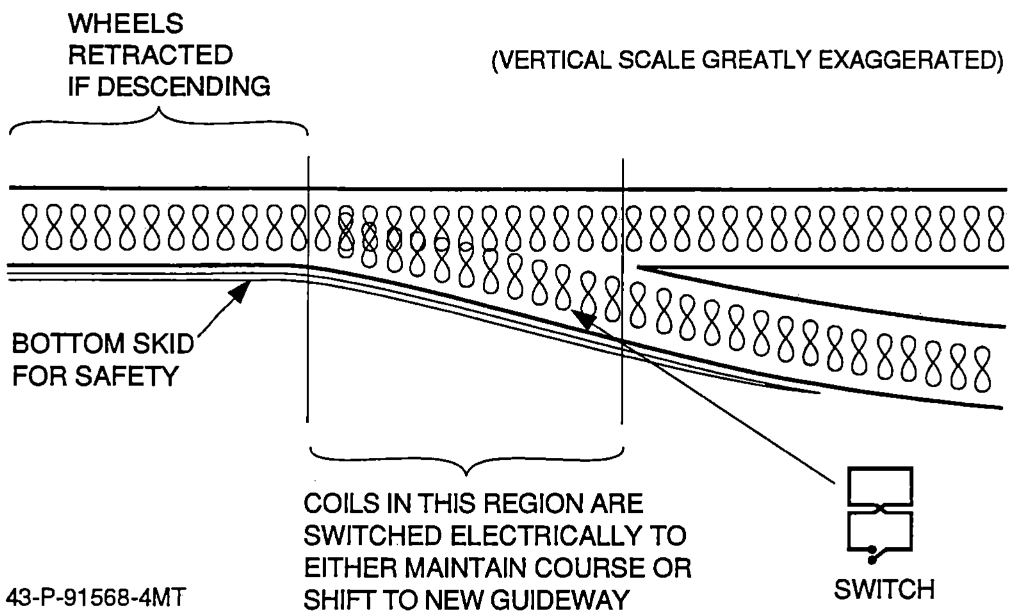


Figure 3-13. Type I-B Open Bottom Guideway Vertical Switch System

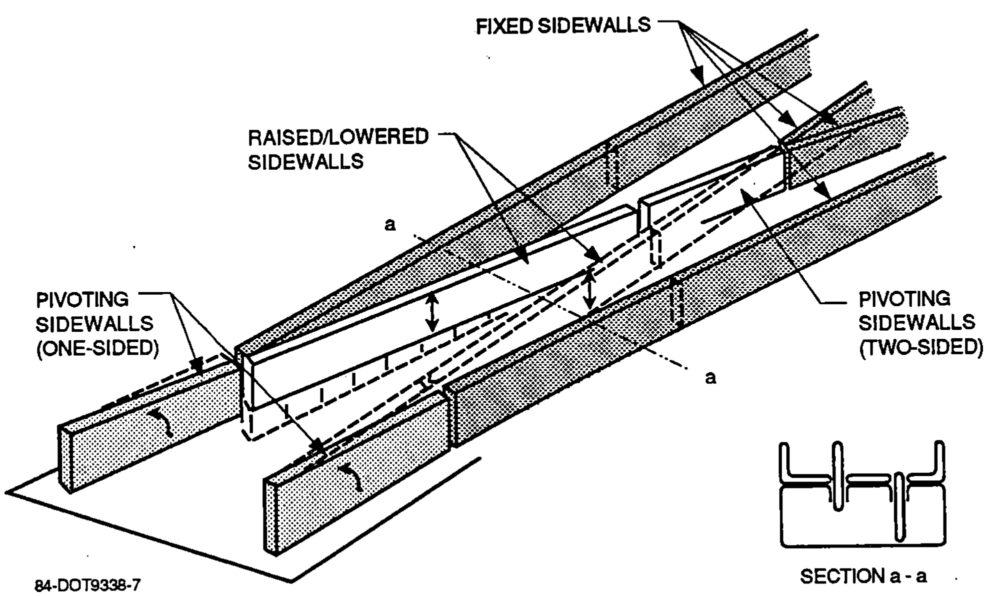


Figure 3-14. Type II Switch Concept for Terminal Areas

guidance still operate. Multiple Type II switches could be further concentrated for compact yard areas with multiple turnouts.

All switching naturally adds costs. The location, number and type of switching required must be decided from a complete operational analysis of the maglev network.

4. STRUCTURAL ANALYSIS AND DESIGN FOR GUIDEWAY CONFIGURATIONS

In this section, we performed the engineering and preliminary design work necessary to obtain actual structural designs for the candidate guideway configurations. For the most important components, the main guideway beams, a thorough study of the dynamic interaction effects that take place between multi-car consists and the guideway was performed. This used multi-car, multi-span computer dynamic modeling techniques. Essential design guidelines for stiffness (via primary bending frequencies) and span connectivity were developed over a range of spans and speeds. This is detailed in the following subsection.

The structural design parameters and procedures used are then described, including specific treatment of the design loads, material properties (especially for the high strength concrete and nonmetallic post-tensioning), and prestressed beam design procedures.

The principal design work for the candidate beam cross sections was then performed, both for a range of spans and for different end connectivity conditions. This led to the development of actual cross sections, including reinforcing schemes (both steel prestressing and nonmetallic post-tensioning). Concrete volume and beam weights were estimated and used as cost indicators.

Other important elements of the guideway system include the support pylons and footings. Their design approach is also described, followed by structural design. Since their parameters are not overly sensitive to the various detail differences in the main beam configurations, these designs are made for the most efficient configuration engineered above.

The issues of transportation, erection and alignment of the guideway elements are then addressed, including a description of the methodology to be employed in the Foster-Miller guideway.

4.1 Guideway Dynamic Response

The analysis and prediction of guideway dynamic response is particularly important in the design of maglev guideways. This is necessary to guide the structural design of the main guideway beams by determining the required flexural stiffnesses, fundamental bending frequencies, and dynamic load factors (DLF) for moment and deflection.

The maglev design criteria for vehicle speed and passenger capacity generally require high speed operation of multi-car consists. The resulting speed and loading combinations can induce undesirable dynamic coupling effects between the vehicle and guideway, producing excessive guideway deflection and stress and may adversely impact passenger ride comfort. The analysis presented in this section therefore has the following objectives:

- Qualitatively and quantitatively assess the effects of vehicle-guideway dynamic interaction using parametric studies;
- Determine if these interaction effects can generally be avoided or mitigated; and
- Recommend a practical range of guideway design parameters (stiffness and frequency) which will result in an acceptable vehicle-guideway dynamic response

The following subsections detail the methods and results of this analysis.

4.1.1 Dynamic Modeling and Analytical Procedure

Any rigorous study of guideway dynamics must include not only the simple calculation of guideway natural frequencies, but also the dynamic interaction between the guideway and vehicle. Analysis of guideway dynamic response and vehicle-guideway dynamic interaction is important for evaluating peak dynamic loads and bending moments. Due to the high speeds of maglev vehicles (134 m/s or more), significant dynamic coupling problems can arise between the guideway and the vehicle as it crosses several spans per second. The guideway and vehicle must be designed to avoid resonance effects not only with vehicle passage, but also with the vehicle suspension and chassis bending frequencies. Guideway primary bending frequencies, especially in vertical flexure, must generally be in the range of 3 to 5 Hz or more to avoid these coupling effects. For pre-stressed beams in the 25 to 35m span range, this means that section properties are usually stiffness driven; ultimate beam strengths are thus considered primarily for safety under extreme conditions.

Guideway dynamic response due to vehicle loading can be calculated and used to determine the acceptable guideway stiffness range for avoidance of resonance effects. Consideration here is first given to a simply supported guideway subjected to a long series of point loads, each separated by a span length, L_S, as shown in Figure 4-1. This corresponds to a multi-car maglev vehicle with

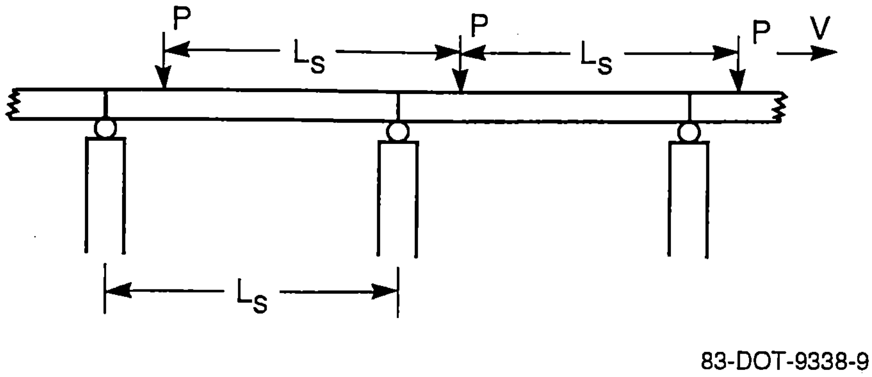


Figure 4-1. Simply Supported Guideway with Synchronous Point Loads

bogie spacing approximately equal to the span length (assumed to be the worst case). The primary bending frequency of the guideway is given by

$$f_1 = \frac{\pi}{2} \sqrt{\frac{EI}{\mu L_s^4}} \quad \text{(Hz)}$$

where

EI = guideway bending stiffness
μ = guideway mass/length
L_s = span length

To always avoid resonance between guideway flexure and vehicle passage, the guideway bending frequency (f_1)must be greater than the vehicle passage frequency (f_p):

$$f_p < f_1, \quad \text{or} \quad \frac{V}{L_s} < f_1$$

This results in a minimum stiffness-to-mass ratio for the guideway, given by

$$\frac{EI}{\mu} > \left(\frac{2VL_s}{\pi}\right)^2$$

Thus, for a desired maximum speed and span length, the above equation determines the minimum stiffness-to-mass ratio to avoid vehicle passage resonance in the simply supported span.

This is shown in Figure 4-2 for spans in the range of 24 to 30m. Note that for typical concrete guideway designs, a reasonable range for the stiffness-to-mass ratio is approximately 1.7 to 4.3 MN-m^3/kg. For the desired range of speeds (134 m/s or greater), Figure 4-2 shows that the resonance condition in simply supported spans cannot be avoided for practical designs. At some critical vehicle speed, the passage frequency will match the guideway bending frequency, unless the span length is very small.

For double span guideways, this analysis yields the same requirements for stiffness, since the fundamental frequency of the double span is once again given by the equation above. However, in the fundamental mode one semi-span is traveling upward while the other is traveling downward. The series of vehicle loads then does not directly excite the fundamental frequency; one load reinforces the vibration, but the adjoining load tries to cancel it, as shown in Figure 4-3. The resonance problem for the double span excited by multiple loads may then be less severe than found in the single span.

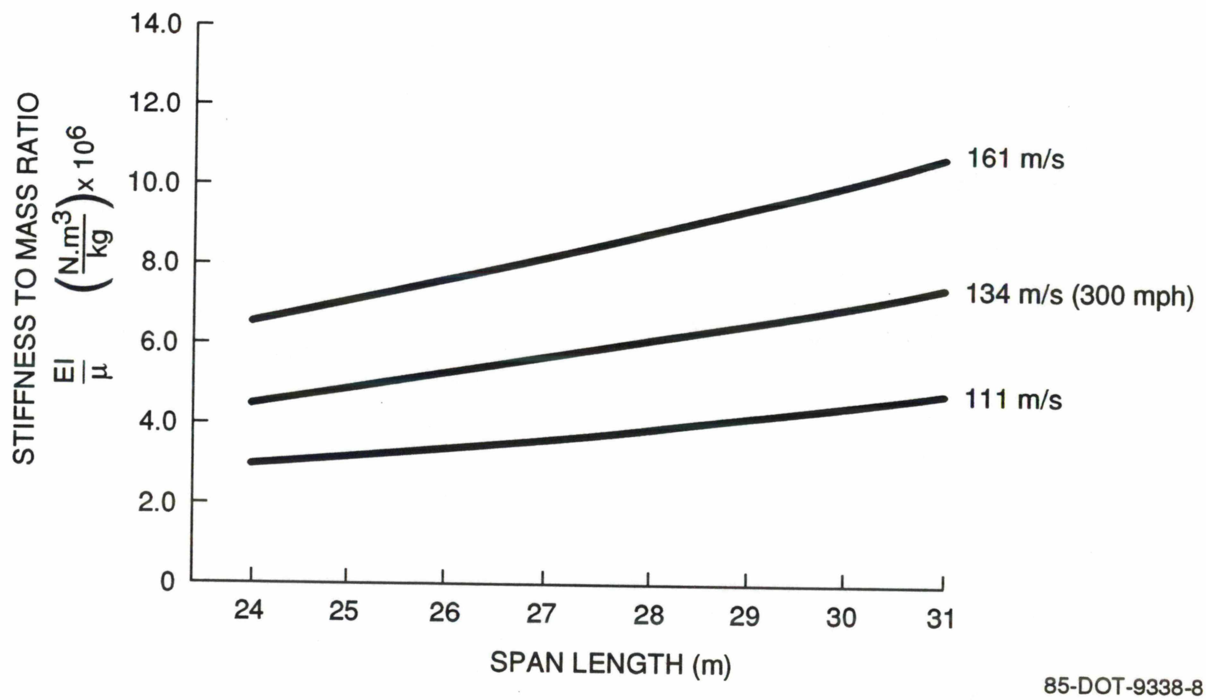


Figure 4-2. Span Length for Minimum Stiffness/Mass ($f_1 \geq f_p$)

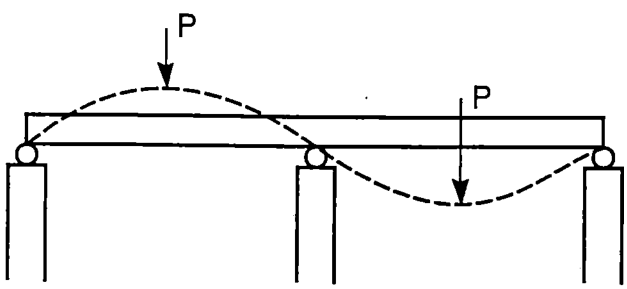


Figure 4-3. Loading and Primary Modeshape of a Double Span Guideway

As discussed above, the dynamic effects of coupling between vehicle passage and guideway flexure generally cannot be avoided with practical designs, regardless of the span continuity. It may therefore become necessary to design the guideway for the maximum possible dynamic load factor. Generally, the design driver here is the maximum allowable deflection, which in turn defines the required stiffness. Maximum dynamic deflection must be limited to a permissible value due to its potential effects on passenger ride quality and guideway stress and fatigue.

Calculation of the guideway dynamic deflection requires the use of single or multiple degree of freedom models containing both vehicle and guideway. The simple case of a moving constant force was analyzed in earlier work by Ford (3). This work showed that a dynamic deflection magnification factor of three is possible in single spans when the vehicle passage frequency matches the guideway fundamental flexural frequency. Other work by Richardson and Wormley (4) showed that even greater dynamic magnification factors (5 or more) could be achieved in damped, simply supported spans when subjected to a very long series of evenly spaced point loads, each separated by one span length. Here again, the critical condition in the single spans occurred when the vehicle passage and guideway flexural frequencies were equal.

To better analyze the vehicle-guideway dynamics for the single and double span designs under consideration here, a dynamic model was employed and is shown in Figure 4-4 for a single span guideway. The guideway is modeled as a uniform isotropic beam. The effects of transverse shear and rotary inertia are neglected, and a light damping of 2 percent is assumed. Since the thrust of this work is to examine the guideway deflection response (rather than the acceleration response of the vehicle), the loading is modeled as moving concentrated loads, positioned at the vehicle bogies. This assumption ignores the vehicle primary and secondary suspensions. This is acceptable since a high performance maglev vehicle suspension will be generally designed so as to limit vehicle

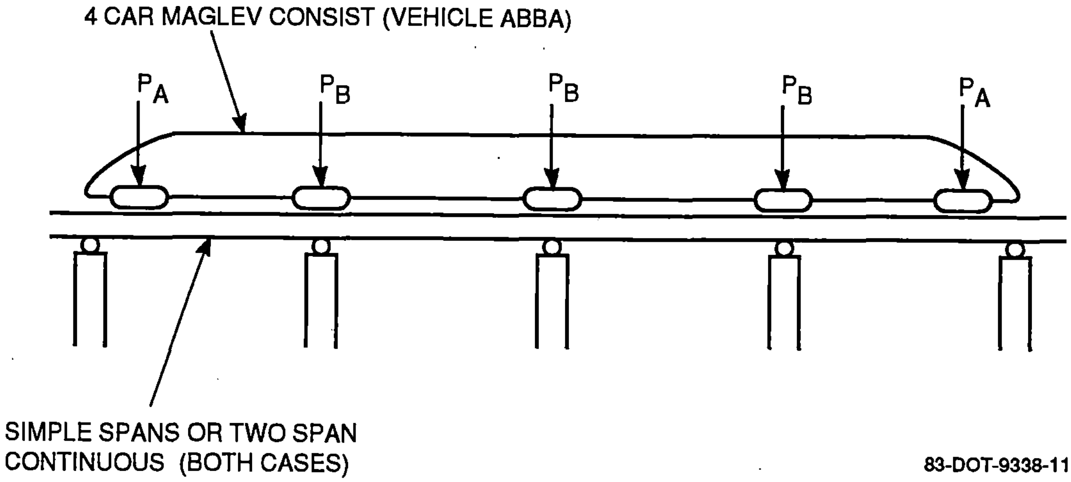


Figure 4-4. Dynamic Model of Guideway Loads

accelerations to 0.05g or less. The guideway deflection profile is then not significantly affected by the dynamic suspension forces; the guideway loading is effectively limited to the vehicle static weight.

The differential equation governing the guideway is given by

$$EI\frac{\partial^4 y}{\partial x^4} + b\frac{\partial y}{\partial t} + \rho a\frac{\partial^2 y}{\partial t^2} = p\,(x,t)$$

where

y = guideway deflection
b = damping coefficient
ρ = mass density
a = cross-sectional area
$p(x,t)$ = applied loads

The boundary conditions are defined by the characteristics of the beam supports. At the simply supported ends, the guideway deflection and bending moment both vanish; at intermediate continuous supports, deflection vanishes but bending moment continuity is maintained. The loading is a function of both position and time, since the point loads are moving at the vehicle speed, V.

Solution of the differential equation above may be obtained by means of modal analysis, as described in reference (4). The motion of the guideway is represented as an infinite series of the natural modeshapes, as given by

$$y\,(x,t) = \sum_{m=1}^{\infty} A_m\,(t)\,\phi_m\,(x)$$

where

A_m = modal amplitude
ϕ_m = modeshape

The modeshapes are determined from the unforced vibration of the beam. The time varying coefficients A_m depend on the guideway loads and can be determined from the ordinary differential equation

$$\ddot{A}_m + 2\,\xi_m \omega_m \dot{A}_m + \omega_m^2 A_m = \frac{1}{\rho a L} \int_0^L p(x,t)\phi_m(x)\,dx$$

where

ξ_m = modal damping ratio = $b_m/2\omega_m\rho a$
ω_m = modal natural frequency

Given the vehicle bogie loads, p(x,t), the guideway dynamic deflection response can be determined via the above equations.

The following sections will examine in detail the dynamic response of several candidate guideways. Parametric studies will also be used to investigate the effects of span length, span continuity, and vehicle loading.

4.1.2 Dynamic Response of Typical Guideway Designs

The methods described above will now be applied to several candidate guideway designs to determine the dynamic deflection and bending moment response. The designs are listed in Table 4-1. Each design is a variation of the baseline Foster-Miller U-shaped guideway. The candidate designs reflect reasonable variations in section depth and flange thickness. A general computer program was written to calculate the section properties of the guideway designs. The baseline vehicle loading is shown in Figure 4-4. A four car consist (vehicle ABBA) was assumed and modeled using equivalent concentrated loads. The guideways were examined using the dynamic model to determine the maximum midspan dynamic deflection for a 30m double span (a total beam length of 60m). The results are shown in Figures 4-5 and 4-6, which plot the non-dimensional dynamic response, y/y^*, against the non-dimensional vehicle speed, V_c, for each of the two spans in the double span guideway. The non-dimensional terms are defined as follows:

y = max guideway dynamic deflection at midspan
y^* = max single span deflection due to a static concentrated force at midspan

$$y^* = \frac{PL_s^3}{48\,EI} \quad (P = \text{bogie load} \approx 255\text{ kN})$$

V_c = Ratio of span passage frequency to the fundamental guideway bending frequency

$$V_c = \frac{V}{L_s f_1}$$

Figures 4-5 and 4-6 show several designs, each having a different stiffness and natural frequency. However, when plotted using the nondimensional axes described above, the data coalesce into the single composite curves shown on the figures. Theoretically, the characteristic curves defined in Figures 4-5 and 4-6 will change only if the span length, span continuity, vehicle consist, or vehicle bogie spacing are changed.

The results shown in Figures 4-5 and 4-6 indicate that as the vehicle speed increases, the dynamic interaction effects become apparent. For a double span guideway with the four car ABBA vehicle consist, the maximum y/y^* is approximately 1.7. The characteristic curve shows two distinct peaks at speeds in regions slightly above and below $V_c = 1$.

Table 4-1. Candidate Designs for Dynamics Analysis

Design	EI ($GN\text{-}m^2$)	m Mass/Length (kg/m)	EI/m ($MN\text{-}m^3/kg$)	Fundamental Frequency (Hz)		
				L = 24 m	L = 27 m	L = 30 m
A	23.69	5464	4.34	5.68	4.49	3.63
B	20.09	5400	3.72	5.26	4.16	3.37
C	17.61	5720	3.08	4.78	3.78	3.06
D	11.33	5513	2.06	3.91	3.09	2.50
E	25.21	5927	4.25	5.62	4.44	3.60
F	9.72	5141	1.89	3.75	2.96	2.40
G	8.11	4768	1.70	3.56	2.81	2.28

Notes: Each design includes an allowance for miscellaneous connection hardware

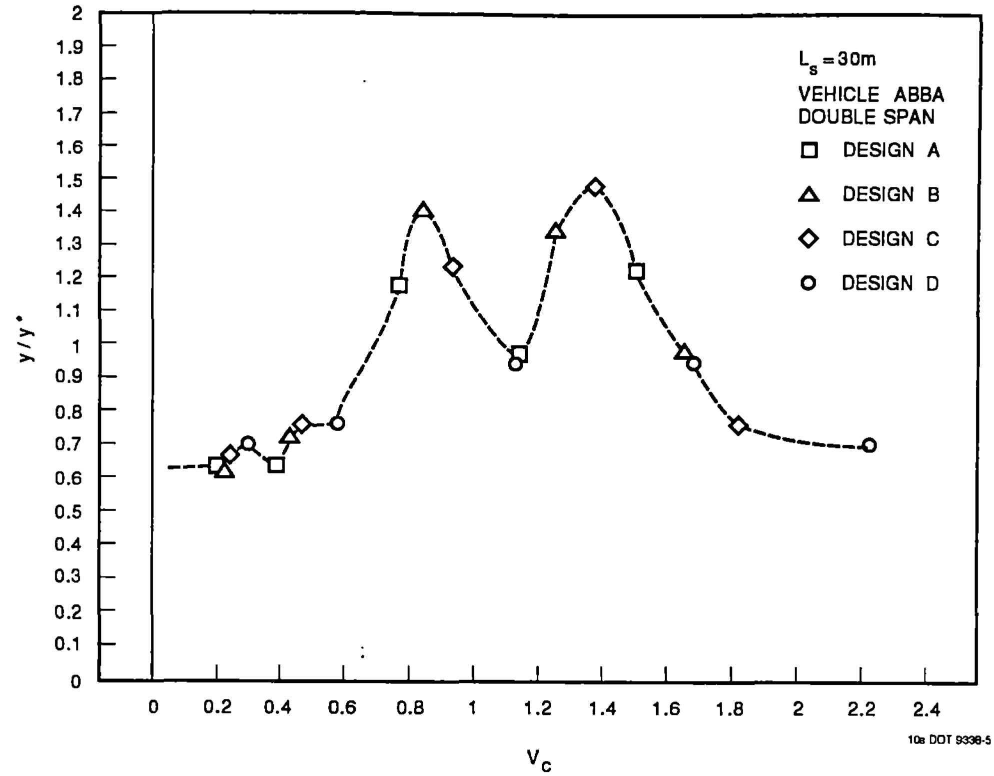


Figure 4-5. Dynamic Response - First Span of a Double Span Guideway

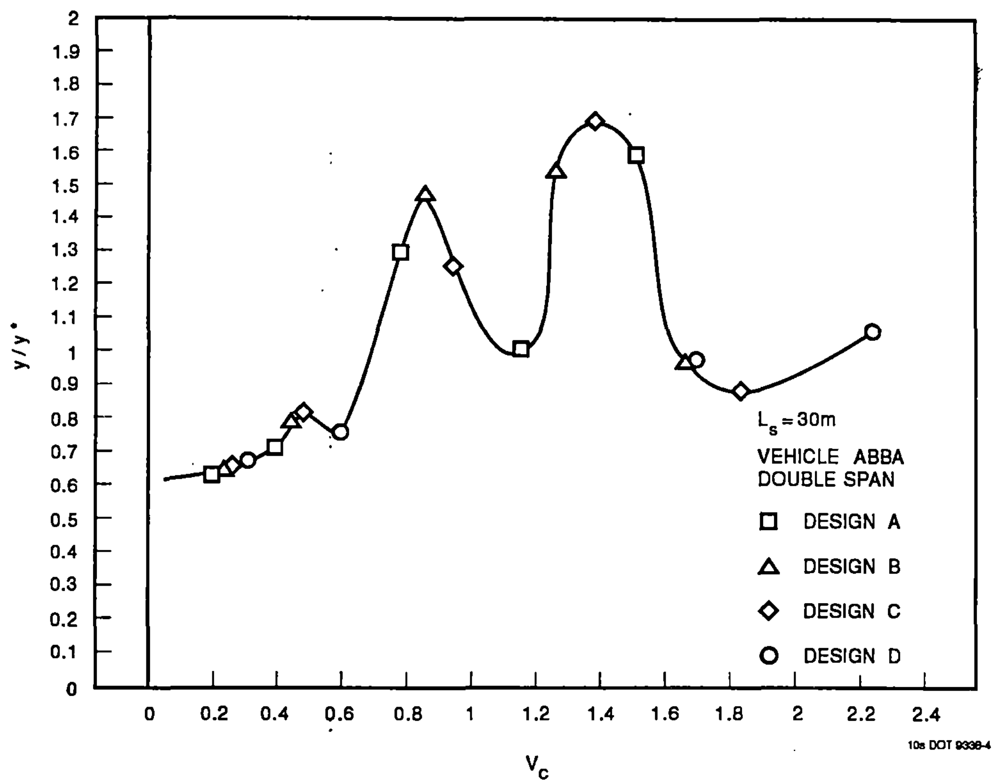


Figure 4-6. Dynamic Response - Second Span of a Double Span Guideway

Figure 4-7 shows the results of a similar analysis using a 30m single span guideway with the ABBA vehicle consist. Here the characteristic curve was generated using a single guideway design. As noted above, any other guideway designs should also fall on this same curve. The maximum dynamic load factor here is much higher, greater than 3, and occurs at a single peak at speeds where $V_C \approx 1$. This is in good agreement with the results of previous works (4) which showed that when excited by multiple loads separated by slightly less than one span length, the dynamic deflection of a single span is greater than that of multiple spans.

Comparing the double and single span results, it is apparent that the double span guideway provides better dynamic deflection response. The dynamic amplification of deflection is greater in the single span guideway, implying that the single span guideway must be designed to withstand considerably greater bending moment capacity. This will result in an unusually stiff (and consequently large and heavy) guideway in comparison to the double span design.

4.1.3 Parametric Studies

The results of the previous section have shown the dynamic load factors for 30m single and double spans with the four car consist. To further examine the effects of vehicle weight, vehicle consist, and span length on the dynamic deflection, a parametric study was performed. For each

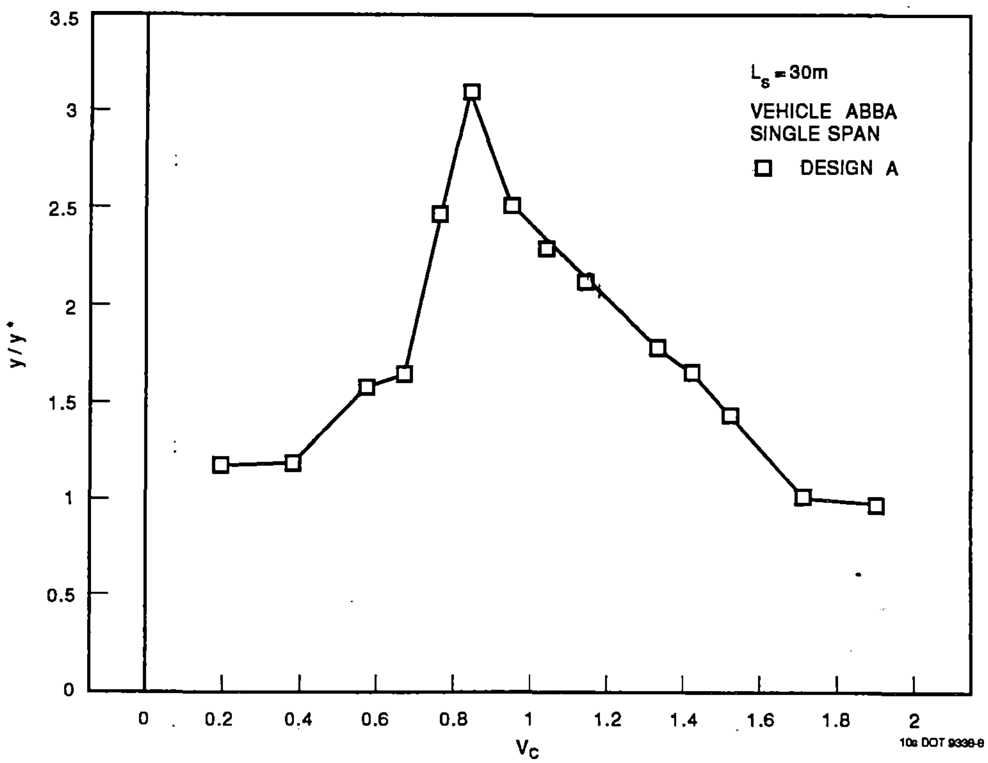


Figure 4-7. Dynamic Response - Single Span Guideway

case, the characteristic response curve was determined for both single and double spans. The results are discussed below.

Effects of Vehicle Weight

Decreasing the vehicle weight (keeping the consist and bogie spacing constant) will naturally decrease the absolute magnitude of the dynamic deflection and bending moment and will allow a smaller and lighter section design. However, the non-dimensional quantity y/y* will not change, since the static value y* decreases proportionally with the decreased static bogie load. The characteristic curves thus will not change with changes in the vehicle weight.

Effects of Vehicle Consist

Changing the vehicle consist will affect the dynamic response of the guideway. To illustrate this, three different vehicle consists were studied: a single car vehicle (A), a double car vehicle (AA), and the four car ABBA vehicle described in the subsections above. Using a single guideway design and 30m single and double spans, the dynamic response for each case was calculated. For the case of double spans, the results are presented for the maximum of the first or second spans.

The results are shown in Figures 4-8 to 4-12. Figure 4-8 shows the dynamic response for the single car (A) vehicle for both single and double spans. As noted in the previous subsection, the dynamic response of the single span guideway is greater than found in the double span, producing greater dynamic deflection. Similar results are obtained for the AA and ABBA vehicles, as shown in Figures 4-9 and 4-10. In each case, the dynamic deflection of the single span is much greater than that for the double span.

The effects of vehicle consist can be directly seen in Figures 4-11 and 4-12, which compare each of the three vehicles for single and double spans, respectively. The single vehicle is seen to produce a much smaller dynamic response than the multi-car consists, regardless of the span continuity. However, the two car (AA) consist produces deflections nearly as large as the four car (ABBA) consist. Further increases in vehicle consist length beyond four cars are not expected to appreciably increase the dynamic deflection response.

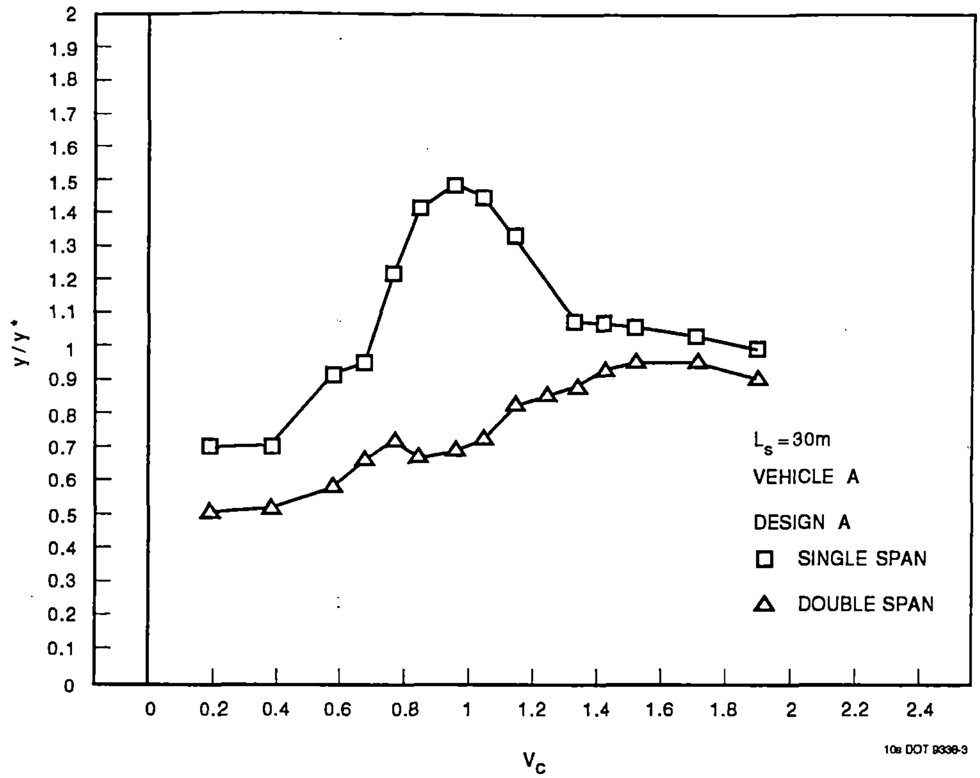


Figure 4-8. Dynamic Response for Vehicle A

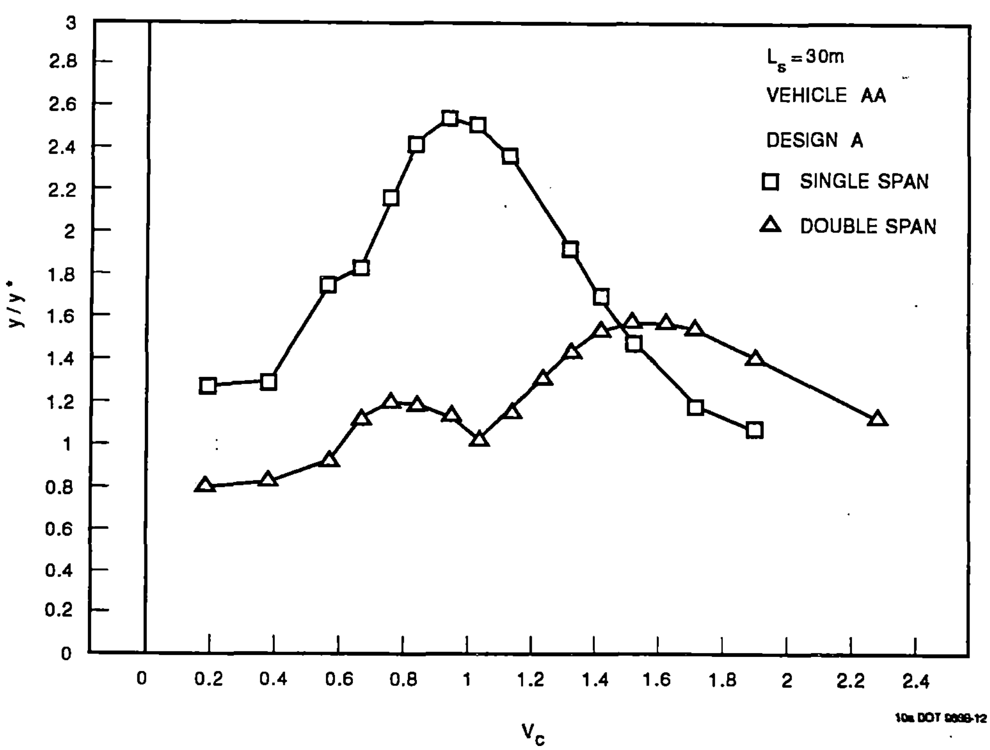


Figure 4-9. Dynamic Response for Vehicle AA

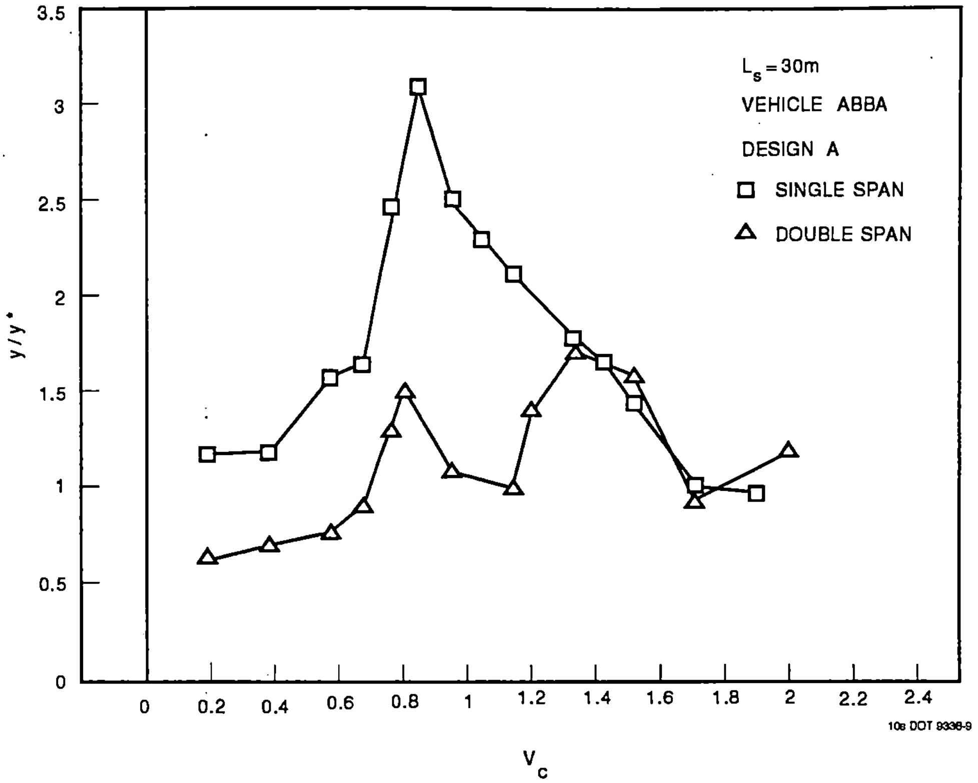


Figure 4-10. Dynamic Response for Vehicle ABBA

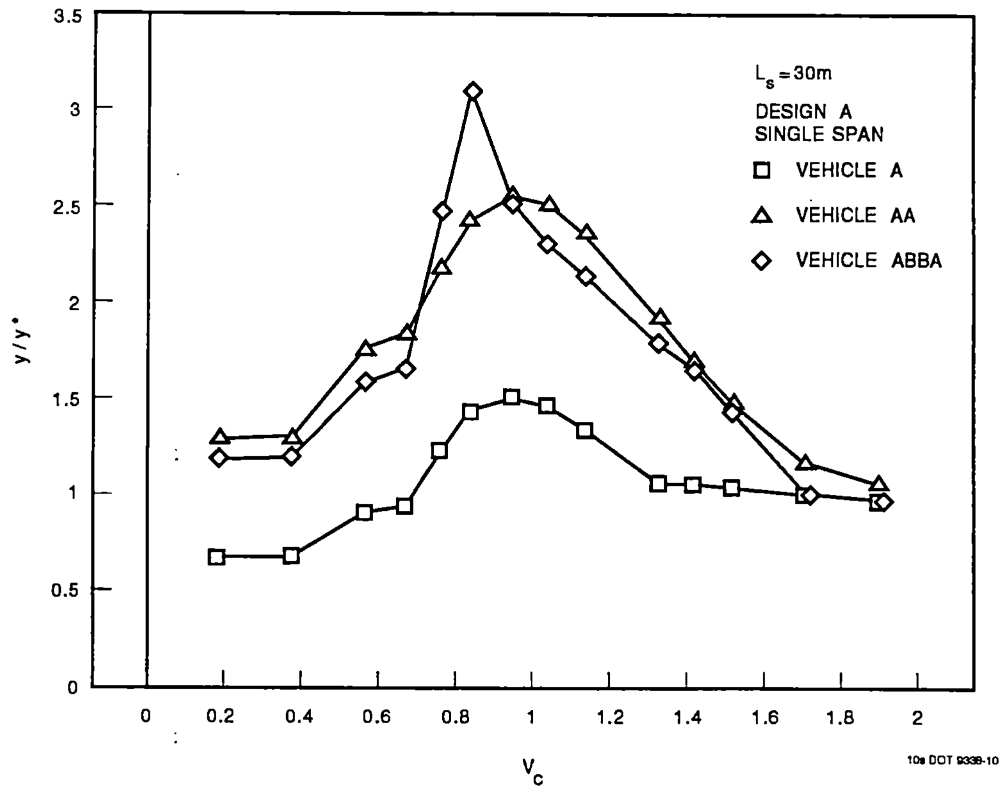


Figure 4-11. Effect of Vehicle Consist - Single Span

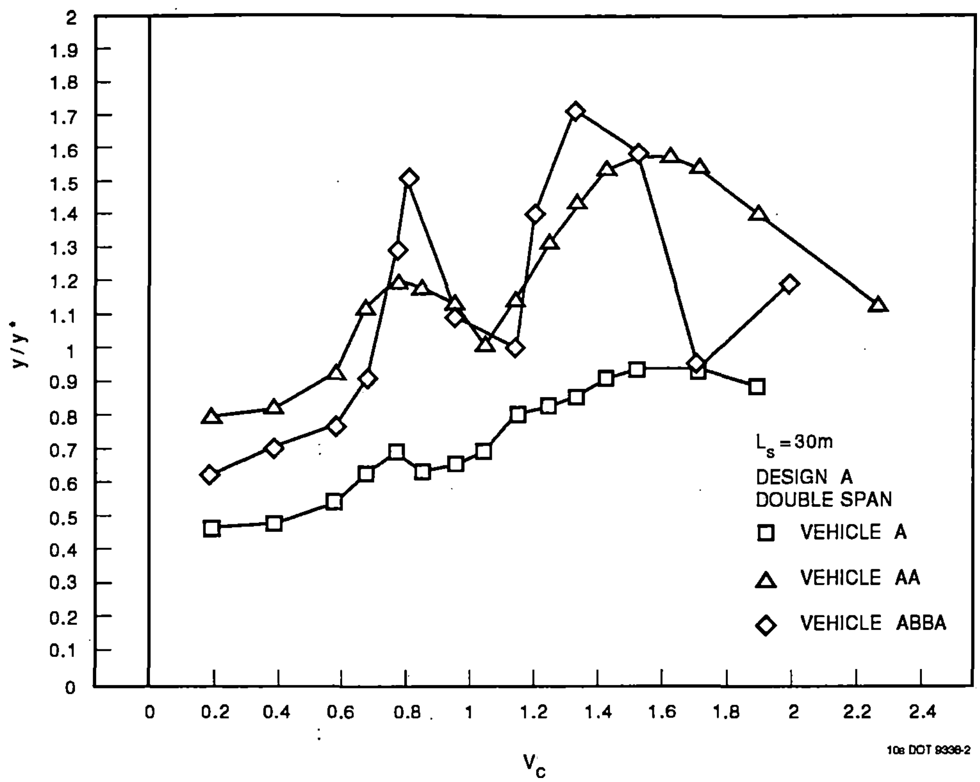


Figure 4-12. Effect of Vehicle Consist - Double Span

These results conclusively demonstrate the need to design for vehicle capacity growth. Designing the guideway strictly for single car vehicles will allow for a somewhat lighter and less stiff guideway, since the dynamic load factors are smaller. However, any future increases in capacity and vehicle size cannot then be accommodated, since capacity growth via longer consists (even two car consists) will produce significantly greater dynamic response and require a heavier, stiffer guideway.

Effects of Span Length

For a given vehicle loading, changes in the guideway span length will change the dynamic response of the guideway. The dynamic response y/y* increases as the span length approaches the vehicle bogie spacing. This is illustrated in Figure 4-13 to 4-16 for the ABBA vehicle on single and double spans of 24 and 27m lengths. The characteristic curves show that the dynamic response is again greater for the single span guideway, with y/y* greater than 4.5 for the 24m single span. Comparison among the three span lengths reveals that the dynamic response increases with decreasing span length, and is greatest in the 24m span, where the span length and bogie

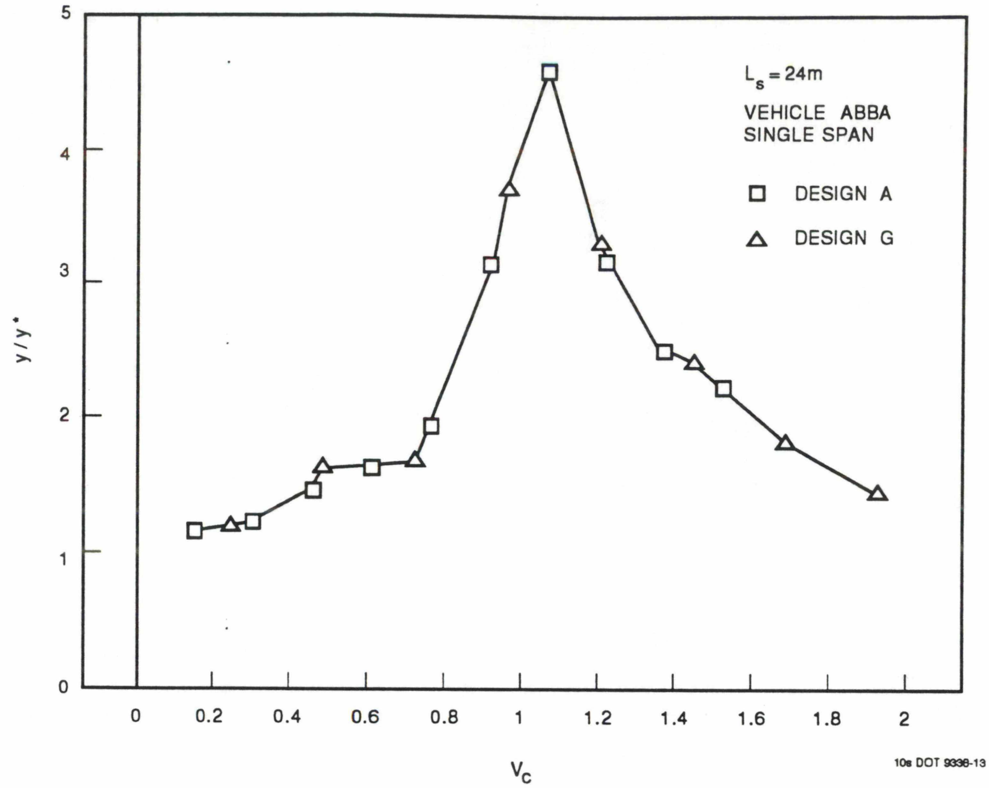


Figure 4-13. Dynamic Response - 24m Single Span

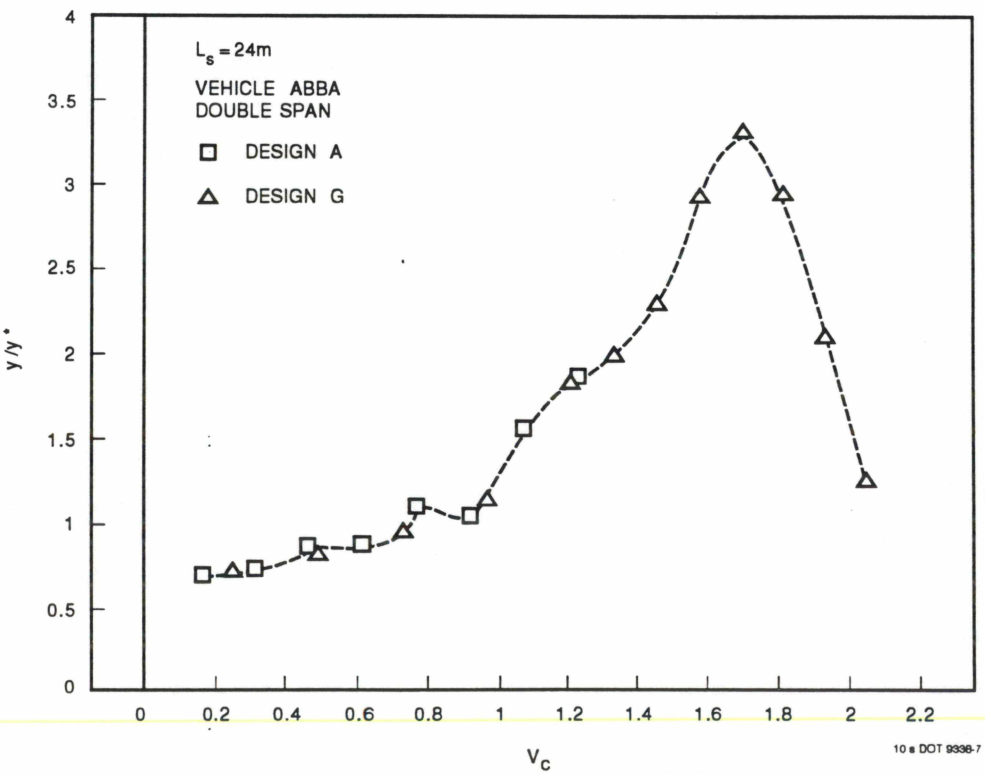


Figure 4-14. Dynamic Response - 24m Double Span

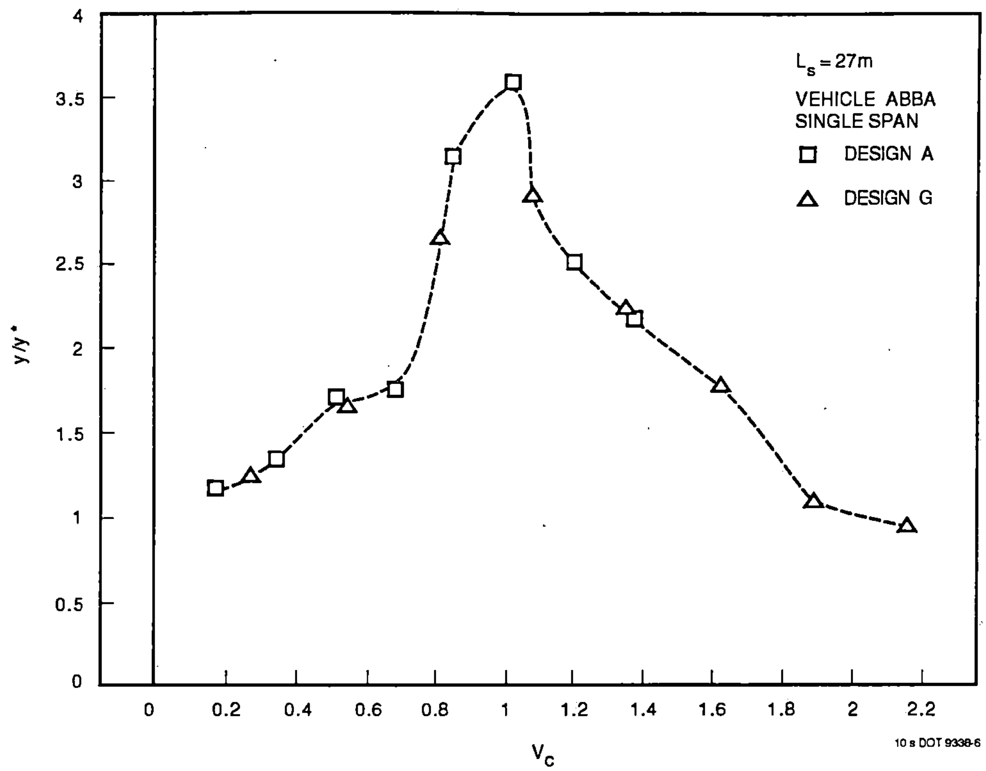


Figure 4-15. Dynamic Response - 27m Single Span

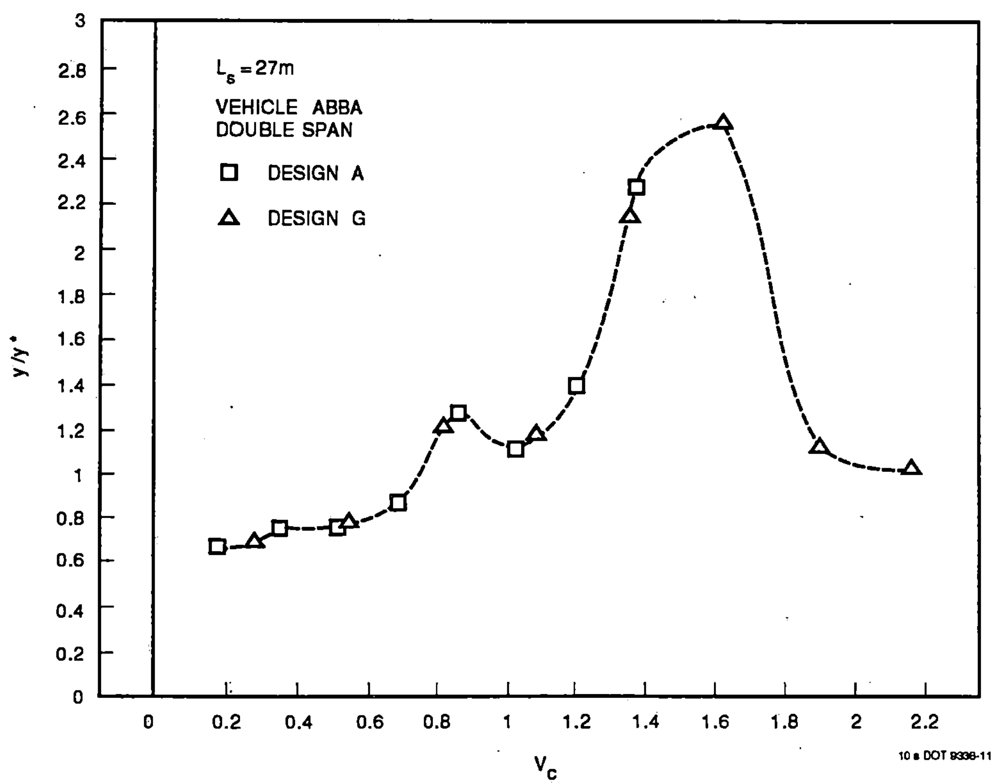


Figure 4-16. Dynamic Response - 27m Double Span

spacing are most closely matched. However, this does not necessarily mean that the absolute magnitude of the dynamic deflection increases in the shorter spans, since the static value of y* is also reduced.

4.1.4 Calculation of Dynamic Bending Moment

The dynamic bending moment can be approximately calculated by assuming the guideway vibration to be primarily in the fundamental mode. That is, the maximum dynamic deflection is assumed to be described by

$$y(x) = y_{max} \sin \frac{\pi x}{L_s}$$

where

y_{max} = maximum dynamic deflection at midspan

The maximum dynamic bending moment can then be calculated by

$$M = EIy'' = y_{max} \left(\frac{\pi}{L_s}\right)^2 EI$$

To non-dimensionalize terms, the characteristic single span bending moment due to a midspan point load is defined as

$$M^* = y^* \left(\frac{\pi}{L_s}\right)^2 EI$$

The maximum non-dimensional bending moment, M/M*, is thus given by

$$\frac{M}{M^*} = \frac{y}{y^*}$$

Obviously, this is only an approximate result. Rigorous assessment of the dynamic bending moment requires that several deflection modes be considered. However, this approximate analysis does show that the non-dimensional dynamic bending moment is proportional to the non-dimensional dynamic deflection and should follow the same trends. The y/y* trends shown in the results of the previous section are applicable to dynamic bending moment as well. The same parametric conclusions can then be drawn for the dynamic bending moment response: similar to the dynamic deflection, the dynamic moment, M/M*, will be greater for single spans than double spans, particularly if multiple car consists with bogie spacing equal to the span length are used.

The results of the parametric studies presented here will now be used to determine the dynamic deflection and bending moment response of a specific guideway design. This is discussed in the following subsection.

4.1.5 Numeric Example

To quantify the results of the parametric studies, one of the candidate guideway designs, design A (Table 4-1), was analyzed using the methods described in the previous subsections. The dynamic deflection and bending stress were calculated for 30m single and double spans using the ABBA vehicle consist. For this specific example, the dynamic bending moment was calculated using two separate methods: first by assuming that M/M* and y/y* are equal, and calculating the dynamic moment from the y/y* results, as discussed above; and secondly by directly using a rigorous solution for bending moment which incorporated several deflection modes, as calculated by the dynamic model. In each case the bending moment was then used to calculate the bending stress.

The deflection results are presented in Figure 4-17. As was shown in the parametric study, the dynamic deflection is much greater for the single span than for the double span, reaching a peak of nearly 2 cm very near the design cruise speed of 134 m/s. In contrast, the maximum deflection in the double span guideway is approximately 1 cm. As noted previously, the dynamic deflection must be limited to a permissible value due to its potential effects on passenger ride comfort and guideway stress and fatigue. Figure 4-18 shows the dynamic bending stress for the single and double spans. The results show that the approximate solution for bending moment (M/M* = y/y*) provides reasonably accurate results when compared to the direct calculations of the full dynamic model. The data follow the same parametric trends as y/y*, with the bending stress being greatest in the single span. At the resonance condition, the maximum dynamic bending stress is estimated to be approximately 7 MPa (1015 psi) in the single span, and approximately 5 MPa (725 psi) in the double span. For other, less stiff designs, the dynamic deflection and bending stress will be correspondingly greater. These stresses can be either tensile or compressive, and could exceed

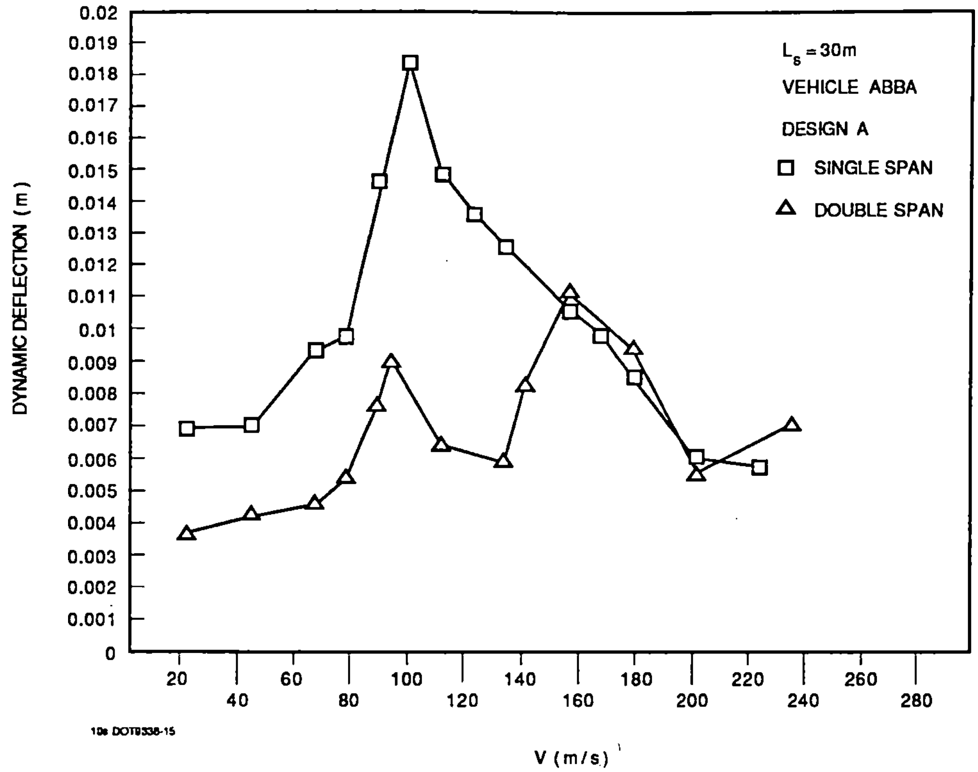


Figure 4-17. Numerical Example of Guideway Dynamic Deflection

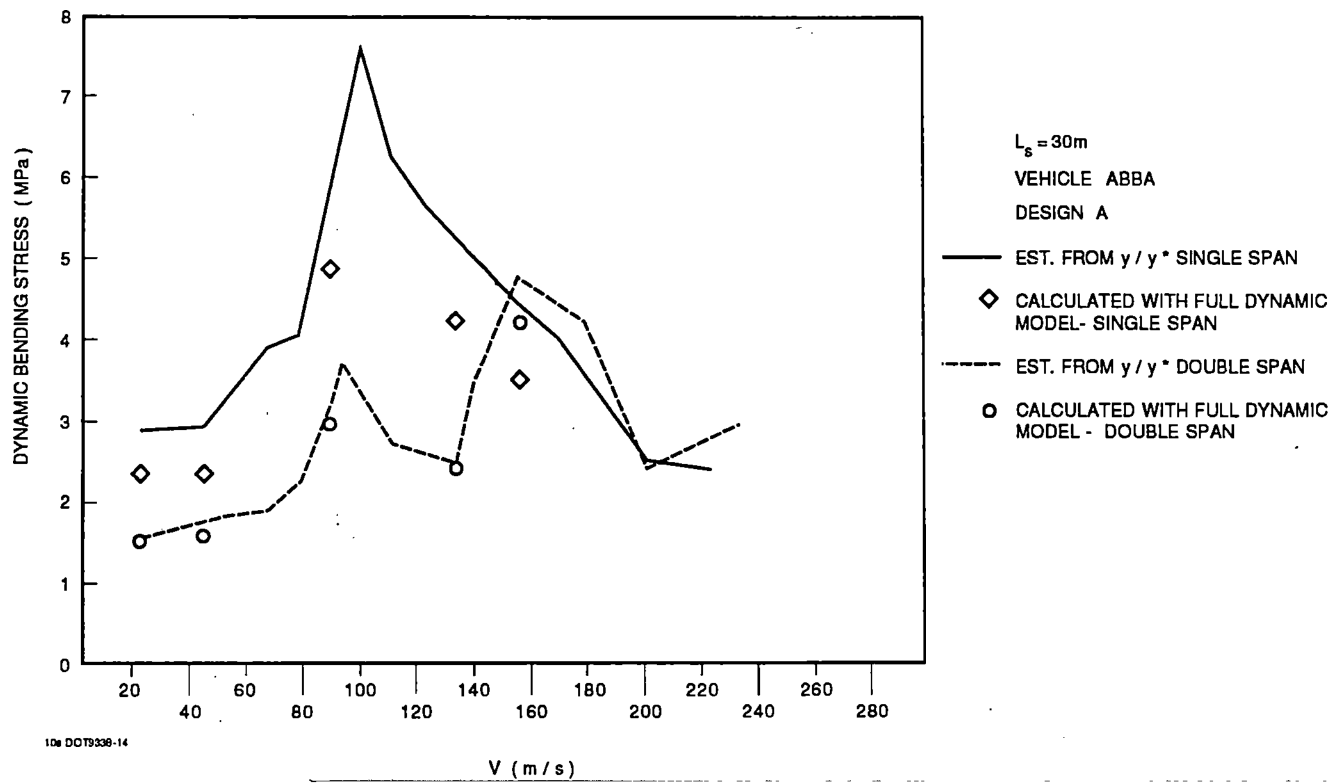


Figure 4-18. Numerical Example of Guideway Dynamic Bending Stress

desired limits for fatigue or ultimate strength. Fatigue is a particularly important issue, since these bending stresses will occur with every vehicle passage.

4.1.6 Stiffness Requirements

In this section, a method will be outlined to determine the deflection and stiffness requirements to avoid excessive passenger acceleration. This method will then be used to determine a range of useful guideway stiffness and natural frequency.

As noted previously, the maximum dynamic deflection must be limited to permissible levels so that excessive acceleration loads are not induced in the maglev vehicle. The dynamic deflection response calculated in the preceding sections can be used with the required deflection limits to determine the necessary guideway stiffness. The maximum allowable deflection can be estimated by using a simple, one degree-of-freedom model, as shown in Figure 4-19. As stated previously, it is reasonable to assume that the guideway deflection profile is not appreciably affected by the vehicle dynamic suspension forces, since the vehicle accelerations are generally small (<0.05g). The calculated guideway dynamic deflection can then be used as an input to the vehicle model to determine vehicle acceleration levels. As shown in Figure 4-19, a fixed sinusoidal guideway deflection is assumed, with an amplitude equal to one-half of the maximum dynamic deflection, as given by

$$y = \frac{1}{2}\, y_{max} \left(1 - \cos \frac{2\pi V t}{L_s} \right)$$

The resulting vehicle acceleration is given by

$$\ddot{y}_{max} = \frac{y_{max} \left(\frac{2\pi V}{L_s} \right)^2}{2\sqrt{\left(1 - r^2\right)^2 + 4\varsigma^2 r^2}}$$

where

$$r = \left(\frac{2\pi V}{L_s} \right) / \Omega_N;\ \Omega_N = \sqrt{k/M} = 0.7\ H_z \text{ (assumed)}$$

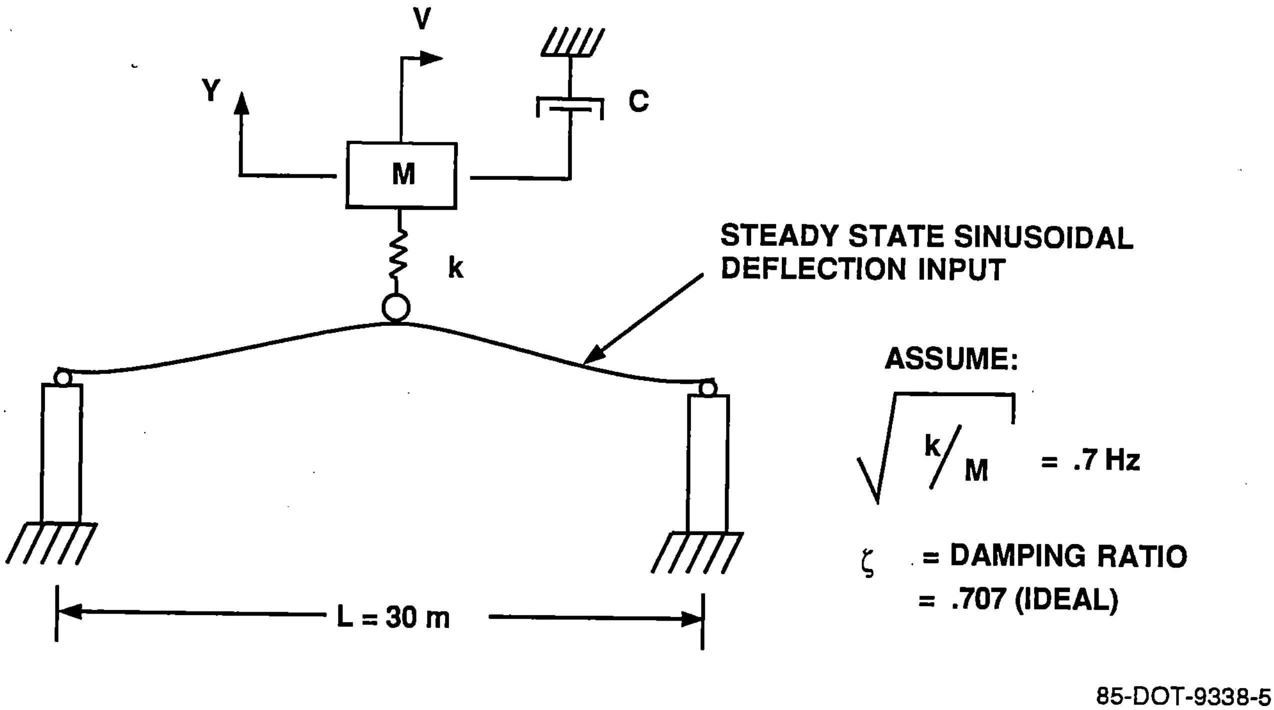


Figure 4-19. Single D-O-F Vehicle Model

ς = vehicle supension damping ratio
= 0.707 (ideal)

At high speeds, a limiting maximum steady-state heave acceleration is reached, and can be calculated from

$$\ddot{y}_{max} = y_{max}\,\frac{\Omega_N^{\;2}}{2}$$

Thus, for the maximum guideway dynamic deflection, the resulting vehicle acceleration can be calculated. The required guideway bending stiffness and natural frequency can then be determined by the following procedure:

1. Assume a span length, vehicle speed, and an achievable design range of guideway bending stiffness and natural frequency (such as from Table 4-1).

2. Calculate V_C for the assumed range of natural frequency and speed. From the corresponding characteristic curves of y/y^* versus V_C, determine the maximum value of y/y^* for each value of guideway natural frequency.

3. For the guideway bending stiffness values corresponding to the natural frequency range, calculate y^* and the resulting maximum dynamic deflection, y.

4. Calculate the maximum vehicle acceleration from the maximum dynamic deflection, using the equations above. Determine which design values of stiffness and natural frequency do not exceed the desired limits of passenger acceleration.

For range of designs presented in Table 4-1, the above procedure was used to determine the resulting vehicle acceleration for single and double 24m spans, assumed to be the worst case. The results of this analysis are presented in Figures 4-20 and 4-21. Each figure shows the estimated vehicle heave acceleration as a function of the guideway natural frequency. The results show that the maximum acceleration decreases with increasing guideway natural frequency. The acceleration levels are greater in the single span, due to its greater dynamic deflection.

Based on the simple vehicle modeling used in this type of analysis, Ford (3) estimated the maximum allowable acceleration to be 0.02g. For this assumed limit, the corresponding minimum natural frequencies are approximately 4.5 Hz for the single span and 3.5 Hz for the double span guideway. In an effort to be conservative, these limits will be used at the minimum allowable natural frequencies for all span designs. These results will be incorporated into the final design selection studies to be presented in the following sections.

4.1.7 Summary of Guideway Dynamics Analysis

Based on the parametric and numeric analyses presented in the preceding subsections, the following conclusions are drawn:

- Due to the high vehicle speeds, crossing several spans per second, dynamic interaction effects between the vehicle and guideway cannot, in general, be avoided. It is then necessary to design for the maximum dynamic load factor.

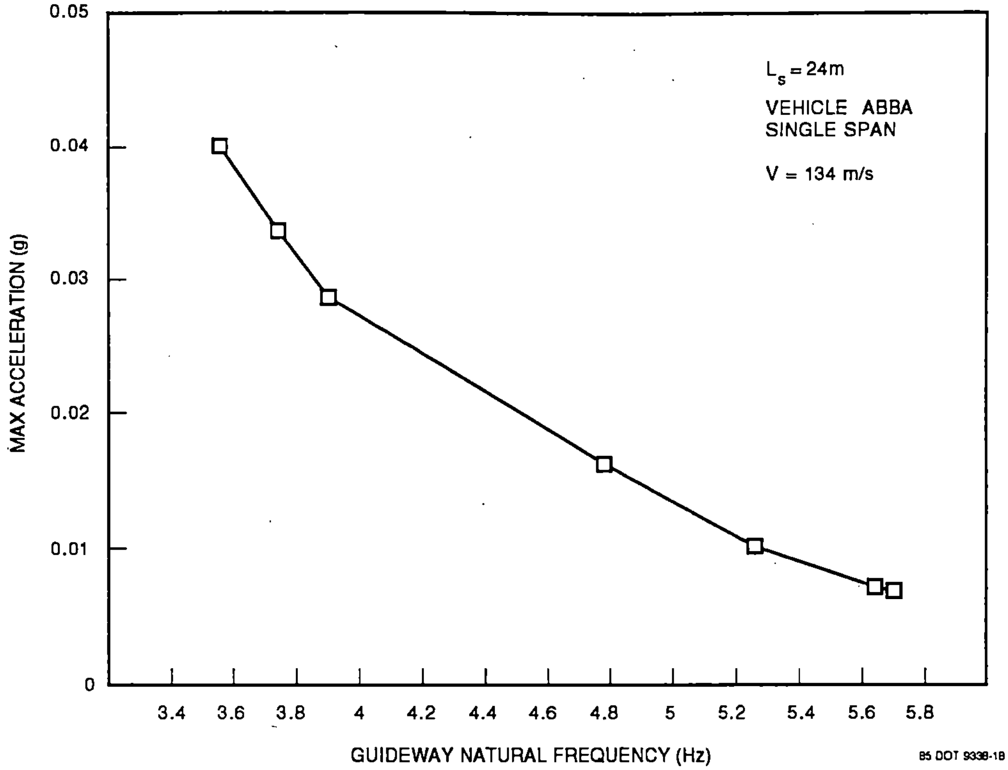


Figure 4-20. Vehicle Heave Acceleration - 24m Single Span

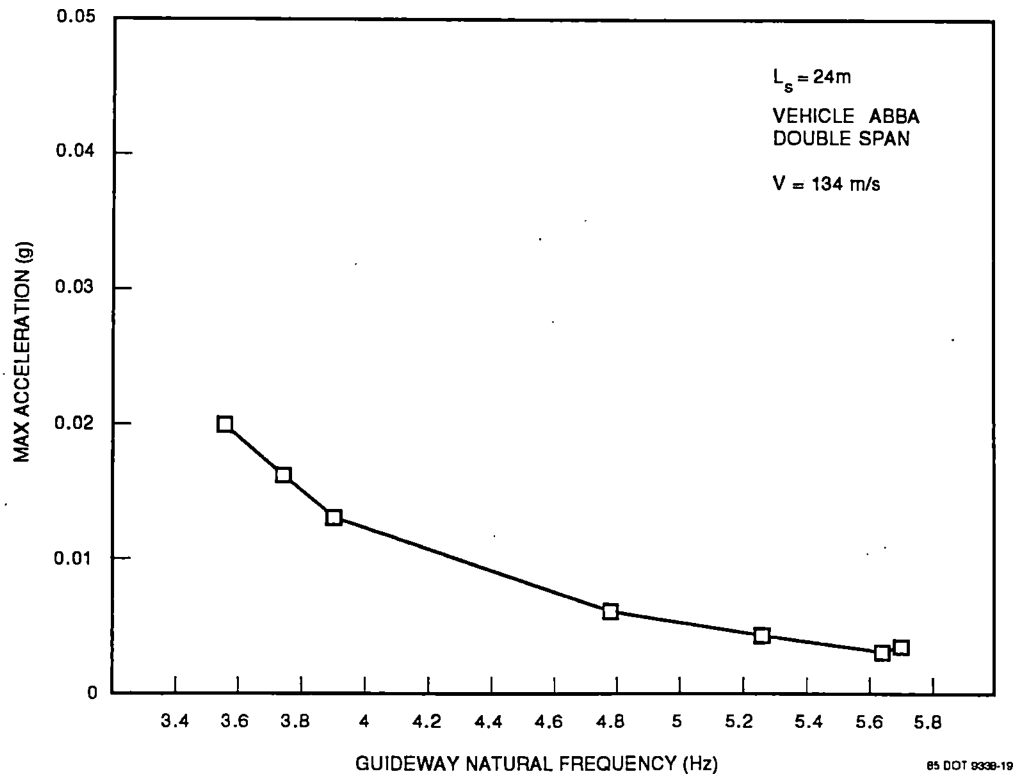


Figure 4-21. Vehicle Heave Acceleration - 24m Double Span

- Due to the multiple loads of multi-car vehicles, single spans generally experience much higher levels of dynamic deflection and dynamic bending stress. The single span design may require an unusually stiff and heavy guideway to provide the desired load capacity.

- The dynamic bending stresses could possibly exceed the desired design limits for fatigue of the concrete guideway. High passenger capacity could produce a large number of bending fatigue cycles, limiting the fatigue life of the guideway. This warrants further study.

- Guideway dynamic response increases with increasing vehicle consist size, to an effective maximum response at consists of four or more cars. Designing the guideway only for single car consists will not provide margin for growth of passenger capacity. Growth to even two car consists will result in a substantial increase in dynamic response, close to that of a four-car consist. Consists longer than four cars do not result in measurably higher guideway stiffness requirements.

- Vehicle heave acceleration is strongly influenced by the guideway stiffness. Guideway natural frequencies should generally be greater than 3.5 Hz for double spans, and greater than 4.5 Hz for single spans. More flexible guideways may produce excessive vehicle acceleration especially in the shorter spans.

- This study shows that the 24 to 30m span range is appropriate for structural design tradeoffs. To avoid undesirable dynamic interaction effects, the span lengths should remain above the anticipated range of vehicle lengths (bogie spacing). This favors spans of at least 24m or greater if reasonable design margin on vehicle lengths are maintained.

These fundamental bending frequency and stiffness guidelines will be used for the structural design of the candidate beam configurations.

4.2 Structural Design of Candidate Configurations

4.2.1 Structural Design Loads

Guideway Self-Weight

The guideway structural components would be constructed of regular weight, high strength, stone aggregate concrete. The gravity force due to the mass of this material is 25 kN per cubic meter. Concrete components include the girders, sidewalls and diaphragm sections. The coils, wires, cables and their attachment/adjustment devices will add an estimated 1.5 kN/m per guideway track.

Vehicle Loads

The structural designs in this report are based on consists of vehicles which are each 22m long and have a weight of 265 kN (59,500 lb). This provides about 10 kN design margin. Levitation forces are generated by the superconductor coils contained in the 6m long shared bogies, which support the end of each vehicle. In the interior of the consist, the bogies straddle the joint between vehicles so that each bogie supports the ends of two adjacent vehicles. The bogies react against two lines of ground coils set in the top horizontal surface of the guideway to levitate the vehicles, transferring the weight of the vehicles to the guideway along those lines. At low speeds, or when the vehicle is at rest, the gravity force of the vehicles is transferred to the guideway through the landing gear wheels which contact the guideway surface just inside the lines of the ground coils. Coils placed on the vertical surfaces of the sidewalls provide the propulsion forces and vehicle guidance. The net lateral force generated has a magnitude of approximately 20 percent of the vehicle gravity force or 53 kN applied over the 6m x 0.6 m height dimension of the bogie. This force is always an outward push of equal magnitudes to the sidewalls on each side of the vehicle. Additional lateral forces, due to curves, winds, etc., are superimposed on these primary propulsion/guidance forces. At low speeds, side wheels deploy and contact the sidewalls above the coils. Longitudinal forces are also generated in the sidewall coils when the vehicles are accelerated or decelerated; the maximum magnitude of these forces in each sidewall approximates 8 percent of the total vehicle weight.

Dynamic Interaction

A dynamic response interaction occurs between the moving vehicles and the spanning guideway structure. Dynamic studies conducted in the previous section indicate that for the vehicles and guideways evaluated a dynamic load factor (DLF) of 3.0 for simple structural spans and of 1.7 for two equal structural spans continuous over one support would be appropriate to multiply by the static vehicle weights to account for the dynamic interaction. These factors could be further refined using vehicle and suspension characteristics at a later stage of design.

The dynamic analysis and guideway beam design was performed for varying multi-car consists with 5m long bogies between cars and at the ends. Some small guideway economies might result with the use of continuous magnet support along the entire vehicle length, in which slight reductions of guideway interactions and bending stresses might be effected. However, the basic stiffness requirement for the guideway beam system to retain a fundamental vertical resonant bending frequency above that of the primary vehicle passing frequency over the pylons remains unaltered, so that this limits potential benefits of the "continuous" magnet arrangement. It should be noted that the discrete bogie arrangement affords many other system benefits such as compact secondary suspensions and tilting, passenger isolation from magnets and easier negotiation of tight curves.

Environmental Loads

The guideways will be subjected to the environmental loads of wind, temperature change, and possibly seismic action. Bulk temperature change does not produce gross structural loads on the guideways studied because in all schemes studied each guideway span is free to expand and contract under volume changes. Temperature change and gradient across the guideway section could have some minor dimensional effects, however. For design forces for wind and seismic action we used the most widely applied national model building code in the United States - the BOCA National Building Code/1990 (Eleventh Edition) published by Building Officials & Code Administrators International, Inc. The magnitudes of wind and seismic design forces, under this Code, vary depending on geographical location within the United States. We decided to produce structural designs which could safely withstand the environmental loads appropriate to the vast majority of geographic locations in the United States, requiring design modification only for very special environmental regions. Design wind speeds vary from a low of 31 m/s (70 mph) to a maximum of 50 m/s (110 mph). We adopted a design wind speed of 35.5 m/s (80 mph) which covers approximately 90 percent of the U.S. land area, excluding only the Gulf Coast, the South Atlantic Coast and the southern Alaska Coast, all for about 40 km (70 mi) inland, and the islands of Hawaii. For purposes of seismic design the United States is divided into four zones - 1, 2, 3 and 4. We adopted Zone 2 as our seismic design criteria which also covers approximately 85 to 90 percent of the U.S. land area, including the very important Boston to Washington corridor. This leaves principally California and parts of some other far western states as locations requiring seismic strengthening of the basic designs of this report. In fact, computations show that for the estimated weight range of the elevated guideway, lateral design forces for Zone 2 seismic are generally greater than for 50 m/s wind regions. Therefore the baseline design will probably be applicable for all of the U.S. except seismic Zones 3 and 4 where, as already mentioned, some modifications would be required.

Strength Requirements/Load Factors

We used the American Concrete Institute's "Building Code Requirements for Reinforced Concrete" (ACI 318-89) for all design requirements including strength requirements. Under these design requirements, stresses in prestressed concrete structural members at working loads (anticipated service loads) must not exceed certain stated allowable stresses which are well below the failure stresses of the materials. Also, all structural concrete members, including prestressed members, must be capable of resisting a certain "overload" before failure. Under this concept, termed Ultimate Strength Design, the failure strength of the member is matched to design loads which are increased by factors which account for overload possibility. In general, dead loads, which presumably can be more accurately defined, are factored by 1.4, and live loads and environmental loads which are more difficult to define are factored by 1.7. It could be argued that the vehicle loads which are accurately known could be factored by 1.4; however, because of uncertainties that still may be present at this stage of development we elected to apply a load factor of 1.7 to the vehicle loads (in turn calculated using DLFs) when making ultimate strength computations in order to maintain a higher level of safety.

A summary of the important structural design loads for the guideway girders is given in Table 4-2.

4.2.2 Structural Materials

Concrete

The principal structural material for the guideway construction is high strength concrete. Structural steel cannot even be considered, because of the adverse effects proximate ferrous

Table 4-2. Summary - Design Bending Moments - Spanning Guideway

	Span	Max. Dead Load Moment, Positive: Lightest Config. Studied (kNm)	Max. Dead Load Moment, Positive: Heaviest Config. Studied (kNm)	Max. Live Load Moment x D.L.F.: Positive (kNm)	Max. Live Load Moment x D.L.F.: Negative (kNm)	Max. Total Ultimate Moments: Positive: Lightest Config. Studied (kNm)	Max. Total Ultimate Moments: Positive: Heaviest Config. Studied (kNm)	Max. Total Ultimate Moments: Negative (kNm)
Simple Span	24m (78.7 ft)	4,028	4,735	3,576	-	11,718	12,708	-
	27m (88.6 ft)	5,214	6,395	4,170	-	14,389	16,042	-
	30m (98.4 ft)	7,164	8,467	4,764	-	18,128	19,953	-
Two-Span Continuous	24m (78.7 ft)	4,028	4,418	1,902	2,020	8,873	9,419	3,434
	27m (88.6 ft)	5,098	5,934	2,178	2,276	10,839	12,010	3,869
	30m (98.4 ft)	6,365	7,823	2,452	2,532	13,080	15,121	4,304

All moments in kNm; divide by 1.356 to obtain kip-ft. D.L.F. - Dynamic Load Facor = 1.7

materials would have on maglev operation. The pylons and foundations are cast-in-place concrete using conventional concrete mix designs. Design economics point to concrete design strengths (28-day) of 343 MPa (5,000 psi) for the pylons and 24 MPa (3,500 psi) for the footings. The elevated guideway structure would be constructed of high strength precast concrete elements with some special concrete mix design requirements. Concrete mix design requirements are related to the need for high early strength for prestressing production, and high concrete strength requirements related to the fact that secondary steel reinforcing is not permitted in the vicinity of the vehicle magnets. To deal with the absence of secondary steel reinforcing, and to reduce the need for more expensive glass fiber/polyester resin reinforcing rods, the concrete mix for the precast guideway elements will be of extra high compressive strength - 55 MPa (8,000 psi). The concrete mix will also contain polypropylene fibers in the amount of 5 percent of cement content to control cracking due to shrinkage and temperature change stresses. Concrete shear strength and concrete tensile strength are a fraction of the concrete compressive strength, using tensile strength = $6\sqrt{f_c'}$. (f_c' = compressive strength of concrete in standard material test $\cong$ 9000 psi in this design.) Therefore, the extra high concrete compressive strength of the guideway elements reduces the need for reinforcing for these stresses. Also, the modulus of elasticity of the concrete, and therefore the flexural stiffness of the concrete girders, increases with compressive strength. Concrete compressive strength of 55 MPa is easily achieved with today's technology. This concrete mix will employ a high range water reducer (HRWR) admixture, and silca fume to achieve high strength and improved corrosion protection for reinforcing.

Steel Prestressing Strands

Steel may be employed at the bottom of the guideway girders because that location is sufficiently removed from the vehicle magnets. The most cost-effective steel reinforcing in this application is high strength steel prestressing wire. The bottom prestress reinforcing will be that routinely employed in prestressed concrete plants for general production: 7-wire strands of nominal diameter of 15 mm (0.6 in.). The wire conforms to ASTM A-421, with a minimum ultimate tensile strength of 1.86 GPa (270,000 psi) and a modulus of elasticity of 186 GPa (27,000,000 psi) and the maximum initial stress which can be applied to a 15 mm strand is 0.74 x ultimate tensile strength or 1.38 GPa. Maximum initial force in a 15 mm strand equals 192 kN (42.9 kips). The steel strands will be bonded to the concrete as a natural consequence of the production process.

Nonmetallic Reinforcing

Some reinforcing of the concrete will be required in locations which are close to vehicle magnet locations. In these locations reinforcing rods made of glass fibers set in polyester resin will be used (glass fiber reinforced plastic, or GFRP). These rods are produced commercially by Bayer A.G. and other companies. The rods are normally produced in 7.5 mm diameter (0.35 in.). The tensile strength of these rods is high, but modulus of elasticity is relatively low for use as concrete reinforcement, 41 GPa (6,000,000 psi). To use the tensile strength available in these rods without permitting strains at which the concrete would crack, GFRP rods must in general be prestressed via post-tensioning to be useful as concrete reinforcing. For schemes requiring span continuity post-tensioning tendons of GFRP will be required. We will employ GFRP tendons of the type used to construct the Ulenbergstrasse Bridge in Dusseldorf, Germany. This bridge of 25m spans is constructed using GFRP tendons composed of 19 - 7.5 mm rods with a post-tensioning force of 600 kN (135 kips) per tendon. The anchorage for these tendons is a "barrel and spike" device which reportedly can develop the breaking strength of the tendon. Owing to the small amount of actual experience with this material, and the lack of general testing standards, the design of these tendons will be treated with conservatism. Also, the GFRP tendons will be installed so that they are not in direct contact with the concrete to eliminate any concerns about the effects that alkali in the concrete might have on the long-term durability of the GFRP.

4.2.3 Special Structural Design Considerations

The structural parameters are varied to explore the most economical elevated guideway structural designs. However, there are some considerations and limitations peculiar to the proposed system which must be satisfied by every candidate solution.

The guideway beam designs must preserve the essential features, described earlier, of the candidate configurations selected. Besides the obvious dimensional compatibility with the vehicle and magnetic gaps, these include:

- Accommodate all coil elements and adjusters
- Low speed/emergency braking surfaces
- Enclosed space for power, signal and services.

The four guideway configurations selected for detailed study were:

- Configuration I - Two-piece, two-cell box, with separately attached sidewalls
- Configuration II - Two-piece, two-cell box, with structurally integral sidewalls
- Configuration III - Two-piece, one-cell box, with separately attached sidewalls
- Configuration IV - Two-piece, two-cell box, null-flux arrangement.

Figures showing these configurations are found in subsection 3.2.

Nonferrous Structural Materials

The operation of a system which must generate large magnetic forces rules out the use of ferrous materials in the guideway in the vicinity of the coils. A concrete structure meets this requirement but practical designs cannot be made without the use of tensile reinforcing. The determination was made that any steel reinforcing used in the structure must be located at least 0.8m (31.5 in.) from any of the vehicles' magnet coils. Locations in the concrete structure requiring reinforcing which are less than this distance from a vehicle coil are reinforced with glass fiber rods (GFRP), post-tensioned. The determination was made that stainless steel bolts could be used for attaching the sidewalls, in the separate sidewall schemes, without significantly affecting coil operations.

Guideway Flexural Stiffness

To limit the dynamic response interaction between the guideway spans and the vehicles under operation to manageable levels, certain guideway flexural stiffness criteria were set in the previous subsection. The criteria were established by dynamic modeling studies conducted for this report. The minimum primary bending frequency of the simple span guideway structures is limited here to approximately 4.5 hz, and the primary bending frequency of guideway structures used in two-span conditions (continuous over one support) is limited to approximately 3.5 hz. Maximum deflection under vehicle gravity load (static) is limited to 8 mm (1/3 in.).

Span Continuity

The study of the dynamic interaction of the vehicle consists and the elevated guideway conducted for this report showed that continuity of span to any degree was very beneficial in reducing dynamic load factors. Even continuity over alternate supports (two span continuity) was quite beneficial. To fully understand the design implications, all designs were executed for both simple span condition and two-span continuous over center support condition. The reinforcing arrangement applied to all configurations for the two-span continuous condition was that the design had bottom steel prestressing reinforcing sufficient to support all dead loads with the girders on the pylons in a simple span condition, and to resist the maximum positive moments from dead and live loads after continuity at the center support had been achieved. Continuity at center support was achieved by the use of GFRP post-tensioning tendons connecting the tops of the adjoining girder spans over the center support. These top tendons were anchored to each adjoining girder at a distance of 20 percent of the span to either side of the support. The force in the top tendons was such that the tops of the adjoining girders always remained in compression under live load conditions and all other sections of the attached girders stayed within allowable stresses under live load conditions. Such an examination required a detailed determination of the design live load forces created by the 6m long bogies spaced at 22 m moving over a two span condition. The linear elastic analysis program, Staad, was used to make these analyses with the bogies moved across the spans in 1m increments.

4.2.4 Girder Design Procedure

The girders were designed to meet the requirements of ACI 318-89 "Building Code Requirements for Reinforced Concrete," Chapter 18 "Prestressed Concrete," using the structural loads discussed in subsection 4.2.1, the material properties discussed in subsection 4.2.2, and the special requirements discussed in subsection 4.2.3.

In order to make an economic comparison between four guideway configurations used in either simple span condition or two-span continuous condition the pertinent structural calculations were set up using a computer spreadsheet program. From an input of cross-sectional dimensions the following results are generated:

- Overall depth of structural girder
- Self-weight of the structural girder
- All geometric properties of the girder cross section
- Flexural stiffness parameter, EI

- Natural frequencies for a range of spans (proportional to $\sqrt{EI/m}$)

- With regard to bottom steel prestressing strands:

  - Minimum number of strands (ACI 318-89, 18.8.3)

  - Maximum number of strands (ACI 318-89, 18.8.1)

  - Maximum number of straight bottom strands that can terminate at the end of the girder without overstressing the top of the girder in tension.

After selecting the number of bottom strands, the following additional results are generated:

- Maximum positive ultimate strength moment capacity

- Tensile stress in strands after losses due to elastic shortening, concrete creep and shrinkage, and steel relaxation

- Stresses in the concrete at top and bottom of midspan due to all dead loads and the prestress force in the bottom strands (the continuous span designs also see this condition before post-tensioning is applied)

- Maximum positive design live load moment which can be added to the dead load moment before top or bottom concrete stresses exceed allowable working stresses

- Mid-span net deflection, simple span, due to all dead loads (down) and the effect of the bottom prestress force (up).

For determining stresses in the two-span continuous arrangements, the additional input of top post-tensioning force and live load moments between mid-span and the continuous support generates top and bottom concrete stresses at sections between mid-span and the continuous support. The computations are made for two conditions: live load position producing maximum positive moment near mid-span and, live load position producing maximum negative moment at the support.

With the spreadsheet program described above the cross-sectional dimensions and top and bottom prestress forces of each candidate configuration are adjusted until the design requirements for flexure were satisfied.

The results of the structural designs produced are summarized in a following section. For reference, the complete program results are included in Volume 2.

Shear capacity requirements involve the ratio of shear-to-moment at various sections due to the moving load along the length of the girders and are checked by separate computations. All of the configurations with ground coils require reinforcement of the top of the beam because the vehicle loads applied there. Since these are locations close to maglev coils, glass fiber reinforcing must be used. Therefore, all of these configurations will have transverse post-tensioned GFRP rods.

Calculations show that the candidate girders should be able to handle the design lateral loads due to wind or seismic forces with little or no additional reinforcing. On the other hand, these lateral forces are the principal design force consideration for the pylon/foundation structural design.

4.2.5 Summary of Parametric Study of Guideway Girders

All candidate configurations use girders that are "box" sections; the variations are the number of "cells" and geometric arrangement and whether or not the sidewall is an integral part of the structural girder. Each of the four candidate configurations was taken through preliminary design focusing on the predominant structural action, flexural action, using the computer spreadsheet set up for this purpose. Structural designs are produced for each candidate configuration varying two parameters, span length and span continuity. Designs are made for span lengths of 24m (78.7 ft), 27m (88.6 ft) and 30m (98.4 ft) and for simple span conditions and two equal spans continuous over the center support. To include all combinations of the variables mentioned above, 24 flexural designs were performed. The results of the parametric study are shown in Tables 4-3 through 4-6.

In addition to the parameters studied above, the sensitivity of guideway material quantity and cost to reduction in vehicle weight was evaluated for a single configuration. Using Configuration I, it was found that a 20 percent reduction in vehicle weight resulted in a design having a beam material reduction of about 4 percent. This gives an approximate example of the relative significance of reducing vehicle weight on guideway cost as this 4 percent reduction in beam cost gives approximately a 3 percent reduction in guideway structure costs and approximately a 1.5 percent reduction in total guideway (including all electrical systems) costs.

Table 4-3. Summary of Results of Parametric Structural Study

CONFIGURATION I

Two Piece, Two Cell Box with Separate Modular Sidewalls

					Precast Concrete Volume One Full Guideway, One Span					Reinforcing Quantities		
	Span	Overall Guideway Depth	Flexible Stiffness EI	Nat. Freq. Hz	Girder(s)	Sidewalls	Diaphragms	Total	Max. Piece Lifting Weight	Prestressing Steel Strand	Post-Tensional GFPR	Concrete Volume per Unit Length
Simple Span	24m (78.7 ft)	3.0m (9.8 ft)	9.3 GNm^2 (19x10^4 K-ft^2)	4.52	37.96 m^3 (49.7 CY)	18.72 m^3 (24.5 CY)	3.60 m^3 (4.7 CY)	60.28 m^3 (78.9 CY)	446 kN (100 Kips)	1113 kg (1.22 tons)	37.8 kg (83 lbs)	2.51 m^3/m (1.00 CY/ft)
	27m (88.6 ft)	3.45m (11.3 ft)	16.7 GNm^2 (34x10^4 K-ft^2)	4.60	49.36 m^3 (64.6 (CY)	21.06 m^3 (27.5 CY)	4.05 m^3 (5.3 CY)	74.47 m^3 (97.4 CY)	580 kN (130 Kips)	1252 kg (1.38 tons)	42.5 kg (94 lbs)	2.76 m^3/m (1.10 CY/ft)
	30m (88.4 ft)	3.9m (12.8 ft)	27.1 GNm^2 (55x10^4 K-ft^2)	4.56	62.24 m^3 (81.4 CY)	23.40 m^3 (30.64)	4.50 m^3 (5.9 CY)	90.14 m^3 (117.9 CY)	731 kN (164 Kips)	1391 kg (1.53 tons)	47.3 kg (104 lbs)	3.00 m^3/m (1.20 CY/ft)
Two-Span Continuous	24m (78.7 ft)	2.7m (8.9 ft)	5.7 GNm^2 (12x10^4 K-ft^2)	3.65	34.16 m^3 (44.7 CY)	18.72 m^3 (24.5 CY)	3.60 m^3 (4.7 CY)	56.48 m^3 (73.9 CY)	402 kN (90 Kips)	1060 kg (1.17 tons)	119.4 kg (263 lbs)	2.35 m^3/m (0.93 CY/ft)
	27m (88.6 ft)	30.0m (9.8 ft)	9.3 GNm^2 (19x10^4 K-ft^2)	3.57	42.83 m^3 (56.0 CY)	21.06 m^3 (27.5 CY)	4.05 m^3 (5.3 CY)	67.94 m^3 (88.9 CY)	446 kN (100 Kips)	1119 kg (1.31 tons)	134.3 kg (295 lbs)	2.52 m^3/m (1.00 CY/ft)
	30m (98.4 ft)	3.35m (11.0 ft)	14.9 GNm^2 (30x10^4 K-ft^2)	3.54	53.26 m^3 (69.7 CY)	23.40 m^3 (30.6 CY)	4.50 m^3 (5.9 CY)	81.16 m^3 (106.2 CY)	626 kN (141 Kips)	1325 kg (1.46 tons)	149.3 kg (328 lbs)	2.71 m^3/m (1.08 CY/ft)

Table 4-4. Summary of Results of Parametric Structural Study

CONFIGURATION II

Two Piece, Two Cell Box with Structurally Integral Sidewalls

					Precast Concrete Volume — One Full Guideway, One Span					Reinforcing Quantities		
	Span	Overall Guideway Depth	Flexible Stiffness EI	Nat. Freq. Hz	Girder(s)	Sidewalls	Diaphragms	Total	Max. Piece Lifting Weight	Prestressing Steel Strand	Post-Tensional GFPR	Concrete Volume per Unit Length
Simple Span	24m (78.7 ft)	21.m* (6.9 ft)	13.9 GNm^{2}* (29×10^4 K-ft^2)	6.01	46.31 m^3 (60.6 CY)	-	3.60 m^3 (4.7 CY)	49.91 m^3 (65.3 CY)	544 kN (122 Kips)	848 kg (0.93 tons)	57.0 kg (125 lbs)	2.08 m^3/m (0.83 CY/ft)
	27m (88.6 ft)	2.1m* (6.9 ft)	13.9 GNm^{2}* (29×10^4 K-ft^2)	4.75	52.09 m^3 (68.1 CY)	-	4.05 m^3 (5.3 CY)	56.14 m^3 (73.4 CY)	612 kN (138 Kips)	1192 kg (1.31 tons)	64.1 kg (141 lbs)	2.08 m^3/m (0.83 CY/ft)
	30m (98.4 ft)	2.6m* (8.5 ft)	21.3 GNm^2 (44×10^4 K-ft^2)	4.50	66.33 m^3 (86.6 CY)	-	4.50 m^3 (5.9 CY)	70.83 m^3 (92.6 CY)	779 kN (175 Kips)	1325 kg (1.46 tons)	71.3 kg (157 lbs)	2.36 m^3/m (0.93 CY/ft)
Two-Span Continuous	24m (78.7 ft)	2.1m* (6.9 ft)	13.9 GNm^{2}* (29×10^4 K-ft^2)	6.01	46.31 m^3 (60.6 CY)	-	3.60 m^3 (4.7 CY)	49.91 m^3 (4.7 CY)	544 kN (122 Kips)	636 kg (0.70 tons)	106.0 kg (233 lbs)	20.8 m^3/m (0.83 CY/ft)
	27m (88.6 ft)	2.1m* (6.9 ft)	13.9 GNm^{2}* (29×10^4 K-ft^2)	4.75	52.09 m^3 (68.1 CY)	-	4.05 m^3 (5.3 CY)	56.14 m^3 (73.4 CY)	612 kN (138 Kips)	894 kg (0.98 tons)	137.5 kg (303 lbs)	2.08 m^3/m (0.83 CY/ft)
	30m (98.4 ft)	2.1m* (6.9 ft)	13.96 NM^{2}* (29×10^4 K-ft^2)	3.85	57.81 m^3 (75.9 CY)	-	4.50 m^3 (5.9 CY)	62.38 m^3 (81.6 CY)	680 kN (153 Kips)	1192 kg (1.31 tons)	152.9 kg (336 lbs)	2.08 m^3/m (0.83 CY/ft)

*Depth of stiffness governed by minimum distance of steel prestress to magnet.

Table 4-5. Summary of Results of Parametric Structural Study

CONFIGURATION III

Two Piece, One Cell Box with Separately Attached Sidewalls

					Precast Concrete Volume					Reinforcing Quantities		
					One Full Guideway, One Span							
	Span	Overall Guideway Depth	Flexible Stiffness EI	Nat. Freq. Hz	Girder(s)	Sidewalls	Diaphragms	Total	Max. Piece Lifting Weight	Prestressing Steel Strand	Post-Tensional GFPR	Concrete Volume per Unit Length
Simple Span	24m (78.7 ft)	2.9m (9.5 ft)	9.9 GN m^2 (21x10^4 K-ft^2)	4.65	47.73 m^3 (62.4 CY)	18.72 m^3 (24.5 CY)	-	66.45 m^3 (86.3 CY)	561 kN (126 Kips)	1166 kg (1.28 tons)	40 kg (88lbs)	2.77 m^3/m (1.10 CY/ft)
	27m (88.6 ft)	3.25m (10.7 ft)	10.3 GN m^2 (35x10^4 K-ft^2)	4.56	58.81 m^3 (76.9 CY)	21.06 m^3 (27.5 CY)	-	79.87 m^3 (104.5 CY)	691 kN (155 Kips)	1312 kg (1.44 tons)	45 kg (99 lbs)	2.96 m^3/m (1.18 CY/ft)
	30m (98.4 ft)	3.65m (12.0 ft)	26.1 GN m^2 (55x10^4 K-ft^2)	4.52	71.81 m^3 (93.9 CY)	23.04 m^3 (30.6 CY)	-	95.21 m^3 (124.5 CY)	844 kN (190 Kips)	1524 kg (1.68 tons)	50 kg (110 lbs)	3.17 m^3/m (1.27 CY/ft)
Two-Span Continuous	24m (78.7 ft)	2.55m (8.4 ft)	5.3 GN m^2 (11x10^4 K-ft^2)	3.52	43.24 m^3 (56.6 CY)	18.72 m^3 (24.5 CY)	-	61.96 m^3 (81.1 CY)	508 kN (114 Kips)	1113 kg (1.22 tons)	138 kg (303 lbs)	2.58 m^3/m (1.03 CY/ft)
	27m (88.6 ft)	2.85m (9.4 ft)	9.1 GN m^2 (19x10^4 K-ft^2)	3.54	52.98 m^3 (69.3 CY)	21.06 m^3 (27.5 CY)	-	74.04 m^3 (96.8 CY)	623 kN (140 Kips)	1252 kg (1.38 tons)	155 kg (341 lbs)	2.74 m^3/m (1.09 CY/ft)
	30m (98.4 ft)	3.20m (10.5 ft)	15.3 GN m^2 (32x10^4 K-ft^2)	3.59	64.55 m^3 (84.4 CY)	23.40 m^3 (30.6 CY)	-	87.95 m^3 (115.0 CY)	758 kN (170 Kips)	1457 kg (1.60 tons)	172f kg (379 lbs)	2.93 m^3/m (1.17 CY/ft)

Table 4-6. Summary of Results of Parametric Structural Study

CONFIGURATION IV

Two Piece, Two Cell Null-Flux Arrangement

	Span	Overall Guideway Depth	Flexible Stiffness EI	Nat. Freq. Hz	Precast Concrete Volume, One Full Guideway, One Span: Girder(s)	Sidewalls	Diaphragms	Total	Max. Piece Lifting Weight	Reinforcing Quantities: Prestressing Steel Strand	Post-Tensional GFPR	Concrete Volume per Unit Length
Simple Span	24m (78.7 ft)	2.0m* (6.6 ft)	11.5 GN m^2* (24×10^4 K-ft^2)	5.44	36.70 m^3 (48 CY)	-	3.80 m^3 (5.0 CY)	40.5 m^3 (53.0 CY)	431 kN (97 Kips)	848 kg (0.93 tons)	41 kg (90 lbs)	1.69 m^3/m (0.67 CY/ft)
	27m (88.6 ft)	2.1m (6.9 ft)	13.0 GN m^2 (27×10^4 K-ft^2)	4.53	42.77 m^3 (55.9 CY)	-	4.28 m^3 (5.6 CY)	47.1 m^3 (61.5 CY)	502 kN (113 Kips)	1133 kg (1.25 tons)	46 kg (101 lbs)	1.74 m^3/m (0.69 CY/ft)
	30m (98.4 ft)	2.6m (8.5 ft)	22.7 GN m^2 (47×10^4 K-ft^2)	4.58	55.77 m^3 (72.9 CY)	-	4.75 m^3 (6.2 CY)	60.52 m^3 (79.2 CY)	655 kN (147 Kips)	1259 kg (1.38 tons)	51 kg (112 lbs)	2.02 m^3/m (0.80 CY/ft)
Two-Span Continuous	24m (78.7 ft)	2.0m* (6.6 ft)	11.5 GN m^2* (24×10^4 K-ft^2)	5.44	36.70 m^3 (48 CY)	-	3.80 m^3 (5.0 CY)	40.5 m^3 (53.0 CY)	431 kN (97 Kips)	636 kg (0.7 tons)	90 kg (198 lbs)	1.69 m^3/m (0.67 CY/ft)
	27m (88.6 ft)	2.0m* (6.6 ft)	11.5 GN m^2* (24×10^4 K-ft^2)	4.30	41.28 m^3 (54 CY)	-	4.28 m^3 (5.6 CY)	45.56 m^3 (59.6 CY)	485 kN (109 Kips)	894 kg (1.0 tons)	119 kg (263 lbs)	1.69 m^3/m (0.67 CY/ft)
	30m (98.4 ft)	2.05m (6.76 ft)	12.3 GN m^2 (27×10^4 K-ft^2)	3.57	46.73 m^3 (61 CY)	-	4.75 m^3 (6.2 CY)	51.48 m^3 (67.3 CY)	549 kN (123 Kips)	1192 kg (1.31 tons)	133 kg (292 lbs)	1.72 m^3/m (0.68 CY/ft)

*Depth of stiffness governed by minimum distance of steel prestress to magnet.

4.2.6 Summary of the Guideway Parametric Study

The results of the parametric study are set out in Tables 4-3 through 4-6 to permit comparison between configurations and between span and continuity conditions. These results are summarized in Figure 4-22.

To meet criteria all configurations must have a flexural natural frequency of at least 4.5 Hz for simple span use; or 3.5 Hz for two-span continuity use. The designs listed in the tables are the minimum concrete quantities in each use necessary to meet stiffness requirements. Since the total cost of the guideway spans is proportional to the volume of concrete in the span, the column at the far right in each table, "Concrete Volume/Unit Length," contains the most useful data in the tables for cost comparison at this point between the various configurations, spans and continuity conditions. Configurations I and III also require additional sidewall mounting hardware.

Among the three configurations applicable to the ground coil levitation scheme, Configuration II, "Two-piece, two-cell with integral sidewall," has the lowest volume of concrete per unit length. This is true for all spans and all continuity conditions. Also, the reinforcing quantities are less for Configuration II compared to the other two ground coil schemes studied.

The fact that the concrete sidewalls are an integral part of the spanning section rather than simply being dead weight to support is the key to the structural efficiency of Configuration II. It is interesting to note that the structure depth, and concrete volume, of the designs for Configuration II could have been somewhat smaller for the 24m simple span and the 24m and 27m two-span continuous condition and still meet stiffness criteria. Note that the natural frequencies listed for those spans in Table 4-4 are slightly higher than the minimum requirements (4.5 hz for simple span and 3.5 hz for two-span continuous). The designs are deeper than structurally required to meet minimum stiffness criteria because our requirement that the bottom prestressing steel reinforcement can be no closer to the vehicle magnets than 0.8 m, and other geometric conditions, results in a minimum overall depth of 2.1 m. A more refined evaluation of the steel to magnet proximity problem could lead to further reduction of structural depth in the configuration.

A two-piece, one-cell configuration with integral sidewalls was not a candidate configuration because of the drainage problems that would come with this layout. However, comparing the results of Configuration III with Configuration I it appears that a one cell configuration with integral sidewalls would require more concrete than Configuration II in any case.

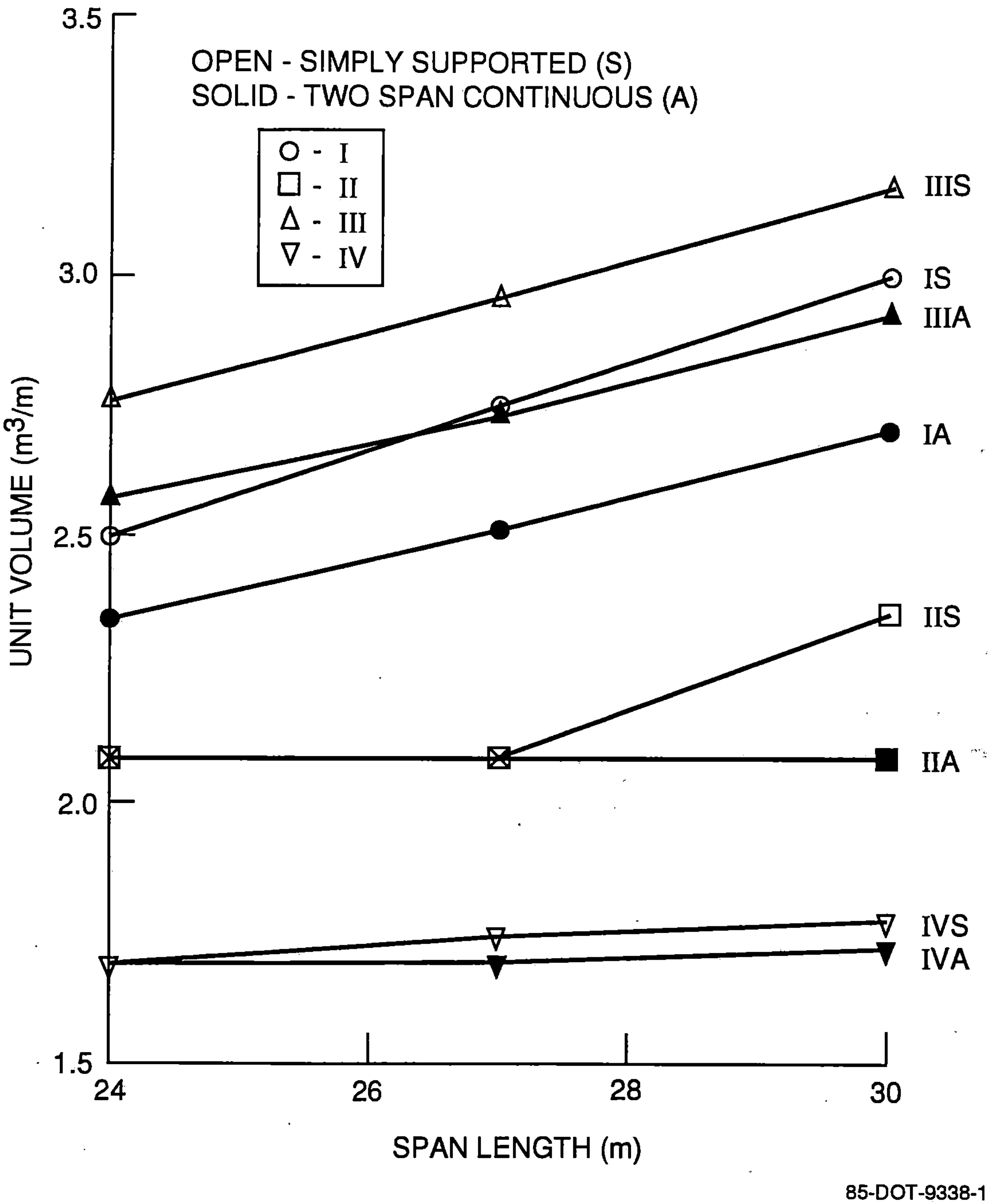


Figure 4-22. Summary of Results of Parametric Structural Study

The configuration appropriate to the null-flux levitation scheme uses less concrete volume per unit length than any of the other candidate configurations. However, the null-flux scheme requires a different vehicle which had not been fully developed for this study. Also, the fully open bottom of this guideway configuration, except for diaphragms, poses unusual safety issues, as well as the potential for complex, higher order dynamic responses (mostly in the lateral direction) that might be worth investigating but are beyond the scope of this study.

In subsection 4.5 we will examine the economics of span and span continuity for Configuration II which appears to be the most economically advantageous while retaining ground coil operation and a partial floor structure: the Two-Piece Configuration with Integral Sidewall.

4.2.7 Pylon/Foundation Design

The elevated guideway is supported on pylons, one pylon supporting the ends of two adjacent guideway spans. For purposes of this study, a height from ground level to top of pylon (seat elevation of guideway) of 10m (32.8 ft) was selected. This height is estimated to be an average height for a long guideway system.

In this study we have examined two span continuity conditions: simple span, and two spans continuous over the center support. Neither of these conditions produces structural loads on the pylons due to bulk temperature change if the seats of the guideway spans are detailed to allow longitudinal movement at one end of the span. The design structural forces of guideway gravity loads and lateral loads perpendicular to guideway spans (transverse loads) are the same magnitude for either of these continuity conditions. However, there is a difference with regard to lateral loads parallel to the guideway spans (longitudinal loads). In the simple span arrangement, longitudinal load due to seismic design load is shared equally by all pylons while in the two-span condition seismic design load is resisted only by the pylons at the continuous support, i.e., alternate pylons. The pylon design was made for three different span lengths: 24, 27 and 30m, to evaluate the effect on pylon design requirements.

For the configurations studied, and the lateral load criteria selected, the design wind load per span (transverse) and the design seismic load per span (transverse or longitudinal) were roughly of the same magnitudes, but the design seismic load was greater in all cases.

The structural shape of the pylons is strongly determined by the cantilever moments generated by the lateral loads resisted at the tops of the pylons. An economical structural shape would have a shaft which becomes wider toward the base as the cantilever moment increases linearly from the top of the pylon to the bottom. The guideway is designed for moderate seismic regions (Zone 2), and since seismic design loads apply in any direction, the base of the pylons for simple span conditions should be square. As mentioned previously, the pylons of the two-span continuous condition see transverse lateral loads at each pylon but in the longitudinal direction the pylons at the continuous supports see lateral loads for two spans and the alternate pylons see no lateral load. In an economic sense structural concrete material will be taken from half of the pylons and added to the other half, although some net increase in material will likely occur. The pylon shaft shape is also affected by this condition with the continuous support pylon being wider in the longitudinal direction and the alternate pylons being wider in the transverse direction.

The general pylon/footing is shown in Figure 4-23. Pylon and footing dimensions and structural material quantities are set out in Table 4-7 and summarized in Figure 4-24 for all options of span and continuity studied.

4.3 Fabrication/Erection Methods

4.3.1 The Logic for Precast Concrete

In order to meet all design requirements economically, the concrete guideway configurations are fairly intricate insofar as formwork is concerned. This fact, plus the known economy inherent in using prestressing strands as reinforcing in long span construction essentially dictates that the guideway spanning elements be precast. Also, steel precasting formwork can be constructed to fine tolerances and stay dimensionally stable through many reuses.

While the formwork for the guideway spanning elements may be intricate and expensive to construct, if constructed of steel they may be re-used many times with only minor maintenance, thereby reducing overall costs.

An application of the guideway system will of course require a large number of mainbeams. A two-way elevated guideway system of even 100 km (62 mi) would have approximately 7,400 spans, assuming spans of 27m. If each guideway is constructed with a two-piece

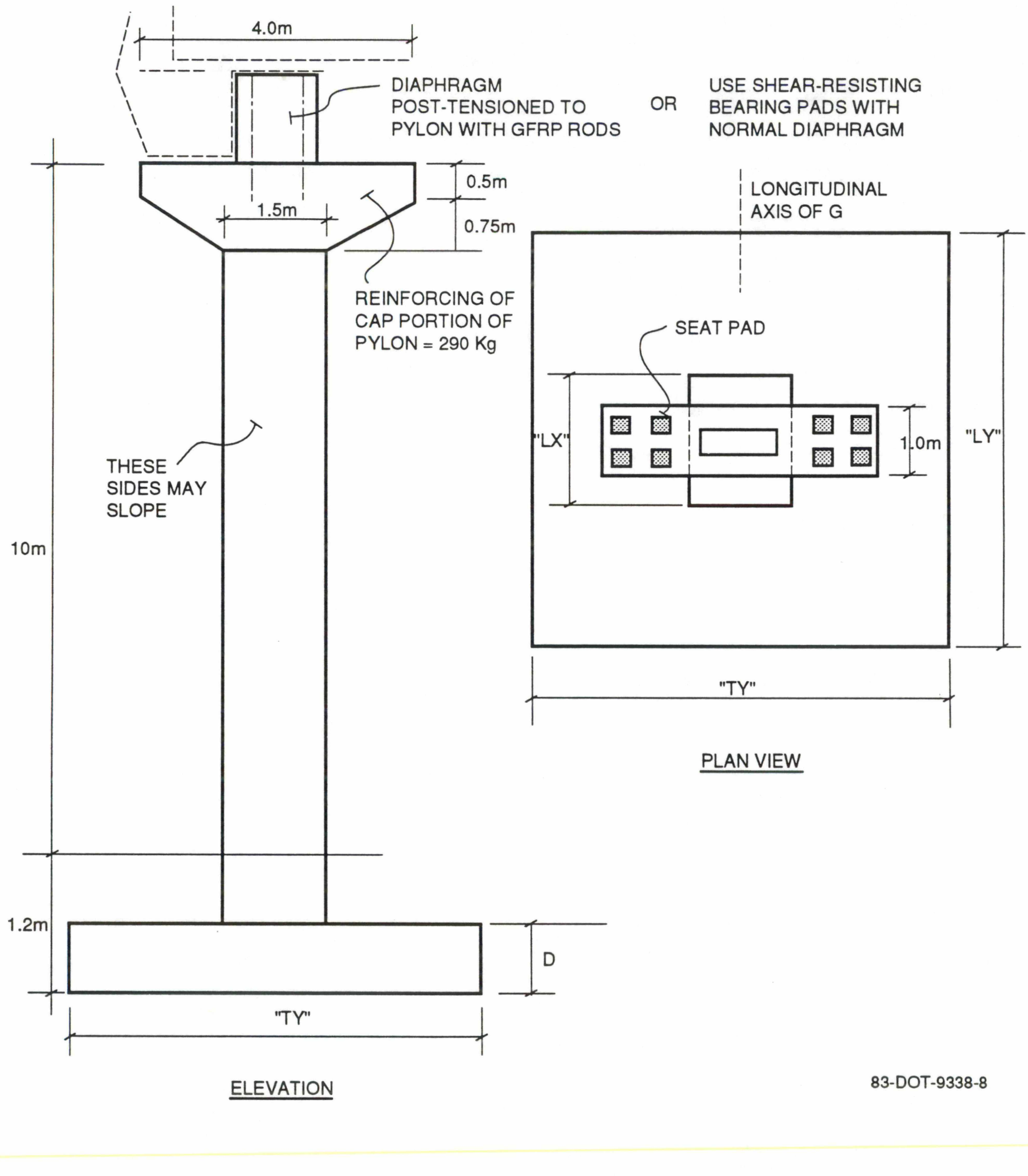


Figure 4-23. Typical Pylon/Footing Configuration

Table 4-7. Pylon and Footing Designs

		Ultimate Axial Forces		Ult. Horizontal Forces Wind & Seismic		Dimensions: Pylon	Dimensions: Footing			Material Quantities Pylon and Footing	
	Span	Dead Load Only	Total	Trans.	Long.	"LX"	"TY"	"LY"	"D"	Concrete	Reinforcing Steel
Simple Span	24m (78.7 ft)	1892 kN (425kips)	2421 kN (544k)	253 kN (57k)	253 kN (57k)	1.5m (4.9 ft)	5.5m (18 ft)	5.5m	0.6m (2 ft)	41.8m^3 (54.664)	4520 kg (5.0 ton)
Simple Span	27m (88.6 ft)	2127 kN (478k)	2744 kN (617k)	284 kN (64k)	284 kN (64k)	1.5m	6.0m (13.5 ft)	6.0m	0.6m	45.2 m^3 (59.064)	4960 kg (5.4 ton)
Simple Span	30m (38.4 ft)	2642 kN (894k)	3332 kN (749k)	353 kN (79k)	353 kN (79k)	1.5m	6.2m (20.5 ft)	6.2m	0.6	47.2m^3 (61.7 CY)	5287 kg (5.8 ton)
Two-Span Continuous	24m (78.7 ft)	1892 kN (425k)	2429 kN (545k)	253 kN	0 / 506 kN	1.0m / 2.0m	5.5m / 5.5m	3.0m / 7.3m	0.6 / 0.76	29.7 m^3 / 57.8 m^3	3850m / 6010 kg
Two-Span Continuous	27m (88.6 ft)	2127 kN (478k)	2761 kN (621k)	284 kN	0 / 568 kN	1.0m / 2.0m	6.0m / 5.5m	3.0m / 7.6m	0.6 / 0.76	30.6 m^3 / 59.0 m^3	320 Kg / 6480 kg
Two-Span Continuous	30m (98.4 ft)	2364 kN (582k)	3078 kN (692k)	353 kN	0 / 632 kN	1.0m / 2.0m	6.2m / 5.5m	3.0m / 7.8m	0.6 / 0.76	1.0 m3 / 60.3 m3	4048 Kg / 6900 kg

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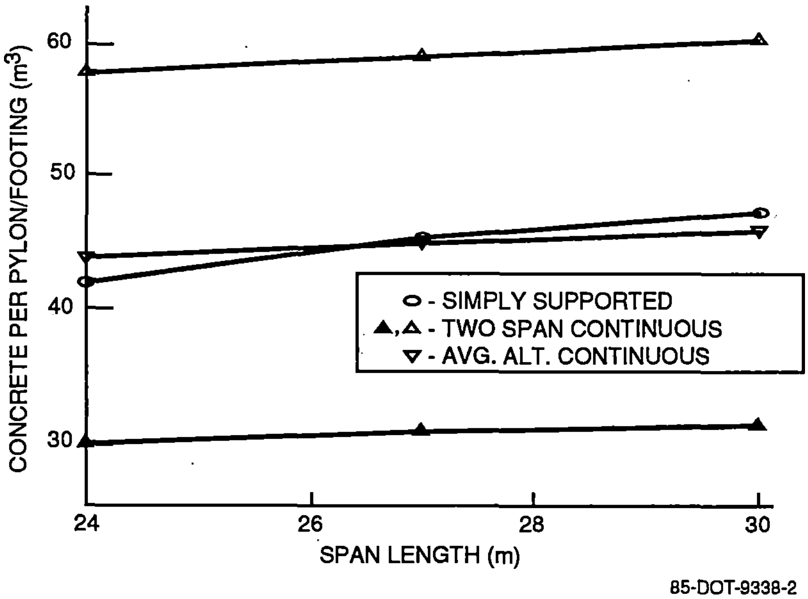

Figure 4-24. Pylon and Footing Designs

configuration per span, and with a guideway in each direction, 14,800 precast structural elements would have to be fabricated. This high volume demand for repetitive fabrications favors plant production of the elements and in a competitive environment will result in the lowest possible cost.

It should be possible to use exactly the same spanning elements for the majority of the guideway right-of-way, keeping the fabrications repetitive. Curves on the right-of-way normally have a very large radius (4,000m) because of the high speeds involved. At this radius the angle between square ended straight sections at a support is only about 0.4 deg, making a gap difference from one side of the guideway to the other of about 30 mm. This difference will be accommodated in the joint design so that the same fabrications can be used on tangents or curves. Potentially, straight guideways can be used at curves with a radius between 4,000 and 2,000m with the ends of the sections cast at a slight angle. Below 1,000m, more expensive curved sections would be required which may be precast or cast-in-place. The pylons will also be standard configurations throughout the system, and may also be economically precast. The foundations, footings or pile caps require very little formwork and will be cast-in-place.

4.3.2 Fabrication and Erection Considerations

Careful thought must be given to the design of the steel formwork. The formwork will be constructed to cast a full span of guideway element in one piece. The guideway configuration will have cells, or voids, running the full length of the element. Small voids in the sidewall section will be formed of plastic to be cast in and not retrieved. However, the inside of the larger cells must be formed surfaces, adding to the complexity of the formwork construction. The formwork will likely be hinged and fitted with hydraulic jacks to open and close the forms. The steel form will have a structural steel framework around it to provide rigid support, and this framework can also be designed to provide anchorage to react the steel strand prestressing forces and the GFRP rod post-tensioning forces.

In addition to the formwork, fabrication plan costs include the labor to place the materials and to operate and maintain the equipment, an environment for proper concrete curing (steam for high volume production), equipment for handling the raw materials and the fabricated pieces, and the costs of owning or leasing the land area required. While the costs of the raw materials (concrete, steel strand, GFRP rods) delivered to the plant can be estimated with accuracy, the plant costs for a new product are more difficult to predict. In Section 5 we attempt to develop a reasonable estimate of the fabrication costs. It is clear that competition for the work is necessary to keep costs in line. The work must be such that any experienced precaster could handle it, keeping competition as wide as possible. To this end it may be wise to bid the design and construction of the special item - the steel formwork frames - separately and provide them to the successful precast bidder for his use.

Transportation of the fabricated precast elements from the fabrication plant to the site is required. The precast elements will be of a length and weight to require special trucking rigs and special permits to travel the public roads. Nevertheless, transportation over public roads is possible since a design goal is to keep beam element weights in the range of 120,000 lb. Transportation costs are a function of plant location relative to the project site; therefore, fabrication and delivery could be bid as one item. The project site will continue to move during the course of the project, and multiple plant locations may also move if economics dictate. It is even conceivable that moving the steel forms and casting along the right-of-way could be an economical approach.

Once at the site, the fabricated precast elements must be lifted onto the previously constructed pylons. The erection of the elements will require two cranes one near each end, to lift and set each piece in accordance with standard construction practice. No falsework or other temporary supports are required, minimizing time and cost.

Alternate beam ends can be spliced to form a continuous joint, significantly adding flexural rigidity and reducing thermal deflections. This approach is routinely used in long-span construction, but in this case will incorporate GFRP post-tensioning tendons due to proximity to the magnets. The beam ends will be designed for an epoxy grout connection. All beam ends will be designed to mate with the adjustable beam seats during the erection procedure. These design details are described in a later section of the report.

4.3.3 Alignment

The precast elements will be constructed to tight tolerances compared to cast-in-place concrete work. With accurate survey work the alignment of the concrete surfaces to which the coils will be later attached can be kept to within 12 mm (1/2 in.). The computed net camber at mid-span of the selected configuration on a 27m span is +5 mm (+3/16 in.) which is the net of 13 mm down due to all dead loads and 18 mm up due to bottom prestressing force after prestressing losses are considered. This is deliberately designed to offset anticipated dynamic (liveload) deflections of 10 mm. Thus, the camber at mid-span will cycle about zero (flat) from a maximum of +5 mm (unloaded) to a minimum of -5 mm (under dynamic loading). However, the maximum "roughness" variation in elevation of the concrete surface should also be expected to be 12 mm. The ground coil and side coil attachments must provide for adjustment for elevation and alignment to the extent their location tolerances are smaller than 12 mm in approximately a 6m length. However, these operations which align the coils with respect to the guideway beam reference points are carried out at the point of beam manufacture, and followed with the pre-wiring operation.

5. COST ANALYSIS

In this section, we will address the estimation and calculation of the guideway costs. This will include both an estimate of construction costs, followed by a general assessment of the recurring costs for projected maintenance activities.

For the four candidate guideway beam designs, a construction cost picture will be built up based on a complete analysis of the materials and the manufacturing, erection and other construction procedures. The pylon and footing structures will also be cast, and the results combined for the total guideway structural costs. Since this is primarily a study of innovative structural configurations for the guideway system, the additional electrical equipment costs are not included here. (These include active and passive guideway coils and coil mounts, power and distribution wiring, signal and communications.) Also, any miscellaneous fixtures such as ladders, walkways and similar items are better estimated through operations and safety analysis and again are not the focus of this study, so they should be added as well.

The anticipated maintenance, repair and other annualized costs associated with such a system, which has only limited test experience to date, cannot be estimated with any precision yet. There is a general acceptance that a well-engineered system using materials and construction techniques that are reasonably related to demonstrated experience will have relatively low maintenance costs since there is no guideway contact under normal operating conditions enroute. Even low-speed operations only involve wheeled contact on rubber tires. This is unlike high-speed rail systems, which undergo heavy loading and wear of track and trackbed components, and thus require large maintenance efforts to preserve the quality and safety of the route. In this study, therefore, we have attempted to itemize the nature of the anticipated maglev guideway maintenance activities, and compare the four candidate configurations on a relative basis via an assessment matrix.

5.1 Guideway Construction Costs

In this subsection we establish the basis for the cost estimates for the elevated guideway construction. All costs will be reduced to a unit cost per meter length of a single guideway (one-way transit). Costs are 1991 U.S. dollars. Many of the unit costs which make up our estimate are taken from the annual publication, "Heavy Construction Cost Data," by the R.S. Means Company, Inc. The costs used are the "national average" costs in the United States, 1991.

5.1.1 Precast Material Costs

- Ready-mix high strength concrete delivered to the precasting yard - The concrete used is higher than normal strength containing 6 percent* silica fume material and 5 percent* polyproprolene fibers. From R.S. Means, and industry sources, we estimate the cost of the concrete to be $\$150/m^3$ (\$115/cy).

- Prestressing steel strand delivered to the precasting yard - The strand used is the normal strand used in the precast industry. We estimate the cost of this material to be \$2.75/kg (\$2500/ton).

- GFRP rods for post-tensioning delivered to the precasting yard or to the site - This material is just becoming commercial available. Recent articles in the literature (1) cite the cost of this material at over \$4.40/kg (\$2.00/lb). Because the market price of this material is not well-established we have made an estimate of the cost of this material, with anchorages, which we believe is conservative - \$13.20/kg (\$6.00/lb).

Tables 5-1 through 5-4 and Figure 5-1 summarize the material costs of all four configurations of the guideway beam designs, stated as total material costs per meter length of guideway.

5.1.2 Precast Concrete Fabrication Costs

- Formwork - Special steel formwork is required. Formwork surface area will be approximately $9\ m^2 \times 27m = 243\ m^2$ (8,600 SF). The formwork surface could be of 3 mm (1/8 in.) thick plate, reinforced with plate stiffeners. The estimated quantity of steel reinforced plate in one form is 24,240 kg, (27 tons). Additionally a steel framework is required to stiffen the form and provide a reaction frame for the prestressing and post-tensioning done at the plant. The framework could be of steel tubes which we estimate would add 16,400 kg (18 tons) of material. There are no exact references for the cost of this work, but we believe a cost estimate of \$6.60/kg (\$6,000/ton) is reasonably conservative. The cost of one fabricated steel form is then 40,640 kg x \$6.60/kg ≈

*Based on cement content only.

Table 5-1. Structural Materials Costs - Precast Guideway Elements Configuration I

Structural Materials Costs - Precast Guideway Elements

CONFIGURATION I

		Material Quantities and Costs - One Way Guideway										
		Concrete			Prestressing Steel			Post-Tensioning GFRP				
	Span (m)	Quantity (m^3/m)	Unit Cost ($\$/m^3$)	Cost/ Length (\$/m)	Quantity (kg/m)	Unit Cost (\$/kg)	Cost/ Length (\$/m)	Quantity (kg/m)	Unit Cost (\$/kg)	Cost/ Length (\$/m)	Sidewall Connection Hardware (\$/m)	Total Material Cost per Unit Length (\$/m)
Simple Spans	24	2.51	150	377	46.4	2.75	128	1.7	13.20	22	10	537
	27	2.76	150	414	46.4	2.75	128	1.7	13.20	22	10	574
	30	3.00	150	450	46.4	2.75	128	1.7	13.20	22	10	610
Two-Span Continuous	24	2.35	150	353	44.2	2.75	122	5.0	13.20	66	10	550
	27	2.52	150	378	44.2	2.75	122	5.0	13.20	66	10	576
	30	2.71	150	407	44.2	2.75	122	5.0	13.20	66	10	604

Table 5-2. Structural Materials Costs - Precast Guideway Elements
Configuration II

Structural Materials Costs - Precast Guideway Elements

CONFIGURATION II

		Material Quantities and Costs - One Way Guideway									
		Concrete			Prestressing Steel			Post-Tensioning GFRP			
	Span (m)	Quantity (m^3/m)	Unit Cost (\$/m^3)	Cost/ Length (\$/m)	Quantity (kg/m)	Unit Cost (\$/kg)	Cost/ Length (\$/m)	Quantity (kg/m)	Unit Cost (\$/kg)	Cost/ Length (\$/m)	Total Material Cost per Unit Length (\$/m)
Simple Spans	24	2.08	150	312	35.3	2.75	97	2.5	13.20	33	442
	27	2.08	150	312	44.2	2.75	122	2.5	13.20	33	467
	30	2.36	150	354	44.2	2.75	122	2.5	13.20	33	509
Two-Span Continuous	24	2.08	150	312	26.5	2.75	73	4.6	13.20	61	446
	27	2.08	150	312	33.1	2.75	91	5.3	13.20	70	473
	30	2.08	150	312	39.7	2.75	109	5.3	13.20	70	491

Table 5-3. Structural Materials Costs - Precast Guideway Elements Configuration III

Structural Materials Costs - Precast Guideway Elements

CONFIGURATION III

		Material Quantities and Costs - One Way Guideway										
		Concrete			Prestressing Steel			Post-Tensioning GFRP				
	Span (m)	Quantity m^3/m	Unit Cost $\$/m^3$	Cost/ Length ($/m)	Quantity (kg/m)	Unit Cost ($/kg)	Cost/ Length ($/m)	Quantity (kg/m)	Unit Cost ($/kg)	Cost/ Length ($/m)	Sidewall Connection Hardware ($/m)	Total Material Cost per Unit Length ($/m)
Simple Spans	24	2.77	150	416	48.6	2.75	134	1.9	13.20	25	10	584
	27	2.96	150	444	48.6	2.75	134	1.9	13.20	25	10	613
	30	3.17	150	476	50.8	2.75	140	1.9	13.20	25	10	650
Two-Span Continuous	24	2.58	150	387	46.4	2.75	128	6.0	13.20	79	10	604
	27	2.74	150	411	46.4	2.75	128	6.0	13.20	79	10	628
	30	2.93	150	440	48.6	2.75	134	6.0	13.20	79	10	662

Table 5-4. Structural Materials Costs - Precast Guideway Elements
Configuriton IV

Structural Materials Costs - Precast Guideway Elements

CONFIGURATION IV

		Material Quantities and Costs - One Way Guideway										
		Concrete			Prestressing Steel			Post-Tensioning GFRP				
	Span (m)	Quantity (m^3/m)	Unit Cost (\$/m^3)	Cost/ Length (\$/m)	Quantity (kg/m)	Unit Cost (\$/kg)	Cost/ Length (\$/m)	Quantity (kg/m)	Unit Cost (\$/kg)	Cost/ Length (\$/m)	Siderail Connection Hardware (\$/m)	Total Material Cost per Unit Length (\$/m)
Simple Spans	24M	1.69	150	254	35.3	2.75	97	1.7	13.20	22	0	373
	27M	1.74	150	261	42.0	2.75	116	1.7	13.20	22	0	399
	30M	2.02	150	303	42.0	2.75	116	1.7	13.20	22	0	441
Two-Span Continuous	24M	1.69	150	254	26.5	2.75	73	3.9	13.20	51	0	378
	27M	1.69	150	254	33.1	2.75	91	4.4	13.20	58	0	403
	30M	1.72	150	258	39.7	2.75	109	4.4	13.20	58	0	425

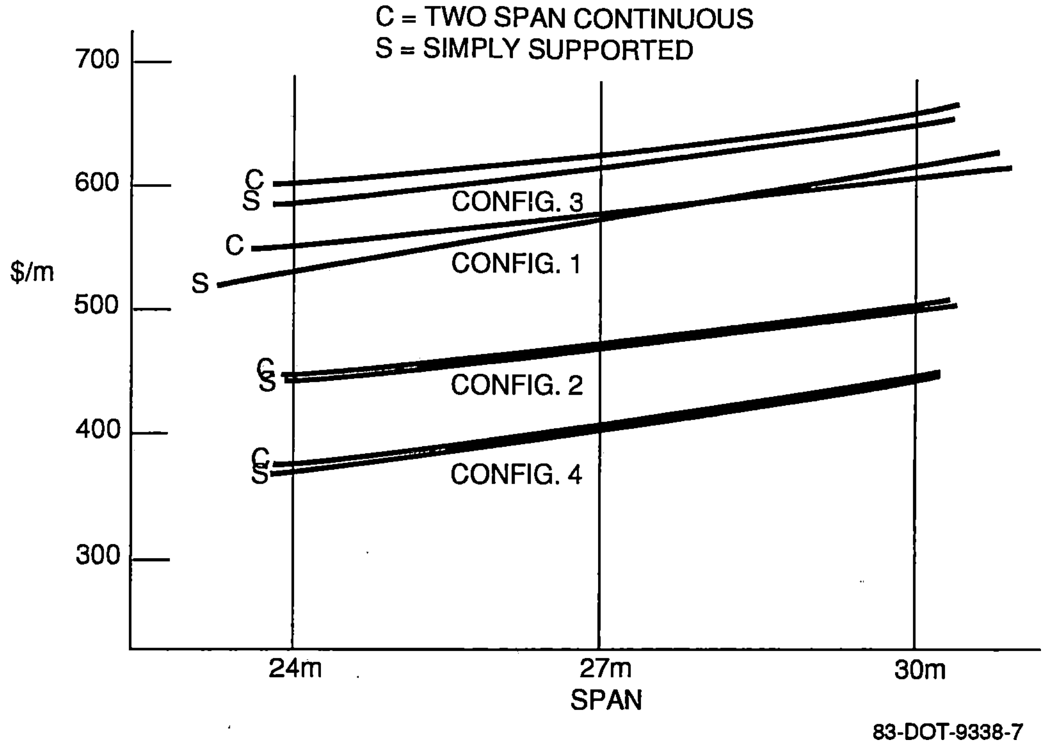

Figure 5-1. Materials Cost for Guideway Main Beams (One Way). Data from Tables 5-1 to 5-4

$270,000. The unit will probably require some jacks and mechanical apparatus for opening and closing the forms and perhaps even wheels for mobility. The estimated total cost of one form is $300,000. The form will be used to produce precast elements that are 24 to 30m long.

If the form is used to make one element, the cost of the formwork is $300,000/27m = $11,111/m ($3,387/L.F.), but the forms can be reused indefinitely with little additional cost. After the form has been used to make 500 elements (approximately two years of constant use), the average cost of the formwork is $22/m ($6.77/L.F.). We will take this number as the cost for a system of at least 30 km (18.6 mi) length.

- Plant Labor and Equipment - The normal precast plant crew, cited in R.S. Means' "Heavy Construction Cost Data" includes a foreman, six workers, a 150 ton track crane, operator and oiler at a cost for the crew of approximately $5,000/day. If we assume the crew for a more specialized operation costs $10,000/day and operates four forms turning out three precast elements per day, the labor and equipment cost per element is \$10,000/3 = \$3,333 each or \$3,333/27m = \$123/m (\$38/L.F.).

- Plant Overhead and Profit - We assumed all plant overhead costs including land ownership or lease costs to be 50 percent of the labor and equipment costs, and profit to be 25 percent of the plant operations cost. Our estimate for these costs is \$123/m x 0.875 = \$108/m (\$33/L.F.).

5.1.3 Transportation Costs

The fabricated precast elements must be delivered from plant to site. Based on data published by R.S. Means Company and industry sources, because the rigs must be special and the haul must be escorted, we estimate a 81 km (50 mi) haul for one precast element to cost \$2,000 or \$2,000/27 m = \$74/m (\$23/L.F.). For these moderate piece weights the transportation costs are similar for each of the four configurations. The cost presented is an approximate average.

5.1.4 Layout and Seat Preparation

After the pylons are in place a surveying crew must set the alignment and elevations, and the seating pads must be located and installed so that the precast spans will be properly set. Based on means data for this type of construction, we estimate that this work and seat materials will cost \$2,500 per pylon or \$2,500/27m = \$93/m (\$28/L.F.).

5.1.5 Erection Costs

The precast pieces require two 250 ton cranes to safely handle and set them. We estimate the cost of cranes and five-man erection crew to be \$12,000/day. We further estimate that at least two one-way spans (four precast elements including diaphragms) can be set in one day for a unit cost of \$12,000/4 x (27m) = \$111/m (\$34/L.F.). If the two-span continuous scheme is installed, post-tensioning of GFRP tendons will be a part of the installation process. We estimate this would add 20 percent to erection costs (materials are included in the fabrication costs).

5.1.6 Total In-Place Unit Cost of Guideway Beam

Using the unit prices developed above, we can illustrate how the total in-place cost of a one-way guideway beam is calculated using the case of Configuration II for a 27m span. Using the unit costs of this section and the structural quantity information, the configurations can be cost-estimated, as shown in Table 5-5:

Table 5-5. Total In-Place Cost of Guideway Beam (Structure Only)

	In-Place Cost of Guideway Beams Configuration II, Span = 27m	
	Simple Span	Two-Span Continuous
For one-way: Materials Fabrication x2* Haul x 2* Align, set seats etc. Erection x2*	 $467/m 506/m 148/m 93/m 222/m	 $473/m 506/m 148/m 93/m 266/m
Total:	$1436/m ($438/L.F.) $690/m^3 ($528/CY)	$1486/m ($453/L.F.) $714/m^3 ($546/CY)
*Two sides per guideway beam		

While the two-span continuous design shows a very slightly higher cost compared to the simply supported configuration, the difference in cost between the two approaches is only on the order of 3 percent. This small difference is within the overall accuracy of the cost estimates. We can conclude that the advantages associated with the two-span continuous configuration - increased stiffness, smaller deflections under train load and temperature gradient, possible ride improvement - can be obtained at very little to no extra cost, and therefore this continuity configuration will be adopted.

5.1.7 Pylon/Foundation Costs

Costs for this work, cast-in-place, are fairly well-established. We have observed the following unit costs:

Pylon, concrete (5,000 psi)	=	$106/m^3	($80/cy)
Forms	=	$86/m^2	($8/SF)
Reinforcing steel	=	$2.50/kg	($1.15/lb)
Footing, concrete (3,000)	=	$90/m^3	($69/cy)
Excavation	=	$18/m^3	($14/cy)
Reinforcing steel	=	$1.90/kg	($0.86/lb)

Estimated construction costs for pylons/foundations for all spans of the Configuration II are given in Table 5-6 and summarized in Figure 5-2*.

5.1.8 Total Guideway Construction Costs

Using the costs described in the previous sections and the material quantities developed for the guideway designs and pylon/foundation designs, construction cost per meter of a complete two-way guideway have been computed for all configurations studied and are presented in Table 5-7. We have assumed that fabrication, hauling, and erection are directly proportional to concrete volume. These data are also plotted in Figure 5-3.

Some clarifications need to be made concerning these results before making some general conclusions:

1. In some cases, the minimum beam depth was governed by the minimum distance criterion that we used to separate the steel prestressing from the vehicle magnet (0.8m). In these instances, this did not permit the reduction in depth and section size that would normally be associated with smaller spans. This was seen in the Configurations II and IV (especially in the more efficient alternating continuous span arrangement), in which the sidewall and main section was combined or coincident. These afforded the potential for smaller depths than in the other configurations. The result is that overall guideway costs per meter for these configurations showed a cost trend that decreased slightly with span, because these cost variations were then driven by the decreasing pylon costs per meter. An estimate was made of the effect this restriction had on guideway costs/meter, and is shown in Figure 5-3.

*Average data from R.S. Means

Table 5-6. Pylon Costs (One-Way Guideway)

	Material Quantities Pylon and Footing: Span	Material Quantities Pylon and Footing: Concrete	Reinforcing Steel	Cost per Pylon/Footing each	Pylon Cost per Meter of Guideway
Simple Span	24m (78.7 ft)	41.8 m^3 (54.664)	4,520 kg (5.0 ton)	$20,840	$868
Simple Span	27m (88.6 ft)	45.2 m^3 (59.068)	4,960 kg (5.4 ton)	$22,420	$830
Simple Span	30m (98.4 ft)	47.2 m^3 (61.764)	5,287 kg (5.8 ton)	$23,260	$775
Two-Span Continuous	24m (78.7 ft)	29.7 m^3 / 57.8m^3	3850 kg / 6010 kg	$22,350*	$931
Two-Span Continuous	27m (88.6 ft)	30.6 m^3 / 59.0 m^3	3920 kg / 6480 kg	$22,500*	$833
Two-Span Continuous	30m (98.4m)	39.0 m^3 / 60.3 m^3	4048 kg / 6,900 kg	$23,820*	$794

*Averaged for both types.

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technologies that have not yet entered the mainstream of construction practices, a contingency of several percent or more would normally be added. Also, miscellaneous items, such as provision (in some areas) for concrete guard rails at the pylon base level, any ladders, walkways, unusual degree of traffic control and similar items not directly associated with the guideway structure itself are not included.

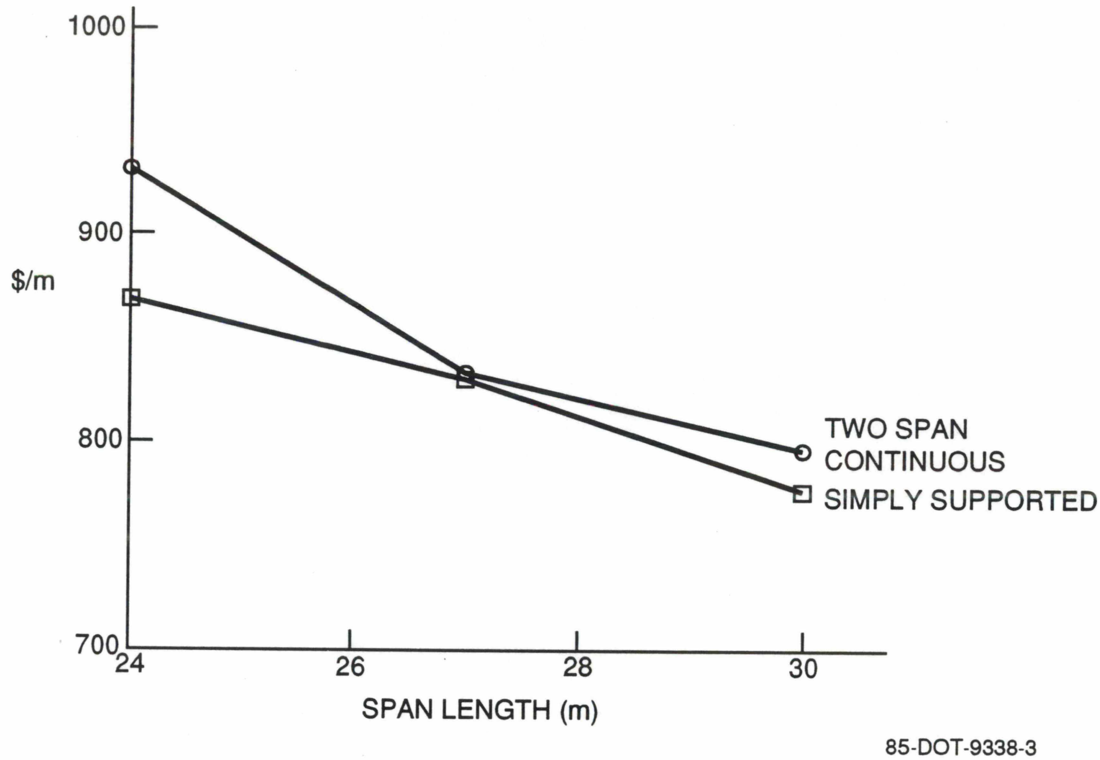

Figure 5-2. Pylon Cost per Meter of Guideway

As a rough guide to these nonstructural costs, we can provide the following estimate (5).

maglev coils, wiring and installation:	\$2180 to \$2800/m (\$3.5 to 4.5 Mil/mile)
Miscellaneous items above:	\$250 to \$500/m (0.4 to 0.8 Mil/mile)
Construction contingency:	\$250 to \$375/m (0.4 to 0.6 Mil/mile)
Total nonstructural cost:	\$2670 to \$3670/m \$4.3 to 5.9 Mil/mile

Table 5-7. Construction Costs for Two-Way Guideway (Structural Only, No Contingency)

					Selected Configuration								
		Configuration I			Configuration II			Configuration III			Configuration IV		
		Guideway	Plyon/ Foundation	Total	Guideway	Plyon/ Foundation	Total	Guideway	Pylon/ Foundation	Total	Guideway	Plyon/ Foundation	Total
Simple Spans	24m	3413	1737	5149	2822	1737	4559	3749	1737	5486	2321	1737	4058
	27m	3720	1661	5381	2872	1661	4533	3984	1661	5645	2419	1661	4080
	30m	4015	1551	5566	3217	1551	4768	4254	1551	5805	2764	1551	4315
Two-Span Continuous	24m	3389	1863	5252	2918	1863	4781	3719	1863	5582	2402	1863	4265
	27m	3607	1667	5274	2972	1667	4639	3925	1667	5592	2452	1667	4119
	($/mile for 27m)			$8.5 mil per mile			$7.5 mil per mile			$9.0 mil per mile			$6.6 mil per mile
	30m	3848	1588	5436	3008	1588	4596	4178	1588	5766	2525	1588	4113

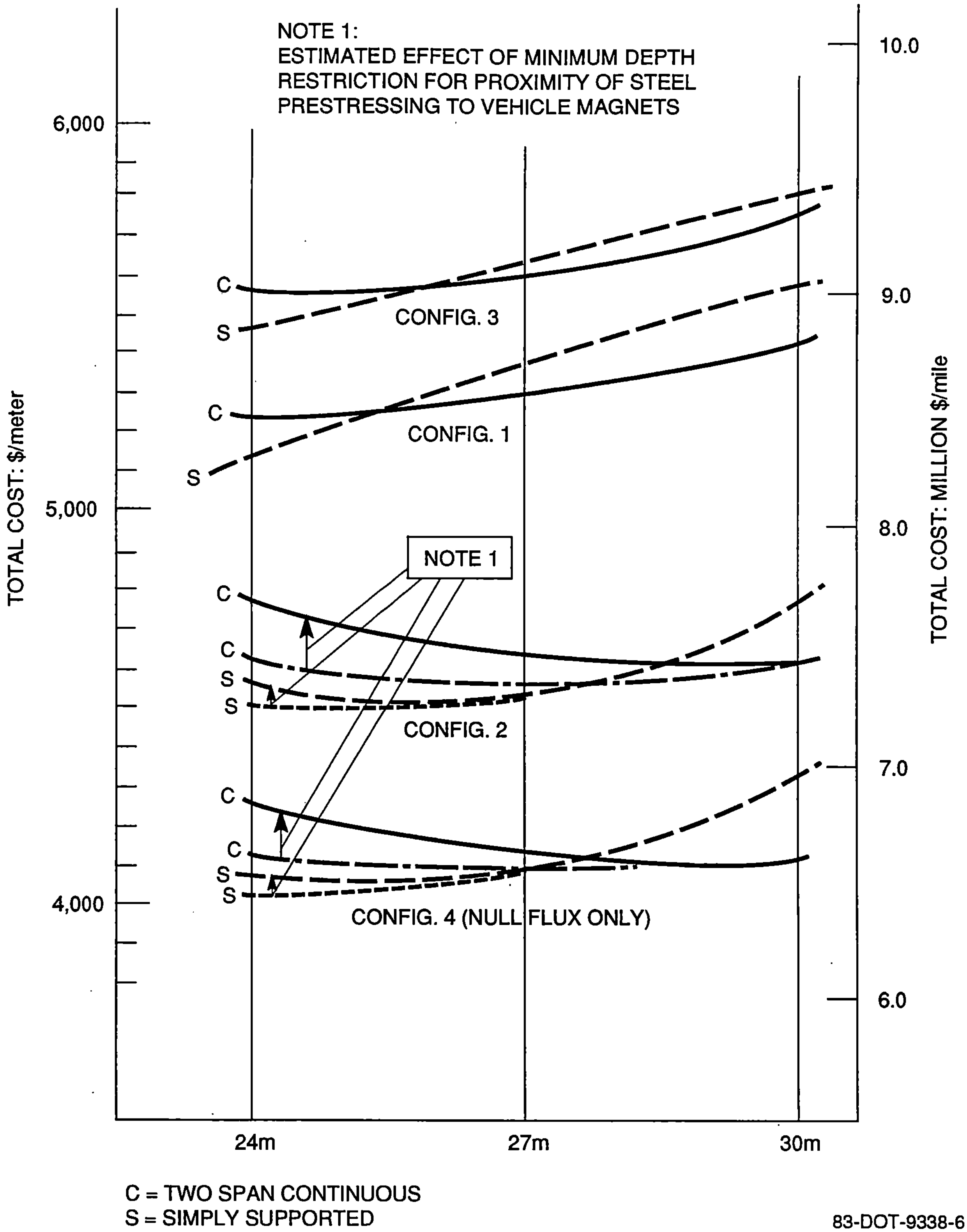

Figure 5-3. Guideway Construction Cost per Unit Length of Two-Way Guideway Structure

5.1.9 Conclusions

Several conclusions can be drawn from the cost results shown above, and will be discussed below. These cost assessments will also be a major factor in the overall ranking procedure used to select the best configuration in the next section (following the subsection on maintenance).

1. Configuration II, the double-cell guideway with integral sidewalls, shows the lowest cost for all configurations compatible with the ground-coil levitation scheme for EDS maglev. This configuration could also accommodate a null-flux scheme with minor modification, retaining the horizontal surface for low-speed running and emergency braking, as well as for use by maintenance crews, etc.

2. The null-flux guideway, Configuration IV showed even lower cost due to its very compact configuration with no "bottom" structure. However, this is not compatible with the ground-coil levitation scheme which has formed the bulk of the EDS maglev test experience to date. Also, this configuration would require a special vehicle incorporating retractable, load-bearing landing gear upon the sides of the car body or bogie structure as well as a lower set for low speed support in stations, etc. These difficulties might certainly be overcome, but it shows the overall effect of such an unusual guideway concept.

3. The higher-cost Configurations I and III show a potential cost minimum at spans below 24m. However, it is desired that the beam spans not agree in length with bogie spacing due to undesirable increases in dynamic loads and deflection, thereby affecting ride quality. Vehicle studies at Foster-Miller and others generally show efficient vehicle lengths in the vicinity of 22 to 24m, and so longer spans might be favored for long-term system adaptability even if a small cost penalty were incurred.

4. The simply-supported and two span continuous beam configurations are very close in cost, with the simply-supported configuration very slightly cheaper in some cases. However, as was pointed out earlier, two span continuous layout has less sensitivity of dynamic load factor to train speed, much better control of thermal gradient deflections and other related advantages that make it the preferred choice. The cost differential is certainly within the accuracy of the overall analysis, so it can be said that continuity can be incorporated with no significant impact on cost.

5. Although the direct cost calculations show no cost penalties for the longer spans in the integral-sidewall Configurations II and IV, practical experience dictates that the increased difficulties of manufacturing, transporting and erecting the longer, heavier pieces would have to be considered carefully in an actual project. This is even more true in the densely populated metro-corridor environment. The result is that preferred span lengths could remain in the 27 to 30m range when these issues are considered.

5.2 Maintenance Issues

maglev systems by design will have inherently low maintenance costs compared to conventional railroad systems. However, some meaningful maintenance issues do exist that should be considered in the guideway design process. This section discusses the factors affecting recurring costs, and provides a relative assessment of the various contributors. (Non-recurring costs, which in some flexible guideways could include up to full guideway replacement due to fatigue damage prior to the design goal of a 50 year life.) The four candidate guideway configurations developed under this program were described in Sections 3 and 4. All use a similar high-stiffness U-section design. The variations on this design could influence recurring (maintenance) costs, and a relative assessment of the likely contributors to these maintenance costs will be made for all the guideway configurations.

Inspection

Due to the high speeds and precision alignment requirements of a maglev system, periodic inspection is required to monitor the condition of the guideway. Such inspections are likely to involve a dedicated inspection vehicle passing along the guideway. The costs of such a procedure will likely be similar for the four Foster-Miller configurations. However, for the more flexible, and more fatigue susceptible type guideways, more frequent detailed structural inspection will be required.

Alignment

The close tolerance alignment of the guideway coils will require periodic maintenance. In all of the Foster-Miller designs, individual coils are adjustable with respect to the guideway. Further, the baseline guideway design with sidewall beam segments permits adjustment of the entire sidewall as a unit. Although the other Foster-Miller configurations do not have this option, the high structural stiffness of all four configurations will substantially reduce the need for realignment. The alignment maintenance of other coil systems is likely to be similar. However, the use of continuous sheet guideway (CSG) will require constant daily track work to mitigate thermal stress induced alignment problems. The extremely high maintenance (3500 workers per night) of the Shinkansen continuous welded rail is an example of the alignment difficulties inherent in a continuous metallic structure.

Pylon Settlement

Alignment can also be degraded by settlement of the pylon footings over time. Periodically, on the order of once every few years, adjustments may need to be made to correct the guideway alignment. The baseline Foster-Miller design facilitates these adjustments with its modular design and independent sidewalls. The single cell two-piece guideway may provide the greatest alignment problems as no adjustments can be made to the relative positioning of the floor and sidewalls. The advantages of longer spans can also be seen. Not only will there be fewer pylons, but settlement of any one will obviously result in a smaller angular misalignment over a long span than the same settlement over a short span.

Snow Removal and Weathering

In northern areas snow and ice buildup can pose substantial maintenance problems for a U-section guideway. The open floor/open sidewall design of the baseline configuration will reduce or eliminate this maintenance item. The integral sidewall and null-flux configurations will also have open section floors. The single cell two-piece configuration will require a snow removal vehicle to pass along the guideway. Such a device will likely induce further maintenance costs from contact with the guideway.

The open section design will also reduce normal weathering. By preventing precipitation buildup in the guideway, degradation of the concrete structure will be reduced. Further, the likelihood of corrosion of electrical system components will be reduced. As with snow removal, the single cell two-piece configuration is expected to be more susceptible to weathering degradation.

Vibration

Concrete transportation structures are inherently susceptible to vibratory strain degradation. Excessive vibratory loads can result in fatigue and, most visibly, in spalling. Spalling of concrete into the guideway could present significant safety risks to a high speed vehicle. The associated inspection and maintenance costs to repair this damage could also be significant. The four proposed Foster-Miller configurations are designed for low vibratory loading and should not be susceptible to this type of degradation. Flexible guideway configurations are much more likely to incur substantial maintenance costs from this issue.

Accident Damage

In the overall estimation of maintenance costs, an allowance must be made for repair of accident damage. Although contact of the vehicle and the guideway is unlikely, repair of the resultant damage must be considered. In this issue, the Configuration I design has the significant advantage of removable sidewalls. As damage from an accident will most likely occur in these sidewalls, large cost savings should result from the ability to replace only the sidewall. Unrepairable sidewall damage to one of the other configurations will necessitate replacement of that span.

A summary of these maintenance issues and the relative comparison of costs for all four configurations is given in Table 5-8.

Table 5-8. Maintenance Issues Summary - Relative Cost

	Foster-Miller				Others	
Issue	Baseline I	Integral Sidewall II	Single Cell Two Piece III	Null Flux IV	Flexible w/Coils	Flexible w/CSG
Inspection	Medium	Low	Low	Low	High	High
Alignment	Low	Low	Low	Low	Medium	Very High
Pylon Settlement	Low	Low	Low	Low	Medium	Medium
Snow Removal/Weathering	Low	Low	High	Low	Low	Medium
Vibration	Low	Low	Low	Medium	High	High
Accident Repair	Low	Medium	High	Medium	Medium	High
Overall Relative Maintenance Costs	Low	Low	Medium	Low	Medium	High

6. TRADEOFF ANALYSIS

In Section 3 on guideway configurations, the U-shaped guideway has been assessed as the most appropriate for maglev applications. This conclusion has also been independently reached by other investigators (5). The focus of our efforts in this report is to further narrow the available options within U-shaped configurations and determine the best configuration to further develop for the EDS maglev. The criteria for optimization are varied, and the application of the criteria must be done systematically for an objective selection. In the following subsections, the criteria are listed with appropriate weight factors. The weight factors are based on engineering judgement of the overall requirements on safety, performance and cost-effectiveness. Since the eight factors can still be subjective, they can be varied over a reasonable range and the resulting score for candidate maglev guideway cross sections can be parametically studied, if required.

6.1 Development of Multiple Objective Criteria

The criteria considered are presented here:

- Cost - The cost elements include initial fabrication, transportation, erection and maintenance components. The costs of fabrication and erection can be reasonably estimated, whereas the maintenance costs will be approximate. The configuration with the least cost is initially given a score of 10, and others are proportioned on the basis of actual cost estimates. The weight factor for cost is taken as 3 (the total of all weighing factors is 10).

- Load Capacity - The maximum vehicle load carrying capacity is an important factor for future expansions, increased passenger and freight loads. This can be examined through the ultimate strength in the designs. The weight factor for this is 1.

- Working Stress - The working stress is a measure of potential loss of prestress in tendons, and reduced fatigue life. The weight factor for this is 0.5.

- Natural Frequencies - The fundamental natural frequencies of vibration for the guideway structure must be high enough to prevent undesirably high dynamic load factors and dynamic deflections during high speed operation, while at the same time not having large higher order modes coupling with vehicle structural frequencies. These sections are evaluated here in terms of first, efficiently achieving their margin for fundamental required bending stiffnesses; and second, having the potential for control of lateral, torsional and higher order bending modes. The weight factor for this parameter is taken as 0.5.

- Tolerance Control - Vertical and lateral alignments of guideway are important in regard to passenger ride comfort and also transient instabilities generated in the primary magnetic suspension. The instabilities can induce alternating currents in the super cooled dc magnet and thus contribute to the magnet heating and potential quenching. Control of guideway alignment is an important factor in the guideway design. A weight factor of 0.5 is assigned to this.

- Ice and Snow Removal - Ice and snow buildup has been a problem in conventional railroad switches, and on highways, and calls for frequent maintenance in winter. The Japanese U-shaped maglev guideway also suffers from this disadvantage. In the open form guideway proposed here, the ice and snow problem is practically eliminated; however, the cost of assembly of the double cells will be an issue. To compare the open form guideways with the single cell conventional U-shaped guideway, the ice and snow factor is included and its weight is taken as 1.

- Rapid Egress - Rapid egress for passengers is an important consideration in the case of accidents or disabled maglev vehicle. This is determined not only by special exit doors in the vehicle design but also by the guideway configuration. A weight factor of 1 is assigned to this issue.

- Noise - The wayside noise generated by maglev vehicles is to some extent controlled by guideway configuration. The open floor guideway may need some baffle arrangement to reduce the "high pitch siren" as the vehicle moves at high speeds. The weight factor for wayside noise is taken as 0.5.

- Aero Drag - Aerodynamic drag is an important consideration as it affects the vehicle power performance. This is a function of vehicle geometry and clearance of the guideway. An open-center guideway may easily disperse the air in front and thus reduce resultant form drag. A weight factor of 0.5 is chosen for this.

- Accessibility - Accessibility to the guideway top surface, coils, etc., is an important factor in installation, maintenance and repair. Accessibility to the underneath of disabled vehicles is also important in any emergency repairs of brakes, landing gear and other bogie components. This consideration is given a weight factor of 0.5.

- Safety - Safety of passengers in the event of any rare but potentially dangerous failure is an important consideration. Here the focus is on safety in the event of guideway contact due to loss of guidance control or due to instability induced by wind gusts, or by sudden loss of levitation due to magnet quenching, etc. The guideway floor and walls must be sufficiently stiff to "contain" the vehicle. A weight factor of 1 is assigned to this aspect of safety.

6.2 Application to Candidate Configurations

The foregoing criteria will be applied to the four candidate cross sections developed within the U-shaped configuration. For any given criterion, the best candidate identified gets a score of 10. The remaining three will get proportionately lower points. These individual scores will be multiplied by the assigned weight factors, and a total score will be obtained, as shown later.

6.3 Selection of Final Candidate

The total score for each of the candidates is obtained by the equation

$$N = \sum_{1}^{i} w_i n_i$$

where

i = criterion number
w_i = weight factors
n_i = individual score as presented in Table 6-1.

The total score N is also shown in Table 6-1.

From the score, it may be seen that Configuration II, the double-cell guideway with integral sidewalls, is the best and most-effective candidate for further design refinement. This tradeoff showed that Configuration II was superior to the next best candidate by about 8 percent.

Table 6-1. Multiple Objective Ranking Matrix

Criterion No.	Criterion	Weighting Factor	Individual Score - 10 = Maximum 1 = Minimum			
			Double Cell Modular Side Walls (Configuration I)	Double Cell Integral Side Walls (Configuration II)	Single Cell Modular Side Walls (Configuration III)	Side Wall Levitation Configuration (Configuration IV)
1	Cost	3.0	5	8	6	10
2	Load Capacity	1.0	8	10	8	6
3	Working Stress	0.5	8	10	8	7
4	Natural Frequencies	0.5	9	10	8	7
5	Tolerance Control	0.5	10	6	6	6
6	Ice and Snow Resistance	1.0	9	8	3	10
7	Rapid Egress	1.0	10	10	6	5
8	Noise	0.5	6	7	10	5
9	Aero Drag	0.5	8	7	5	10
10	Accessibility	0.5	10	9	5	5
11	Operating Safety	1.0	8	9	8	5
	Total Score Σ		75.5	85.5	64.0	76.0
Maximum possible score = 100						

7. ENGINEERING OF SELECTED CONFIGURATION

This section focuses on the engineering design of the selected guideway in more detail than was used previously, in which the full range of candidate configurations was reduced down to the most structurally economical selection. The structural issues are expanded and the design calculations are carried to a level where these issues are treated adequately to verify the major design features.

From the design results in subsection 4.3 and the cost estimates of Section 5, Configuration II has been determined to best meet the guideway system requirements. In the search for structural economy (lowest concrete volume), the overall depth of all configurations was reduced to the minimum necessary to meet all requirements. The most efficient structural dimensions for Configuration II resulted in a main cell size which was smaller than was anticipated - the cell interior had a cross section of only 0.5 x 0.5m. This area is large enough to contain the necessary track services, but does not permit sufficient access throughout the cell with the cabling in place. Accordingly, we have decided to increase the overall depth of the main cell to 1.05 m (3 ft, 5 in.) and thin the vertical web portions such that the same shear area is preserved. This section will therefore be slightly more efficient via higher stiffness and moment-carrying capability than the original design for Configuration II, without significantly affecting concrete volume or cost. Also, the steel prestressing will now be located farther from the magnets by 0.15m (6 in.).

We will now further develop the details of the Configuration II design, which resulted in a least cost solution for ground coil type maglev operation. In this case the overall depth will be 2.3m, and we will utilize the two-span continuous scheme with 27m (88.5 ft) spans. This span length is the bet compromise for both economic section size and remaining above the potential 22 to 24m range of vehicle bogie spacing.

7.1 Reinforcing/Prestress Details

The principal reinforcing for flexural action is computed and shown in the spreadsheet calculations included in Volume 2.

7.1.1 Bottom Prestressing

The bottom reinforcing required is 16 - 15 mm (0.6 in.) diameter, steel prestressing strands (seven-wire strands) in each of the two structural pieces. The strands must be spaced no closer than 4 strand diameters, center-to-center, at the ends of the members with a minimum spacing of 38 mm. In order to fit all 16 strands in one row, the width of the bottom flange must be 15 (60) + 2 (36) = 976 mm. The preliminary design assumed 900 mm and 150 mm thickness which would permit two layers of strand. An adjustment of the bottom flange to 976 mm width x 100 mm thick would be a better detail and would not significantly affect overall design. From a construction cost standpoint, it would be better if the strands can be straight along the full length of the member, avoiding the construction of hold-downs where the strands are turned and angled up toward the ends. We know from the spreadsheet calculations that if all 16 strands are kept straight all the way to the end of the member that the prestress force will produce too much tension in the concrete at the top of the end of the member. However, a small level of prestress force applied near the top of the section will eliminate the tension overstress. Reinforcing used near the top of the section must be GFRP, as discussed above.

There is another reason for applying minor prestress forces in the extremities of the section, away from the major prestress force. The cross section is not symmetrical so that the major bottom prestressing force will produce biaxial bending in the section. The use of 7.5 mm diam GFRP rods, post-tensioned, correctly placed in the cross section will counteract unwanted tension due to the bottom prestressing force, and will lessen handling problems. We know from the spreadsheet calculations that there is sufficient additional concrete compressive stress capacity to handle significant additional prestressing.

7.1.2 Top Post-Tensioning

Once the guideway pieces are set on the pylons and locked together with diaphragms, negative moment capacity for the vehicle load is developed over alternate supports to create the two-span continuity condition. The necessary negative moment capacity is provided by four GFRP - 36 mm (1-1/2 in.) diam tendons at each side of the guideway. The tendons are placed near the top of the configuration in ducts which have been cast into concrete added to the outside of the configuration for this purpose. The tendons extend 5.4m into each of the adjacent spans which have been butted together with a thin epoxy joint. When post-tensioned the ends of the adjacent spans are compressed together with enough post-tensioning force so that no tension will develop at any location of the joint under the vehicle loadings.

We have also added two smaller 30 mm GFRP tendons in the upper horizontal surface at the inner cell intersection to provide insurance for negative moment capability over the same 5.4 m distance.

7.1.3 Sidewall Forces

Under vehicle operation, lateral magnetic forces maintaining the vehicle in position between the sidewalls push outward on the sidewalls. The magnitude of this force, uniformly applied over the area of the vehicle side magnets (0.6 x 6m), is taken as 20 percent of the vehicle weight, or 53 kN. A more severe load for the sidewall could occur if the retracted vehicle side wheels contact the guideway during an emergency. The magnitude of force could be greater, 1.5 x 53 kN = 80 kN is assumed, and the force is applied higher on the sidewall, producing more bending moment at the base of the wall. Assuming a 3m long section of the sidewall would participate in resisting an emergency wheel side force, the amount of vertical reinforcing required is:

80 kN (1.0 m)/0.4 m (3m) (30 kN per GFRP rod) = 2.2 rods/m

use 7.5 mm post-tensioned GFRP rods vertically on the inside face of the sidewall, spaced at 0.35 m (conservative).

7.1.4 Top Flange Forces

Forces which levitate the vehicle react on the top flange surface. The top flange must span the approximately 0.5m between the sidewalls of the cell while supporting this force. The pressure applied to the slab is a uniform load of magnitude = 265 kN/2(0.5 m x 6m) = 44 kPa.

If the top slab is 150 mm thick,, a 1m wide strip of slab has a section modulus of

$s = 1\text{m}\ (0.15\ \text{m})^2/6 = 3.75 \times 10^{-3}\ \text{m}^3$

Assuming the maximum moment = $wl^2/10$
moment = 44 kN/m $(0.5\ \text{m})^2/10$
= 1.1 kNm

and the tensile stress in the slab would be

$f = 1.1$ kNm/3.75×10^{-3} m^3 = 293 kPa.

The centrally located post-tensioning force necessary to counteract this tensile stress is

$P = 293$ kN/m^3 x 0.15 m^2 = 44 kN, or 1.47 GFRP rods/m.

Again, conservatively, place horizontal 7.5 mm rods at 0.5 m spacing.

7.1.5 Diaphragm Connection

The principal purpose of the diaphragm is to lock the two pieces of the guideway span together so that they resist vehicle loads and lateral loads as a unit. The diaphragm is given an I shape to maintain unified action under loadings that produce tension on the individual pieces. The connection is made by using post-tensioned GFRP rods through the flanges of all connecting pieces. This reinforcing replaces the regular top slab reinforcing where the diaphragm occurs. Shear transfer is accomplished by bearing in the web of the diaphragm piece because it is locked into position by the post-tensioning force. The preliminary design assumes a diaphragm with 0.8 m wide flanges spaced at 6m.* Additional engineering study is required for this final design.

7.1.6 Shear Stresses

Preliminary calculations indicated that webs of 150 mm will be adequate for shear stresses, considering the level of prestress in the elements. Several inexpensive design options are available to improve shear capacity should that be necessary at final design.

7.1.7 Reinforcing Summary

Figures referenced in subsection 7.4 summarize in pictorial form the prestressing and post-tensioning reinforcing required for the selected configuration.

7.2 Manufacturing/Transport/Erection

The selected configuration has precast elements that are 27 m (88.6 ft) long and weigh 612 kN (138,000 lb). These are only moderately long and heavy pieces to lift, handle and transport, and

*3 per span (diaphragms at supports are formed by pylons).

standard highway precast girder sections which are longer and heavier have been successfully handled.

The height and width of the piece (2.1m and 1.5m) do not present transport problems. Because of the length and weight, special trucking rigs will be required to transport the pieces and special permits will be required to move the pieces over public roads. The cost estimate attempts to include cost premiums for handling, transporting and erecting the pieces due to the length and weight of the pieces.

7.3 Alignment and Installation of Components

The pylons will probably be cast-in-place, and therefore will require larger construction tolerance than the present concrete guideway. However, the size of the seating surface on the top of the cap of the pylon will permit the precast concrete guideway elements to be set in alignment even if the pylon construction is slightly off. After the pylons are constructed, a surveying crew will lay out the alignment across the pylon caps and check elevations at the top of the caps. The seat assemblies for the guideway elements can then be set in alignment and to proper elevation to maintain guideway tolerances. The seats for the precast units will be made of steel and will employ bonded Teflon sheets where a slip detail is required. The seat assemblies will be grouted to elevation and attached to the cap with drilled-in adhesive anchors. The seat assemblies will match embedded items in the precast piece to take out lateral forces where required.

The guideway pieces must always be maintained within 20 to 30 deg of a vertical position while handling and after seating* on the pylons because the prestressing has been organized to resist forces produced by the girder weight in the "vertical" position. This may require some special detail at the seats to hold against rotation of the section after the crane is released and before the diaphragms are connected, or some temporary rig could perform that function.

All of the guideway pieces are connected to create a single structural unit before the top-positioning is applied. The top post-tensioning is located so that it is easily reached by crane supported jacks to perform the post-tensioning.

*Anticipated maximum guideway superelevation is in 12 deg range.

7.4 Drawings

Detailed drawings are included at the end of this volume.

8. RECOMMENDED CONCEPT VALIDATION STUDIES

There are some new technological areas which must be further explored to verify the structural or system performance of the guideways proposed in this study. We are highlighting the areas of:

- Magnetic interaction with structural components, including HS steel prestressing
- Mitigation of aerodynamic noise by the guideway
- Confirmation of material properties, including long-term performance, for high strength concretes and GFRP post-tensioning anchorages. Extensive research and development is ongoing worldwide both to confirm the properties of high strength polypropelene reinforced concrete and to develop commercially practical GFRP post-tensioning systems.

The studies proposed here will address areas which are apparently not being directly evaluated. These studies would of course, be accompanied by thorough reviews of current literature in these areas.

8.1 Magnetic Interaction Study for Guideway Reinforcement

8.1.1 Program Description

The purpose of these analyses and tests is to develop guidelines for optimizing the location and amount of prestressing steel reinforcements in the guideways. These procedures will also assess the comparative magnetic drag and eddy-current losses for various reinforcing schemes.

8.1.2 Technical Discussion

maglev guideways physically resemble the elevated highway structures and continuous box girder bridges. However, using standard prestressed concrete bridge designs for maglev guideways could introduce significant operational problems in the form of magnetic drag on the vehicles and induced currents in the guideway structure. These currents may lead to accelerated corrosion of metallic guideway elements and might even pose a safety hazard. The general relationships between magnetic drag, vehicle speed and reinforcing location are depicted in Figure 8-1.

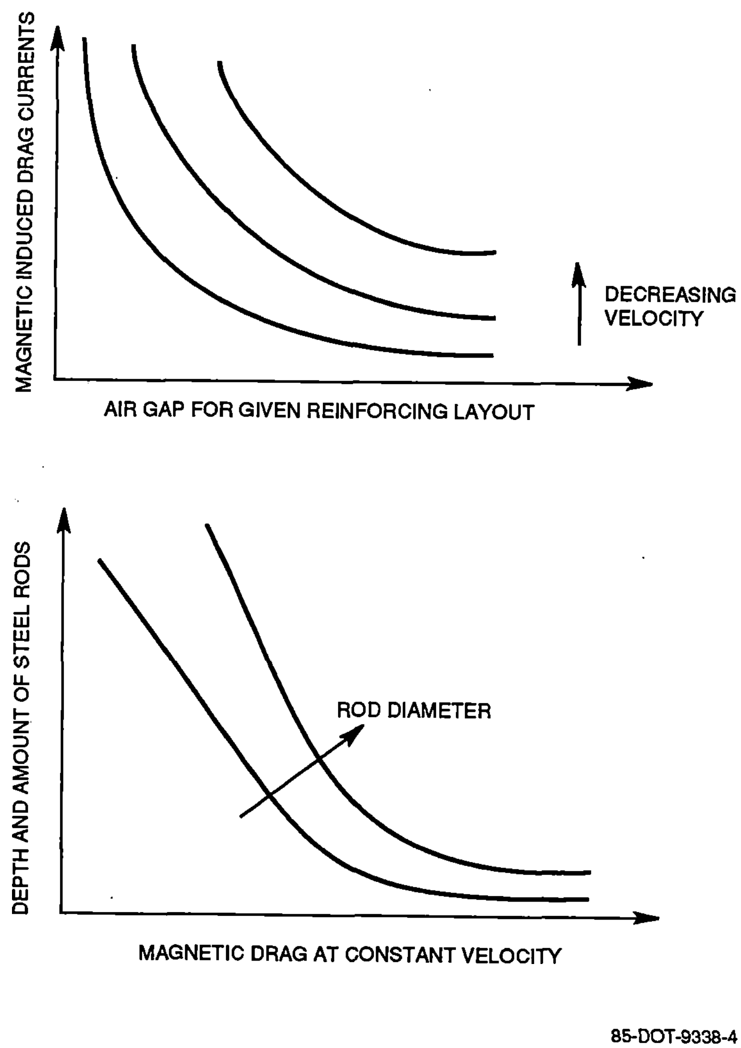

Figure 8-1. General Relationships for Magnetic Drag

The use of high strength steel for prestressing reinforcement still provides the most cost-effective solution to strength requirements in box girder bridge type structures. The locations and amounts of this reinforcement that can be accommodated by the maglev system will dictate to some degree the design of the guideway cross section. Of course, it is recognized that nonmetallic prestressing and reinforcement will be required in many areas of the guideway in close proximity to the magnets but it is desired for reasons of cost and limited demonstrated field experience to use these only where necessary.

There are well-known standards and codes available for designing prestressed concrete structures. But, there are no known design guidelines for magnetic interaction available for

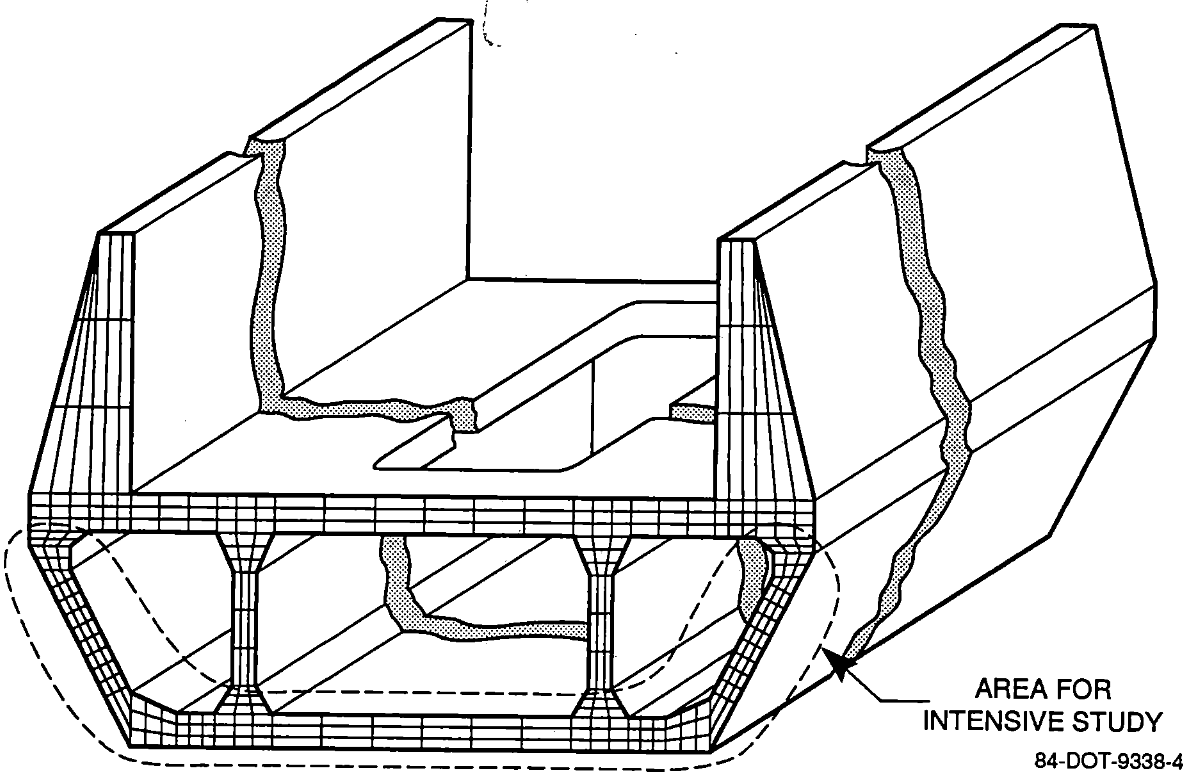

Figure 8-2. A Proposed Finite Element Model

sector will be positioned in the path of the magnet, and will be instrumented to collect the test data by automatically using digital computers.

The tests will be repeated for new reinforcement layouts by rearranging the reinforcement rods in the plastic beam structure. Different beam structures can easily be made for substantially different guideway configurations.

8.2 Aerodynamic Noise Evaluation Study

8.2.1 Program Description

Noise levels generated by maglev system operation need to be evaluated both from the environmental and the passenger comfort points of view. At maglev speeds of 500 kph, high sound levels can be generated in the guideway due to the rapid displacement of air. The magnitude and distribution of the sound is difficult to predict analytically and needs to be verified. This is necessary to evaluate design features of the Foster-Miller guideway which potentially can mitigate the sound levels, especially in the downward lateral direction.

designing the amount, location, and size of the steel prestressing. Foster-Miller proposes development of design guidelines by carrying out a thorough computer simulation of magnetic interaction plus subsequent physical testing of selected subscale guideway models.

8.1.3 Finite Element Simulation

Several commercial finite element codes have been enhanced to carry out electric and magnetic field analysis. Transient magnetic computer simulation can be used to compute magnetic fields in a given vehicle-guideway section. Using these magnetostatic analyses scalar potentials can be used to estimate the power losses in a magnetic field. Magnetodynamic simulation techniques can evaluate the magnetic drag and induction effects due to eddy currents. Foster-Miller currently uses ANSYS and NISA finite element codes which possess the capability for these analyses.

A set of designs with different reinforcement layouts reflecting the best guideway configurations can be modelled on workstation/PC based systems with a reasonable effort. The reinforcement steel can be located in various positions and amounts in the modelled guideway sections.

Figure 8-2 shows a finite element (FE) model that would be appropriate to study the guideway section. The modeling of the cross section can be carried out using automated mesh generation techniques on a 486 workstation. The results can be studied using a 3D graphical post-processor which can display the magnetic flux and induced currents in the elements and nodes of the FE model.

8.1.4 Physical Test Program

A 1/10th physical model will be developed to check the magnetic and induced current effects. This fixture will be used for these tests and, with minimal adaptation, for the tests of subsection 8.2. As such, the design requirements will be jointly defined by the two test activities. Figure 8-3 shows the schematic of such a test setup for this program, which is designed to be highly cost-effective. The 1/10th scaled guideway section will be designed as a curved sector allowing use of a simple rotating fixture. The guideway model will consist of the scaled steel reinforcing moving electromagnets and plastic guideway frame to hold the reinforcing.

An electromagnet on a support arm will rotate about a horizontal axis. The speed of the magnet will be controlled using a synchronized electric motor and feedback control. The guideway model

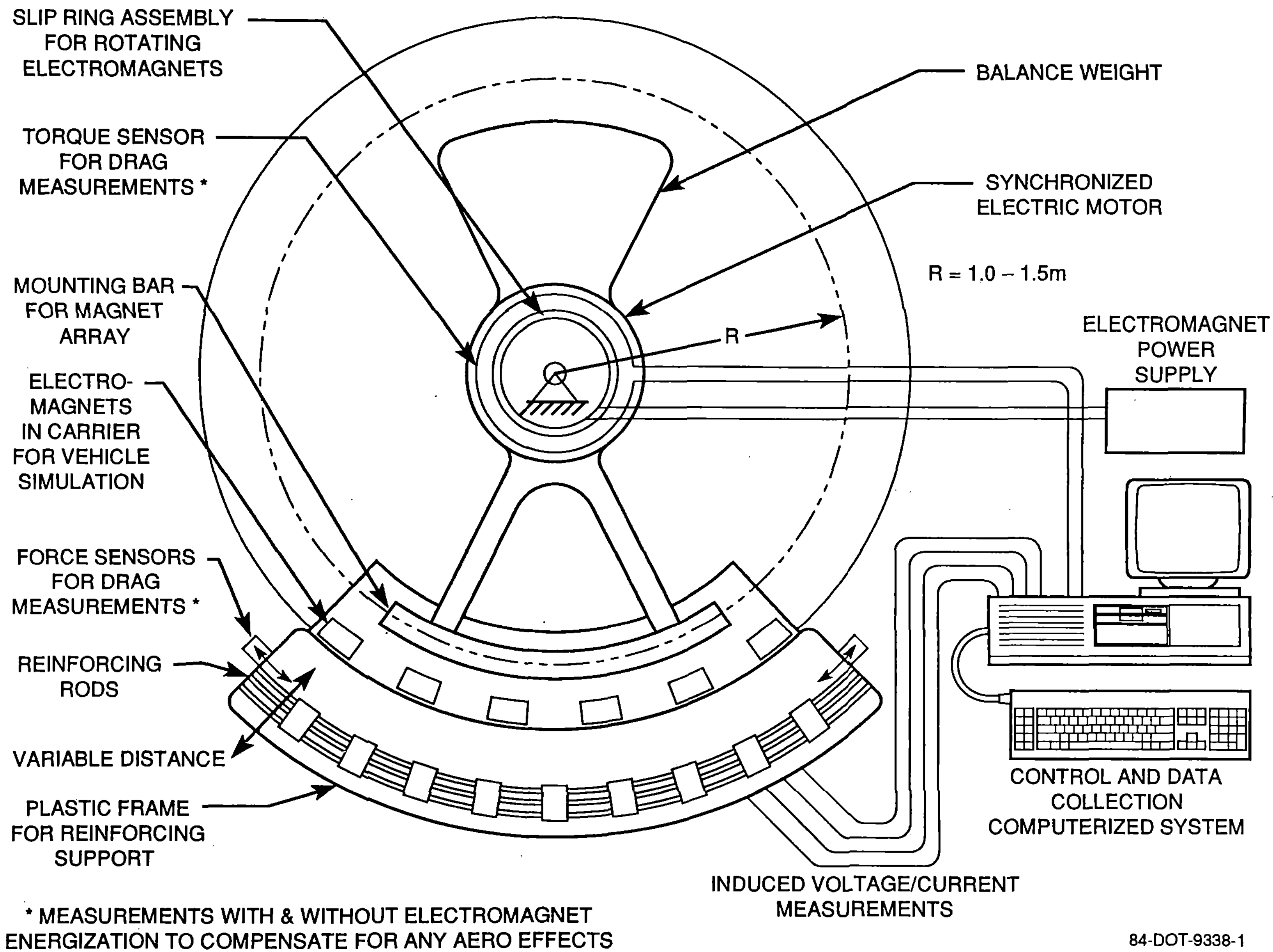

Figure 8-3. Interaction Test Setup (Same Test Machine as for Acoustic Study)

8.2.2 Technical Discussion

The aero noise levels generated by the maglev system depend on the aerodynamic profile of the vehicle, number of cars in the consist; type and nature of vehicle, exterior design, details (fairings, gaps, etc., and configuration of the guideway).

The noise effects from frontal airflow are primarily due to the generation of duct entry type sounds which can be controlled to some degree. The air flow between the vehicle and the guideway forms a couette type of flow with the vehicle boundary layer growing enough to interact with the guideway wall. This generates additional vortices which adds to the one generated by the wake, which is a major noise contributor.

It is known that the level of noise in the current Transrapid maglevs at 300 km/h is of the order of 80 - 90 dB at a distance of 25m laterally and 1.2m in height above ground level. At 550 km/h it will be significantly higher. For a new vehicle and new guideway the operational noise levels need to be established by tests. Corrective actions, if necessary can be taken much earlier in the design phase by studying the test model's noise. Thus cabin and ambient noise can be limited to comfort level standards of the community. Tests will be required to see if any unacceptable noise generation will result.

8.2.3 Test Program

The 1/10th scaled model, used in the tests of subsection 8.1, will have been jointly developed to achieve dynamic similarity for fluid dynamic parameters. Scaling laws will be used to estimate the noise parameters at full-scale. The test setup will simulate the correct relative motions between the vehicle, guideway and ambient air. Thus a moving vehicle with minimum external noise is proposed in this test scheme.

Figure 8-4 shows the test setup for the noise level studies. The dynamically balanced vehicle and arm rotate at high speed about a horizontal axis. The power source can be a speed-controlled direct drive electric motor. The motor, arm and counterweight components should be designed for minimum noise contribution. A representative guideway sector is aligned in the vehicle path. Both the vicinity of the guideway and, in the opposite position without guideway, can be instrumented with a calibrated microphone array, with the outputs stored and reduced in a digital computer. The vehicle would be rotated to the appropriate scale speed and the electric drive motor shut down. The noise data would then be collected by the computer in the design rpm ranges. The comparison in

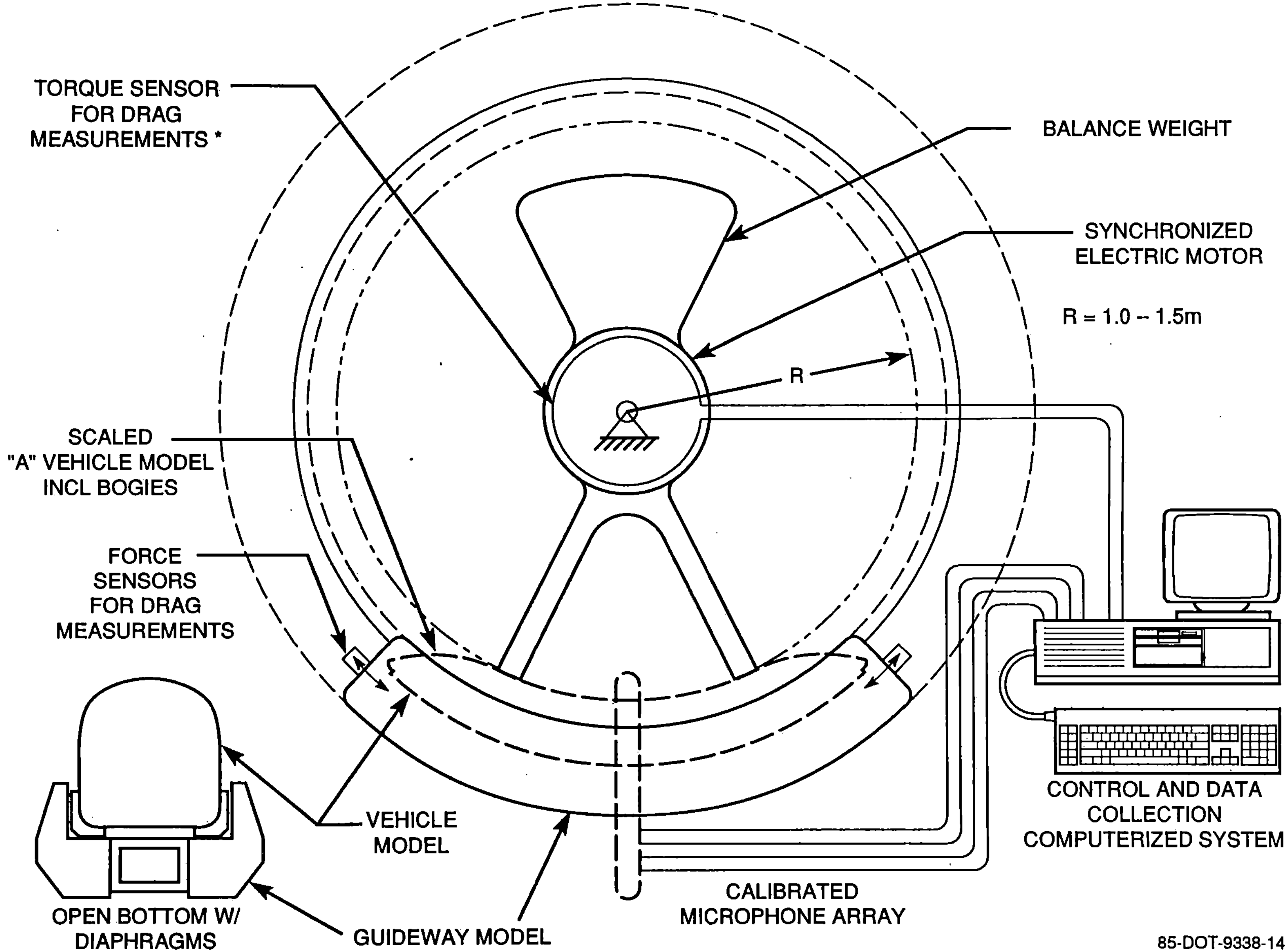

Figure 8-4. Aerodynamic Drag and Acoustic Emission Test Setup (Same Test Machine as for Magnetic Effects Study)

the reduced data between the guideway sector and the opposite side of the vehicle path without the guideway will provide further information to generate the actual noise distribution due to vehicle-guideway interactions.

9. SUMMARY AND CONCLUSIONS

This program identified the guideway requirements for a United States EDS maglev system and reviewed potential approaches to its design. Based on this study, four candidate guideway designs were developed. Extensive dynamic analyses of these candidates were conducted to quantify design parameters. Each configuration was sufficiently defined to permit cost and design tradeoff analyses. A recommended configuration was thus identified and a detailed design was conducted.

From the work conducted under this program, the following conclusions can be drawn.

- A U-section guideway with a partially open floor and high stiffness for long life is the preferred configuration for a United States maglev system

- Based on these analyses, 30m spans of the selected configuration are practical for minimizing corridor disruptions

- A two span continuous arrangement is superior to a simply supported arrangement

- The total structural costs of the candidate guideway configurations (including fabrication, erection, and alignment) are estimated to be $4.1 to 5.6 million per kilometer ($6.6 to 9.0 million per mile). The total structural cost of the selected system is estimated to be $4.7 million per kilometer ($7.6 million per mile).

- Further research and development of the more advanced system aspects (GFRP post-tensioning systems, vehicle magnet and steel reinforcement interaction, system aerodynamics, etc.) will permit additional improvement and optimization of the guideway system and further reduce costs.

10. REFERENCES

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NOTE

To avoid unnecessary costs, Volume II, "Design Calculations for Prestressed Guideway Beams (Girder Elements)," is not included. If required, copies are available at Foster-Miller, Inc. and with the COTR.