CONCRETE GUIDEWAYS FOR MAGLEV VEHICLES

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SUMMARY

This paper discusses parameters of concrete guideway beams for Maglev systems. Concrete beam parameters discussed include beam cross section, beam stiffness, vehicle/guideway dynamic interaction, constructed geometric accuracy of vehicle/guideway interface surfaces, maintaining geometric accuracy of vehicle/guideway interface surfaces, deflection stability, and choice of optimum span length. Two methods of providing and maintaining required geometric accuracy of vehicle/guideway interface surfaces are also discussed. One method uses good modern construction techniques; the other method reaches outside the box to develop an automated production facility through an extensive research and development effort. Typical costs are provided for concrete Maglev guideway beams. Potential cost savings are also presented to show the result of automating concrete beam production.

INTRODUCTION

Scope of Paper

Guideway beams for Maglev vehicles are a significant part of the Maglev transportation system. Guideway beams support vertical and lateral vehicle loads, guide the vehicles, and house the subsystems that operate the vehicle system. Furthermore, Maglev vehicle guideways are even more critical elements of the complete system than in other transportation systems since tolerance control and deflection control are system features provided by guideway structures. Maglev guideways are key components to a Maglev system since 50 to 70 percent of the cost of the system is attributed to the guideway. This paper will limit its discussion to dual-lane guideway beams for high-speed (> 300 kph) aerial Maglev guideways. "At-grade" guideways and guideways in tunnels will not be discussed in this paper. Substructures (crossheads, columns, and foundations) will also not be discussed.

TYPES OF MAGLEV SYSTEMS

There are two basic types of Maglev Vehicle systems, Electromagnetic Systems (EMS) and Electrodynamic Systems (EDS)[1]. In EMS, magnets in the vehicles are attracted upwards towards ferromagnetic rails supported by the guideway located above the vehicle magnets. Dimensional control of the air gap between the vehicle magnets and the guideway ferromagnetic rails is critical to efficient operation of the system. Propulsion is provided by linear induction motors (LIMs) or linear synchronous motors (LSMs). The secondary reaction rail of the LIM is attached to the guideway. Guidance is provided by lateral guide rails that are also attached to the guideway. Slide surfaces are provided to support Maglev vehicles when the vehicles are at rest or when a failure in the magnetic levitation system occurs. A schematic diagram of a Maglev EMS is shown on Figure 1.

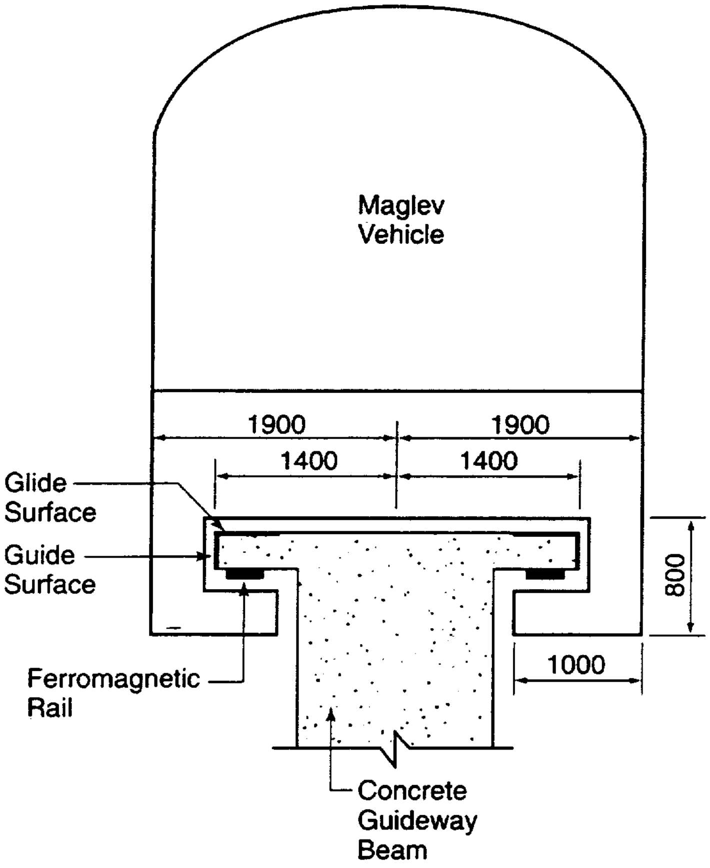


Figure 1. EMS vehicle/guideway interface

In EDS, conductive coils are provided in the guideway levitation surface. Repulsive magnetic forces are produced when coils in the vehicle move past coils in the guideway. This force is generated as the vehicle moves relative to the guideway levitation surface, and when the speed of the vehicle reaches "take-off" speed, the force is sufficient to support the vehicle. Guidance is provided by lateral guidance rails similar to EMS. Propulsion is also often provided by LIMs or LSMs. Slide surfaces are provided to "land" the vehicle when approaching stations or when a failure in the magnetic levitation systems occurs. An important feature of guideways for an EDS is that guideway materials within a certain distance of the vehicle coils must have specific magnetic characteristics and/or be non-conducting to prevent interference with the system operation. A schematic diagram of a Maglev EDS is shown on Figure 2.

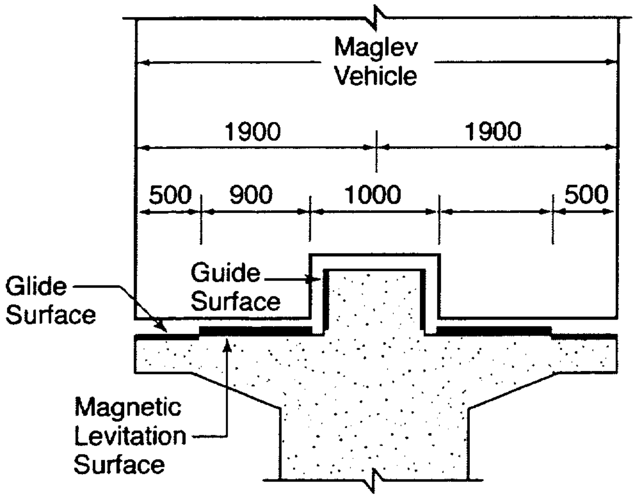


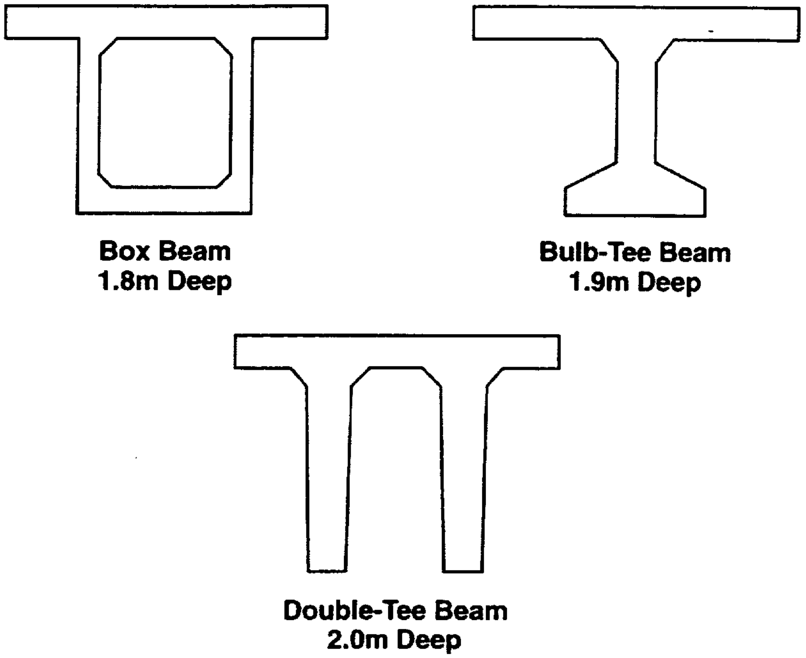
Figure 2. EDS vehicle/guideway interface.

Dimensions shown on Figures 1 and 2 are not intended to be representative of any particular Maglev vehicle system.

CONCRETE GUIDEWAY PARAMETERS

Beam Cross Section

Typical concrete guideway beam cross sections are shown on Figure 3. These beam cross sections are capable of supporting vehicle static and dynamic loads, and are also designed to house Maglev subsystems. Box beam cross sections are often used for aesthetic appeal and greater torsional strength. Open sections are less costly to produce using current methods. Also



Box Beam
1.8m Deep

Bulb-Tee Beam
1.9m Deep

Double-Tee Beam
2.0m Deep

Figure 3. EMS guideway cross sections for 30m spans.

for open sections, intermediate span diaphragms, located at approximately the 1/4 points of the span, would be required to couple beams supporting each lane of the dual-lane guideway.

Guideway beams for Maglev systems will generally span from support to support. Longer span beams can be achieved using other methods, such as segmental construction techniques.

Construction Materials

Concrete guideway beams for EMS would use conventional concrete, reinforcing steel , and prestressing steel materials. As the use of composite materials in civil engineering facilities progresses, the use of composite materials in conjunction with concrete should be explored. The use and benefits of lightweight or semi-lightweight concrete should also be explored.

Concrete guideways for EDS would use non-magnetic and/or non-conductive materials for a distance of approximately 1 meter from the magnetic levitation surface. This is required to prevent interference with the operation of system. These materials can include nitronic stainless steel or carbon reinforcing elements. Conventional concrete, reinforcing steel, and prestressing steel would be used in the remainder of the guideway beam cross section. Similar materials have been used in magnetic silencing facilities for the U.S. Navy. Design and fabrication of this guideway beam will impose unique material selection challenges for vertical reinforcing components.

Beam Stiffness and Vehicle/Guideway Dynamic Interaction

Beam stiffness or deflection due to vehicle loads is important for efficient and comfortable operation of a Maglev system. In the vertical direction, this interaction is often controlled by limiting the vertical deflection generated by the Maglev Vehicle to 1/4000 of the span length.

Vehicle/guideway dynamic interaction is controlled by limiting the vertical deflection as discussed above or by separating the crossing frequency (CF in spans per second) of a span, vehicle velocity divided by span length, and the natural frequency of the guideway beam (SF). The basic structural frequency for a single span or for a series of equal multiple spans is expressed as

$$SF = \frac{\Pi}{2L^2}\sqrt{\frac{EI}{m}}$$

L = span length
E = dynamic modulus of elasticity
I = vertical moment of inertia
m = mass per unit length

Studies[2], for point vehicles, have shown that multiple-span structures reach maximum dynamic amplification at a CF/SF = 2 and also have shown that there is little or no dynamic amplification at CF/SF ratios less than 1.0. Single-span structures reach peak dynamic amplification at a CF/SF = 1.2 with significant dynamic amplification at CF/SF ratios form 0.6 to 3.0. See Figure 4. This would indicate that for the same beam bending stiffness, same span length, and same vehicle velocity, beams with 60 percent of the beam bending stiffness can be used with multiple span structures and still limit dynamic vehicle/guideway amplification to acceptable levels.

Lateral Deflections

Lateral deflections of guideway beams are also critical parameters. Lateral deflections are controlled primarily by the stiffness of supporting columns and foundations. Discussion of these guideway components is outside the scope of this paper.

Constructed Geometric Accuracy of Vehicle/Guideway Interface Surfaces

The constructed geometric accuracy of vehicle/guideway interface surfaces is critical to efficient, comfortable, and safe operation of Maglev Vehicles. These interface surfaces are shown on Figure 1 for EMS and on Figure 2 for EDS. Critical surfaces for EDS are the guideway ferromagnetic rails, the horizontal guidance surfaces, and the gliding surfaces. The same interface surfaces, but arranged in a different pattern are critical for EDS.

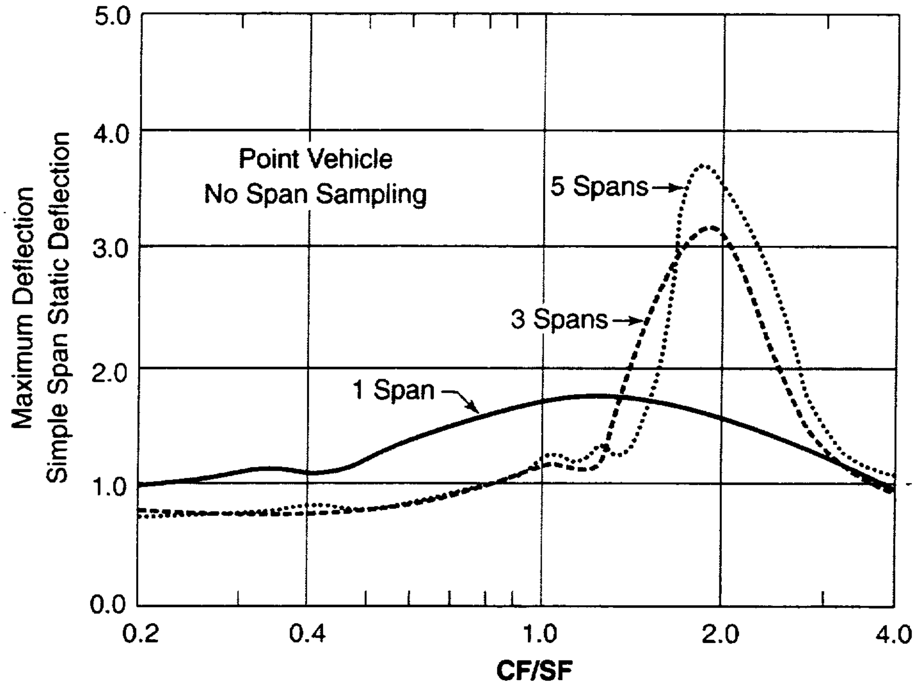


Figure 4. Dynamic to static deflection ratio vs. CF/SF ratio (from Reference 2)

There are fundamentally two basic approaches to providing and maintaining adequate interface tolerances.

Method 1

Manufacture concrete beams with conventional "industry standard" interface tolerance surfaces and mechanically attach horizontal guide surfaces, levitation/propulsion surfaces, and gliding surfaces. These interface surfaces have sometimes been packaged into pre-assembled modular units to minimize the amount of field assembly required. Generally, these surfaces are secured to guideway beams through mechanical fasteners. See Figure 5.

Some discussion of "industry standard" interface tolerances is warranted. Concrete beams must be produced to accurate horizontal curvature, vertical profile, and superelevation so that Maglev modules can be economically attached to these beams. Special adjustable forms would be used to fabricate these beams. These type of forms have been used on past transit projects to fabricate complex geometry guideway beams [3,4,5].

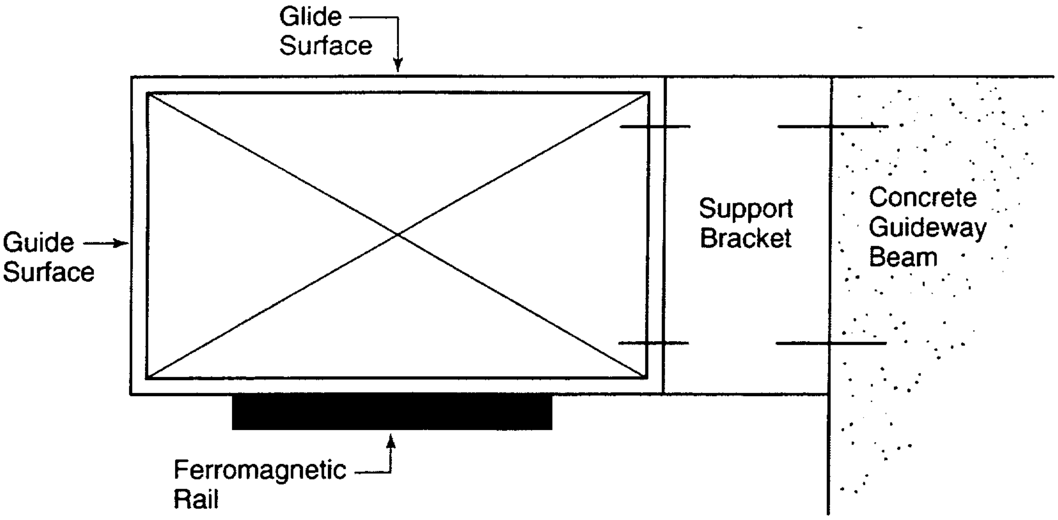


Figure 5. Modular Maglev Subsystem Assembly

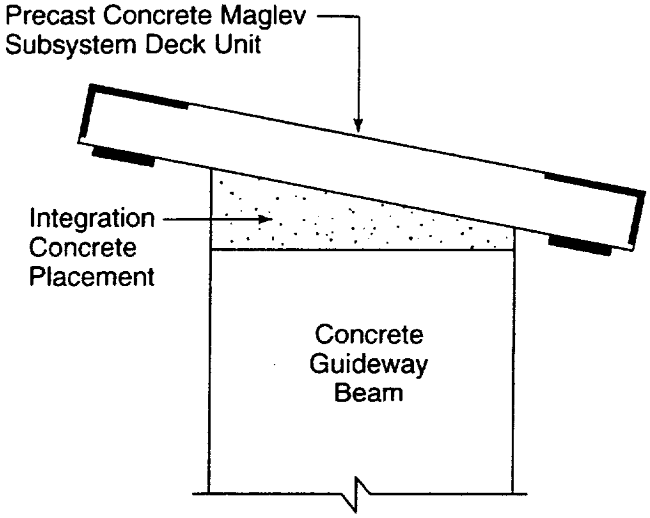


Figure 6. Use of precast concrete maglev subsystem deck unit.

A variation on this method is shown in Figure 6. The beam cross section is made up of bulb-tee, double-tee, or box beams supporting precast subsystem deck units. Precast deck slab units are fabricated to the true horizontal alignment, vertical profile, and superelevation of the spatial geometry. Special adjustable forms will be used for production of these deck units. Lengths of subsystem deck units will be multiples of ferromagnetic rail lengths and LIM secondary rail modules. Precast subsystem deck units are integrated with beams through cast-in-place closure pours. Precast concrete beams are cast as straight components. These beams chord across horizontal curves. Superelevation is provided by varying the height of the integration concrete placement between the concrete girder and precast subystem slab units.

Method 1, or variations thereof, have been used to construct most of the Maglev guideways to date. This method is used since it is an extrapolation of good modern construction practices.

Method 2

Manufacture concrete beams with accurate "custom tolerance" interface tolerance surfaces. Horizontal guide surfaces and/or assemblies, levitation/propulsion surfaces and modules, and glide surfaces are built into concrete beams at the beam production facility. This method would use computer-controlled machines that could configure a mold to a wide range of lengths, horizontal and vertical curvatures, and superelevations. The beam manufacturing process would be automated so that reinforcing steel, prestressing steel, and Maglev assemblies would be placed very accurately and reliably.

Developing such a process would take a substantial research and development (R&D) effort. This effort would entail marrying technologies of automated production of precast elements with precision surface production technology from the machine industry and could involve a National Aeronautics and Space Administration (NASA) scale R&D effort. This method could be a combination of concepts shown on Figures 5 and 6. However, the economics of Maglev systems and guideways warrant an investment of this scale. Possible economics and potential cost benefits of this method will be discussed in a subsequent section of this paper.

Maintaining Geometric Accuracy of Vehicle/Guideway Interface Surfaces

Maintenance of these critical interface tolerances is as important as initially providing them, since maintainability is an important consideration for a system that will have many hundreds of kilometers. Guideways should be designed to provide ways to continually maintain these interface tolerances.

Using Method 1 described above, maintenance of interface tolerances is achieved through continually monitoring and adjusting attachment fasteners. This relatively simple means of maintaining tolerances may also pose the biggest disadvantage to this method; that is attachments that can be adjusted to maintain tolerances can also get out of adjustment to allow deterioration of tolerances.

Maintaining tolerances using Method 2 would require a special machine that grinds interface surfaces to required tolerances. The machine could index off guideway global geometry measurements and levitation/propulsion surfaces, and grind horizontal guide surfaces and gliding surfaces to achieve smoothness and relative dimensional tolerances to fractions of centimeters as required.

Maintenance of tolerances using either method, for Maglev systems of several hundred km in length, would require machines or a train of machines similar to maintenance equipment that is used by railroads to measure track alignment and profile, realign rails, retamp ballast, replace ties, etc. Maintenance equipment of this scale will be needed to make Maglev systems feasible, comfortable, and safe.

Deflection Stability

Deflection stability of critical Maglev interface surfaces (therefore of supporting concrete beams) is also a **key parameter.**Concrete guideways for aerial structures will be constructed using prestressed concrete beam elements. Generally, these beams will also be precast under factory controlled conditions. In addition to providing the manufacturing environment necessary for close tolerance fabrications, factory precasting beams that are components of long repetitive type structures is an economical approach to guideway construction. Prestressed concrete guideways utilize steel prestressing strands that are stressed to high prestress forces to counteract applied loads. However, prestressing forces shorten guideway concrete beams and also usually generate upward vertical deflections in these beams. Concrete, being an elastic-plastic material, also undergoes long-term deflections associated with these prestress forces due to concrete creep. Differential (varies throughout the guideway beam cross section) concrete shrinkage strains can also cause guideway vertical deflections. **All of these considerations must be addressed in a successful Maglev guideway design.**

Multiple-span guideway structures are better suited to maintaining deflection stability than single-span guideway structures. Strain effects, in multiple span guideways, are resisted by combinations of deflections and internal forces. Strain effects in single-span guideways primarily result in deflection while minimizing internal forces. Past efforts in dealing with deflection stability have considered continuous concrete guideways that are similar in principal to continuously welded rails for rail transportation systems. Guideways would be continuous between guideway anchor structures. These anchor structures would be capable to resisting the continuous guideway thermal force. Similar to thermal forces generated in continuously welded rails, this force would equal

$$= A_c \; E_c \; \alpha_c \; \Delta T$$

Ac = Area of concrete cross section
Ec = Elastic modulus of concrete
α_c = Thermal coefficient of concrete
ΔT = Temperature rise or temperature fall

Consideration has been given to use semi-lightweight concrete to reduce Ec and to reduce the thermal coefficient of concrete.

Typical dual-lane guideway beams would generate dual-lane guideway anchor forces equal to approximately 25,000 kN. Anchor structures would be provided every 2 to 3 km.

Optimum Guideway Span length

Selecting the optimum "system" guideway span length depends on many factors. The span length for guideway beams is an important parameter in limiting the live load deflection of the guideway beam. Live load deflection is

$$\Delta_{LL} = k W_{LL} \ell^4 / E_{dyn} I$$

If this deflection is less than 1/4000 of l, then

$$\ell \leq (E_{dyn} I / 4000 W_{LL} k)^{\frac{1}{3}}$$

ℓ = Span length
k = deflection constant
E_{dyn} = Dynamic modulus of elasticity
I = Vertical moment of inertia
W_{LL} - Equivalent uniform vehicle load (vehicle + passengers)

The constant k depends on the structural configuration of the guideway. This constant can be reduced if the guideway beam is partially fixed at one or both ends. The modulus of elasticity is related to the square root of the compressive strength of the concrete. The dynamic modulus of elasticity is approximately 25 percent greater than the static modulus of elasticity computed in accordance with conventional formulae for determining this parameter. The vertical moment of inertia of the guideway beam is related to the cross section configuration and to the depth of the cross section. Increasing cross-section depth is the most effective way to increase this value. The equivalent uniform vehicle live load depends upon the weight and length of the Maglev Vehicle.

The optimum span length depends upon relative costs between guideway beams and guideway crossheads, columns, and foundations. The optimum span also depends upon the guideway configuration and upon limiting transport and erection weights of precast concrete beam components. This is especially important for guideway beams that are single elements spanning from support to support.

For purposes of this paper, a "system" span length of 30 m was selected. This typical span length has worked well on past projects and is at the upper end for conventional transport and erection weight and is long enough to span typical obstacles.

CONCRETE BEAM COSTS AND ECONOMICS

Past studies[6] and projects[5] provide the basis for the following discussion. This discussion will focus on the costs and cost savings potential of developing special Maglev guideway concrete beams. Total Maglev project costs include many other items. These items include guideway beam transport, guideway beam erection, guideway foundations, columns and crossheads, Maglev assemblies, Maglev vehicles, passenger stations, maintenance facilities, switches, power distribution facilities, right-of-way, right-of-way improvements, program management, engineering, and construction management.

The manufactured cost of 30-m concrete guideway beams using Method 1, FOB manufacturing facility, cost approximately $50,000. The unit guideway beam cost per meter of dual-lane guideway would cost

= 2 * $50,000 / 30.0 m = $3,333 per dual-lane meter

At this unit cost, the total guideway beam cost for a 500-km long Maglev system equals $1.67 billion.

The above manufacturing cost of guideway beams is broken out as follows.

Materials	$ 24,000
Production Labor	12,000
Contingencies	3,600
Plant Overhead	5,400
General Overhead and Profit	5,000
Total	$ 50,000

If guideway beams were produced in automated manufacturing facilities (Method 2), reasonable cost reduction targets are as follows.

Materials	$ 22,000	- Size discount
Production Labor	3,000	- Production labor reduction
Contingencies	1,200	- Production risk reduction
Plant Overhead	3,000	- Prorated from above
General Overhead & Profit	2,800	- Prorated from above
Total	$ 32,000	

This reduced cost for guideway beams would result in a $600 million savings in guideway beams alone for a 500-km-long Maglev system. This savings is an indication of the R&D investment that would be available to develop specialized production facilities and machines to manufacture concrete Maglev guideway beams and achieve the objectives of the Method 2 approach.

This research and development effort could be undertaken by a consortium of companies each bringing special skills and knowledge to the endeavor. Centralized fabrication facilities could be located in regions throughout the country, or alternatively the specialized machines could be transported to facilities close to project sites.

CONCLUSION

Concrete guideway beams offer several advantages for Maglev systems. Concrete guideways are inherently stiff and have a high unit mass. These features cost-effectively reduce loads resulting from vehicle/guideway dynamic interaction. Concrete guideway beams will last for many years with very little maintenance. Incorporation of composite reinforcing materials into concrete guideway beams will further enhance this benefit. Concrete Maglev guideway beams also offer good possibilities to capture the benefits resulting from being manufactured in automated factories. Significant cost savings could accrue to Maglev systems making them a more economical mode of transportation in the 21st century.

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