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SYSTEM CONCEPT DEFINITION REPORT
for the
NATIONAL MAGLEV INITIATIVE

Volume
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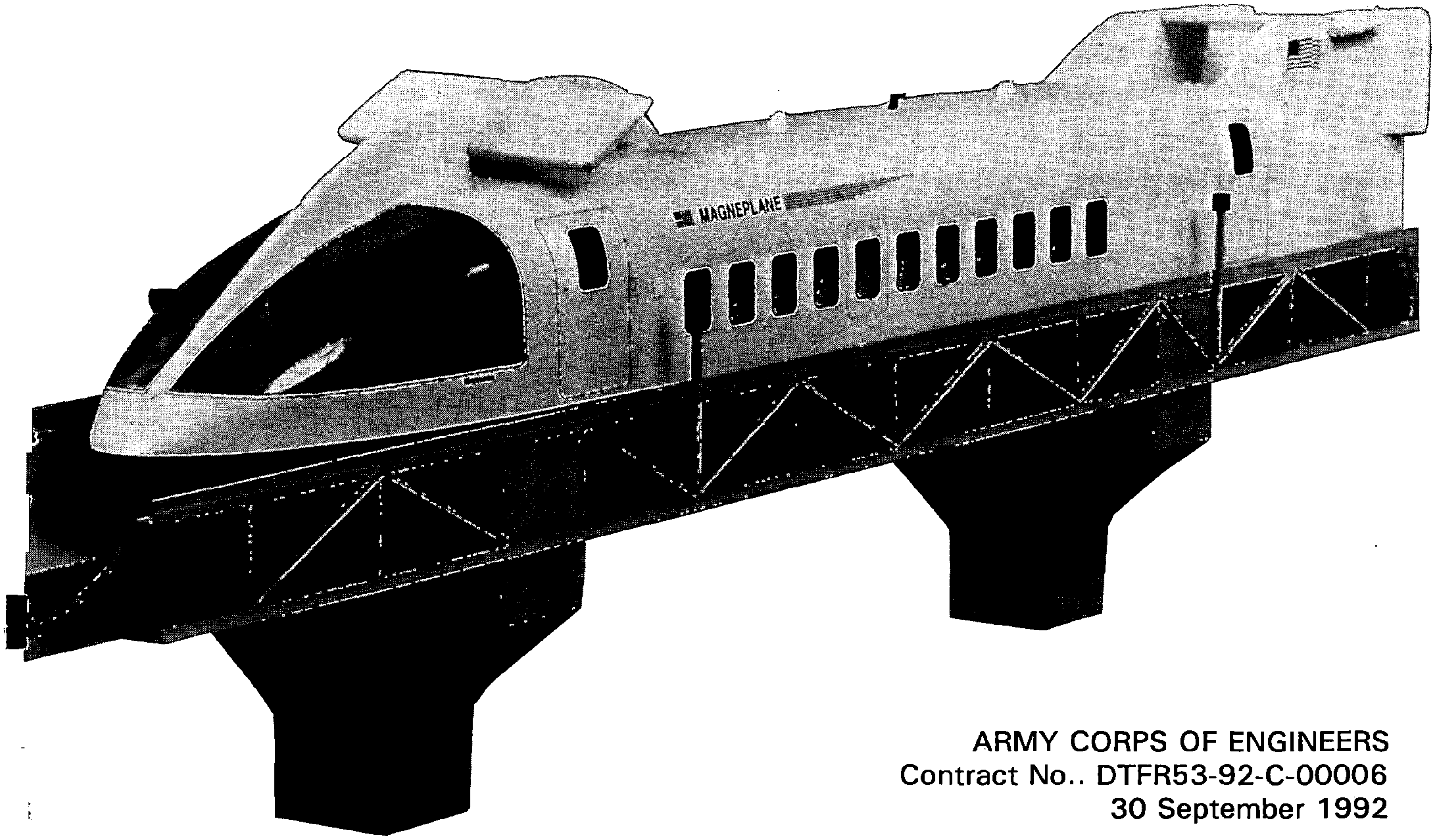

ARMY CORPS OF ENGINEERS
Contract No.. DTFR53-92-C-00006
30 September 1992

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INDEX TO VOLUMES

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5.3.2. TRADEOFF ANALYSES

CONTENTS

FIGURES

5.3.2.1. LEVITATION HEIGHT

5.3.2.1.1. MOTIVATION

Magneplane concept rationale considers resiliency a crucial advantage because, coupled with active phase control, resiliency permits large span deflections, large construction tolerances, and maximum passenger comfort without the need for a secondary suspension or a tilt mechanism. Thousands of flight tests with scale model systems provided intuitive three-dimensional insight into vehicle dynamics, and led to certain design guidelines.

The choice of levitation height was made in the early conceptual design stage, and it provides the basis for many of the other components of design. The selected clearance is large, and is a robust feature of the concept, from the construction and operational standpoint.

5.3.2.1.2. CONCLUSIONS

Levitation height at cruising speed is 0.20 m as measured from the center of the vehicle's levitation coils to the surface of the magway levitation plate.

Levitation height should be approximately one tenth the size of the levitation dipoles (superconducting pancake coils) to take full advantage of achievable belly clearance and resiliency (suspension stroke). This is due to the variation of a dipole magnetic field versus levitation height. For small separations, the field varies slowly, and for large separations, the field drops proportionally to s^3 where s is the separation. A good trade is made when the height is about 10% of the dipole size.

The optimum is fairly broad within this range, but large variations have adverse effects. Reducing the height to 75% of its present size, from 0.20 m to 0.15 m would result in a few percent energy savings due to improved LSM coupling, but reduce the actual belly clearance from 0.15 m to 0.10 m, preserving the minimum required cryostat and radiation shield space of .05 m.

A clearance of 0.10 m (approximately 3 inches) is incompatible with the Magneplane concept, due to a number of negative consequences of this gap:

- reduces the vehicle safety margin over a rough magway
- increases the primary suspension frequency, causing higher demands on aerodynamic and LSM controls
- decreases the allowable flexibility of magway
- increases the minimum radius curve negotiable while levitated

- decreases the allowable vertical and lateral misalignment of magway elements (System will require more frequent and accurate realignment)

5.3.2.1.3. CALCULATIONS

Cost models for the system allow tradeoffs to be performed for several design parameters, including the operating clearance between the vehicle and guideway. In the following we show results indicating that a decrease in clearance would: 1) allow a significant decrease in the amp-turns in levitation modules, but have little impact on system cost; and 2) allow only insignificant savings in terms of guideway real and reactive power reduction. At this stage, the design uses an ample clearance of 0.15 m, an attractive feature when compared to the capabilities of existing systems.

The lift and drag for the levitation modules are dependent on speed, height above the guideway, guideway material, guideway geometry and levitation coil geometry. Both forces can be shown to be proportional to I_v^2, where I_v is the current in one levitation coil in a module, hence it is convenient to normalize the forces to $\mu_0 I_v^2$.

Figure 2 and Figure 3 show the electromagnetic lift and drag forces for one levitation module for the baseline design. The lift to drag ratio is given in Figure 1. The abscissa in all the graphs is speed and, in each case, a family of curves is given for different heights. The height is defined as the distance from the center of the current in the levitation coil to the guideway surface. The present module designs require 0.05 m from the center of the coil to the surface of the cryostat, which could serve as the surface of the vehicle because it is a relatively thick skin (0.375 in. = 9.5 mm). Hence, the clearance beneath the vehicle is the height minus 0.05 m.

The clearance selected for the baseline is 0.15 m, which corresponds to a height of 0.2 m. The latter is marked on each of the previous three figures. Figure 2 shows that the lift force monotonically approaches a high speed limit; Figure 3 shows the presence of a strong drag peak at low speeds that becomes substantially worse at constant current as the height is decreased.

Since the required lift for a system is constant, Figure 2 implies that the amp-turns in the levitation modules could be decreased significantly if the height were decreased. However, section 3.2.1.a.1. showed that the superconducting levitation coil cross-section, which is proportional to amp-turns, did not have a strong impact on module weight, so considerable changes in amp-turns in this area would not be expected to offer a significant cost benefit to the system.

The electromagnetic lift to drag ratio for this system is shown in Figure 1. It is essentially proportional to speed and is not a strong function of height. Hence, for a given lift, the electromagnetic drag force and vehicle drag power at the design point are relatively insensitive to a decrease in height. As a result there is little incentive for decrease from the standpoint of the electromagnetic thrust required or power dissipated in the guideway sheets. However, a decrease in height improves the coupling to the synchronous windings, which would allow a decrease in synchronous winding current.

If there is a specified thrust requirement, wavelength (λ) for the synchronous windings, total amp-turns in the vehicle propulsion coils, and geometry, then a change in height above the guideway, Δz, will lead a fractional change in the guideway current required that is approximately given by $2\pi(\Delta z)/\lambda$. Hence, a decrease in height by 2.5 cm would allow a decrease in guideway winding current of about 10% . For a fixed guideway winding, power efficiency would, therefore, increase by only about 2%. This is clearly not a gain worth trading against a reduction in operating clearance. We have therefore retained the large clearance of 0.15 m as one of the robust features of the Magneplane concept.

If the clearance is made *larger* than 0.15 m, the loss of lift especially at low speeds requires large levitation magnet currents. The LSM coupling becomes steadily worse, which demands more amp-turns in the propulsion magnets. The magnetic fields must be higher for a larger gap.

The number 0.15 m takes all factors into account, and is a proper selection for this phase of the concept development.

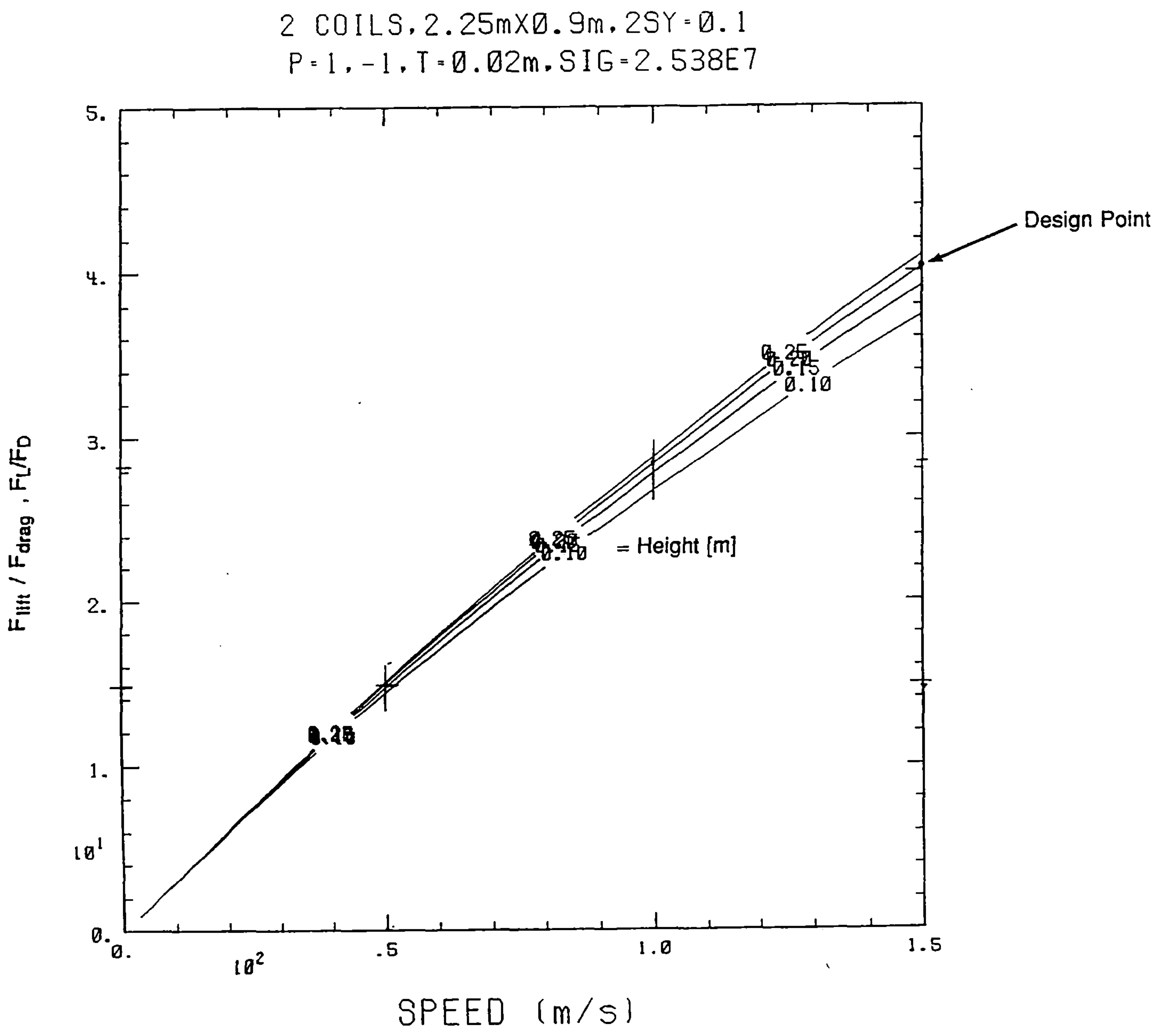


Figure 1 Lift-to-drag ratio for levitation modules

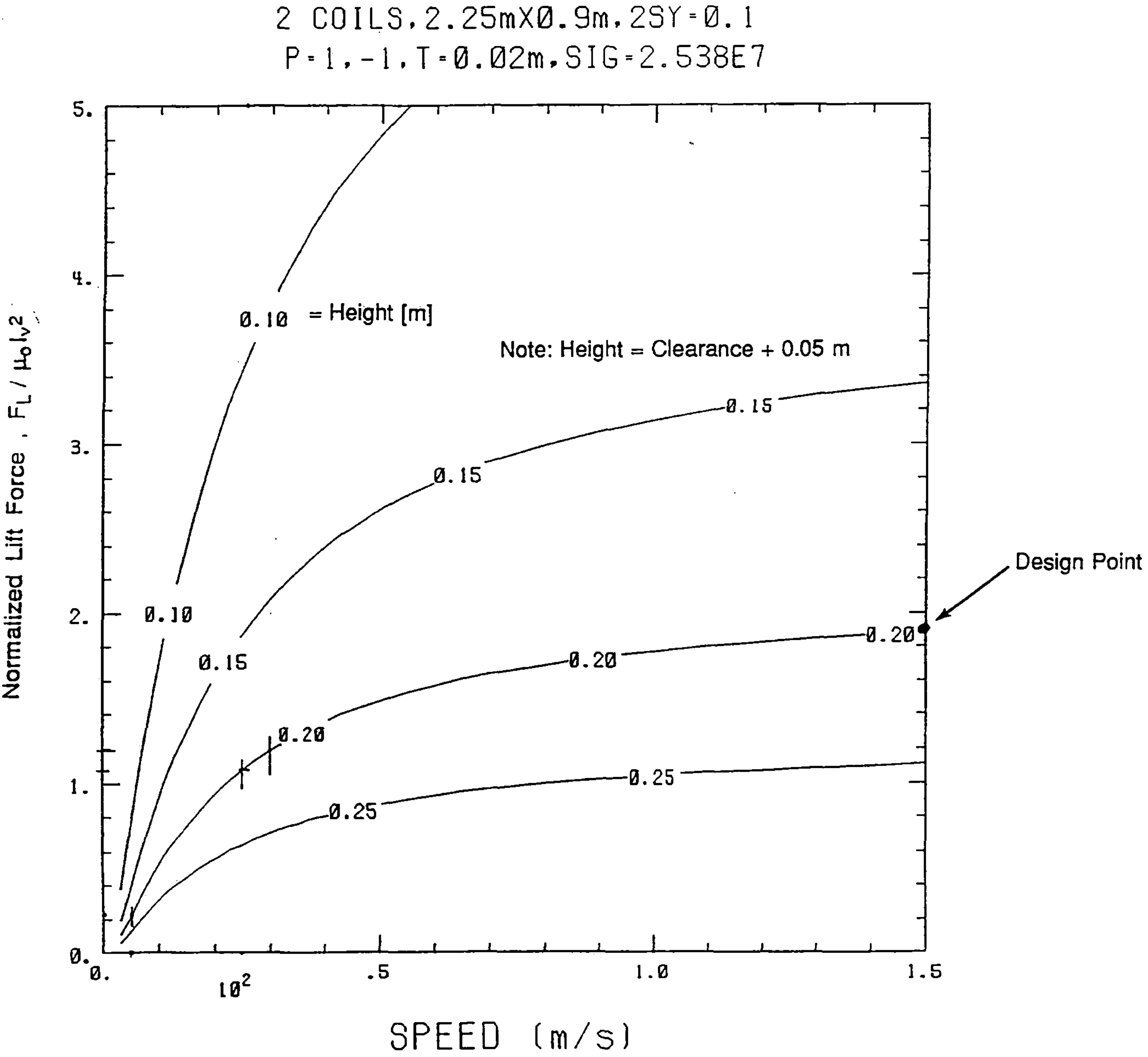


Figure 2 Normalized lift force vs speed for one levitation module

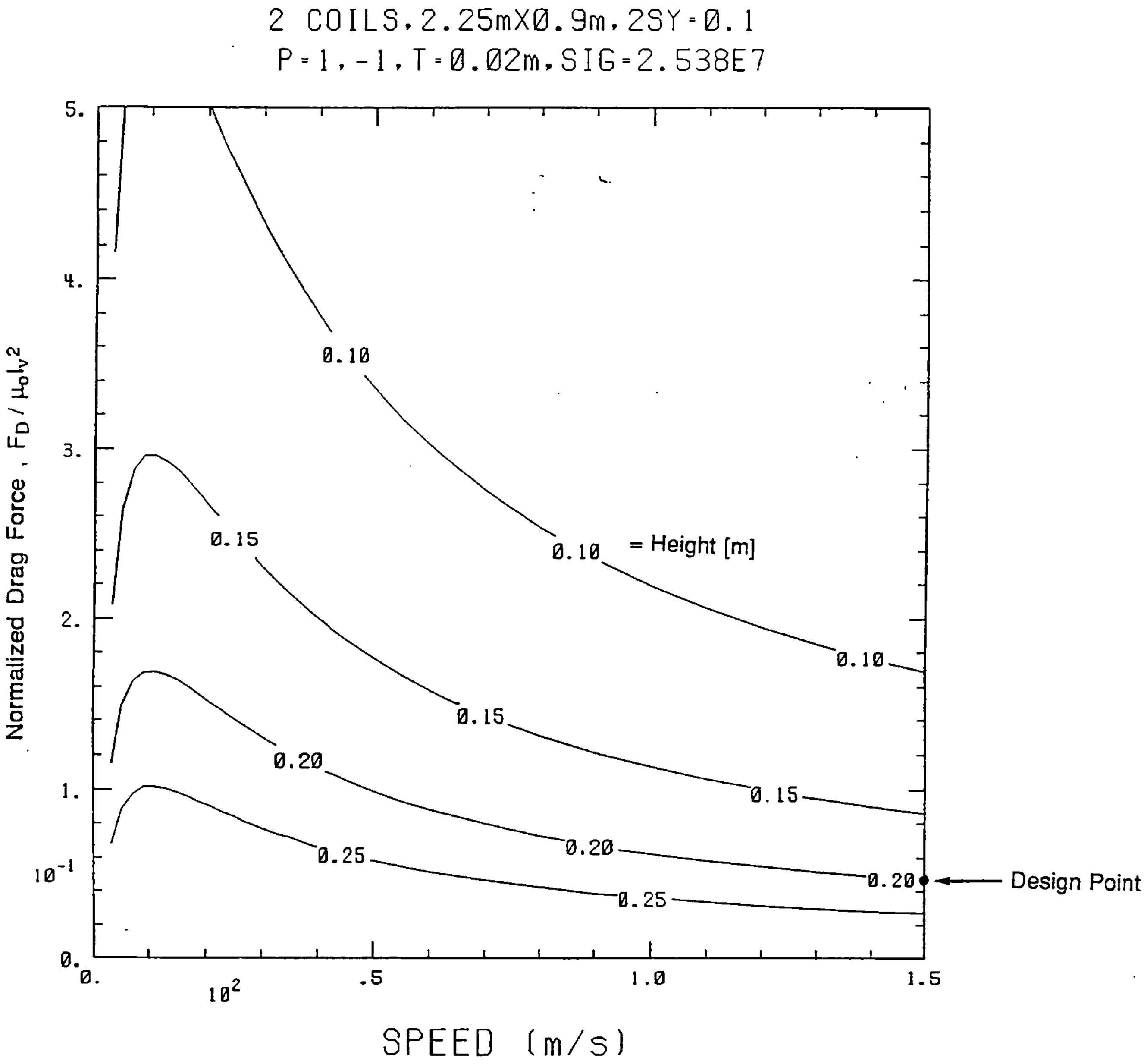


Figure 3 Normalized drag force vs speed for one levitation module

5.3.2.2. METHOD OF ACTIVE DAMPING

5.3.2.1. MOTIVATION

EDS (repulsive) suspensions are inherently stable under steady-state assumptions, but susceptible to catastrophic oscillations if perturbed. This is due to the fact that there is no inherent damping of any oscillation mode, and propulsion energy may be fed into oscillation modes by mechanisms analogous to the violin bow effect. Active damping is therefore necessary to prevent catastrophic oscillations, although this fact has not as yet been recognized elsewhere. How this problem was discovered, studied and solved by the original Magneplane team in the seventies will be described in "Advantages and Disadvantages", section 5.3.7.

In the original Magneplane scale model tests conducted in 1973 and 1974 it was discovered that square trough guideways (such as the Japanese configuration) are particularly difficult to deal with due to an inherent yaw instability which causes vehicles to "fishtail", but that a circular trough guideway makes it possible to damp oscillations actively by using the LSM.

5.3.2.2. CONCLUSIONS

In the second-generation Magneplane system (see 1990 patent), active LSM damping is supplemented by active aerodynamic damping in order to further improve ride quality, particularly with respect to roll oscillations in the upper speed range.

Active magnetic damping is necessary and sufficient to prevent catastrophic oscillations. Active aerodynamic damping is probably not necessary for safety, but will substantially enhance ride quality. It would be foolish not to use it. Aerodynamic damping alone without magnetic damping will not suffice.

Thus magnetic and aerodynamic damping are complementary in a manner analogous to shock absorbers enhanced by sway-bars and anti-roll bars in automobiles. Shock absorbers are necessary because only they absorb energy. Sway-bars are not necessary, but enhance ride quality. The two devices are not really the subject of a trade-off.

5.3.2.3. CALCULATIONS

5.3.2.3.a. MAGPLANE RIDE WITHOUT ANY DAMPING AT ALL

Tests done in 1971 to 1975 with a scale model Magneplane system demonstrated in detail what happens without any damping. The dominant oscillation is one which results from coupling between heave and pitch modes, similar to brake-dip in an automobile, but in an ongoing oscillation.

As the vehicle heaves (plunges) downward, its drag increases and its nose pitches down, because the center of drag is below the center of mass, just as in an automobile. When it heaves upward, the nose pitches up. Since the vehicle has mass and the restoring force is elastic, this results in a galloping motion.

This galloping motion can increase to catastrophic amplitude because the LSM can feed energy into it. This occurs because the LSM adjusts the thrust to compensate for the changing drag as it attempts to maintain a constant phase position of the vehicle with respect to the wave travelling at a desired speed. In other words, the coupled heave-pitch oscillation is also coupled to a thrust oscillation, which in turn is driven by the LSM in its attempt to maintain synchronism.

To further complicate matters, sway, yaw and roll oscillations, some at incommensurate frequencies, are also coupled. This results in a corkscrew type of motion reminiscent of a certain famous aircraft with a V-shaped empennage manufactured by one of our team members (the early Beechcraft V-tail Bonanza).

Fortunately the circular trough guideway which is responsible for the universal coupling between oscillation modes, also provides a mechanism for damping these oscillations, as was discovered in 1973.

5.3.2.3.b. MAGPLANE RIDE WITH ACTIVE MAGNETIC DAMPING ONLY

The wayside cycloconverter was modified so that instead of keeping the vehicle at a constant phase position along the travelling wave, it was made to adjust the phase position in response to a signal from an on-board vertical-axis accelerometer: it changed the phase position to oppose any vertical acceleration. Heave amplitude was decreased by a factor of twenty. The galloping motion ceased.

This active damping system also damped other oscillation modes, but not as effectively as it damped the heave-pitch mode. Heave-pitch damping occurs directly through a second-order servo mechanism, one which is sensitive to the second derivative of an error or deviation (an acceleration), while sway-yaw damping or sway-roll damping occurs only indirectly due to coupling between modes. In other words, sway motion is damped only because it couples to heave; the vehicle can't sway without heaving. Roll motion is damped only because it couples to heave; the vehicle can't roll without also heaving, etc.

The active damping mechanism in the heave direction is more than just a damping mechanism which extracts energy from motion. It actually responds to the second derivative of a position signal, i.e., vertical acceleration, even before a vertical deviation has occurred.

The active damping mechanism for sway, yaw and roll, on the other hand, is a zero-order mechanism. It responds only after an actual deviation in position or attitude has occurred, and only because such a deviation is coupled to a vertical displacement. But the coupling is resilient (soft), and therefore the damping is not instantaneous.

The bottom line is that the LSM is able to damp heave motion very effectively, even before it occurs, but it can damp other motions less effectively because it cannot actually oppose them. It can only damp them after they have caused a heave displacement. The LSM magnetic damping mechanism is second-order in heave and pitch, but zero-order in sway, yaw, and roll. Therefore sway yaw and roll damping are not as effective a heave and pitch damping, particularly at high speeds where the resilient coupling limits response time compared to oscillation frequencies.

5.3.2.3.c. MAGPLANE RIDE WITH ACTIVE MAGNETIC AND AERODYNAMIC DAMPING

Aerodynamic control surfaces on bow (canard) and stern (empennage) can supplement the magnetic thrust and heave control by adding sway forces as well as pitch yaw and roll moments - something the LSM cannot do directly. The LSM can only damp these modes after they have caused heave motion.

With additional aerodynamic control surfaces, sway pitch yaw and roll oscillations can be damped directly by a second-order servomechanism responding to acceleration in these modes.

For example, a roll perturbation caused by a cross-wind gust or by passing an opposite-direction magplane can be countered by aileron deflections at bow and stern in direct response to an appropriate accelerometer system, i.e., a second derivative input signal.

Aerodynamic control authority will increase with velocity. Therefore the supplementary control will become more effective when perturbations are more violent and added damping is more important. Active aerodynamic damping is therefore a logical supplement to active magnetic damping by the LSM.

5.3.2.3. PASSENGERS PER VEHICLE

5.3.2.3.1. MOTIVATION

This study aims to determine the optimal number of passengers per vehicle (or vehicle-consist, hereafter called a train), and justify our choice of vehicle sizes.

Large vehicles or long trains of vehicles have the advantage of slightly less aerodynamic drag per passenger than small vehicles. They could also allow higher system capacity, so long as the acceleration/braking rates are the same for all vehicle sizes.

Small single vehicles have the advantage of requiring less installed power, requiring lighter magways, and being easier to handle in magports, in maintenance, etc. Moreover, the dynamic control system for a single body is more tractable than for a series of linked bodies. Also, single vehicles can more easily compete with automobile traffic due to a number of reasons explained elsewhere in this report (see 5.3.7.).

5.3.2.3.2. CONCLUSIONS

Single vehicles were selected over trains. A variety of sizes of vehicle was selected, rather than just one size. The vehicle sizes that appear most appropriate are between 45 and 140 passengers. Magneplane has given concept designs for 45 and 140-passenger vehicles, although any size in between is equally possible.

A cost-based comparison is given in the "calculations" section below. But this trade was not driven by cost alone. Important operational considerations are also given.

The tradeoff of vehicle size was made early in the concept design phase, before detailed cost information was available. It was made on the following basis:

- The vehicle dynamic control system for a single body is less complex than for a series of linked bodies. In fact, oscillation damping in an EDS system with linked vehicles may be prohibitively complex and expensive.
- A central feature of the Magneplane system is dynamically scheduled service resembling the flow of highway traffic (rather than train-type service), which can compete with the automobile. So low-capacity vehicles would be required to service passengers without stopping large numbers of passengers at each stop.

Number of vehicles in train	**1**	**1**	**2**	**4**	**10**
Size of vehicle(s)	45	140	140	140	140
Number of seats in train	45	140	280	560	1,400
Aerodynamic drag factor per train (normalized)	0.79	1.00	1.66	3.12	7.40
Aerodynamic drag factor per passenger	.0186	.0071	.0059	.0056	.0053 (limit)
Aerodynamic drag factor per passenger (normalized)	262%	100%	83%	78%	74% (limit)
Fraction of total drag that is aerodynamic at 134 m/s	65%	54%	54%	54%	54%
Total drag factor per passenger (normalized)	205%	100%	91%	88%	86% (limit)

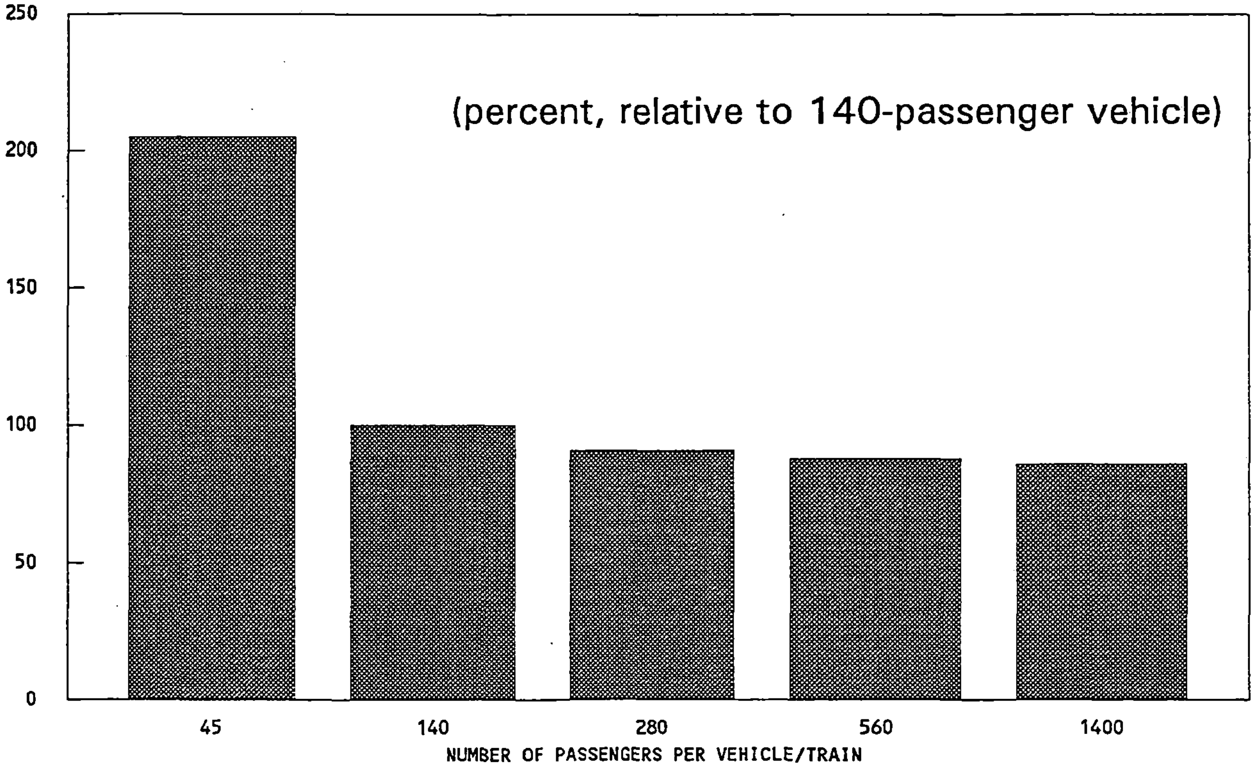


Figure 4 Energy costs shown for different vehicle sizes

- Vehicles should not be so small that the fixed cost of the vehicle drives the per-passenger costs high.

- Based on the projected need for a capacity of 25,000 passengers per hour, Magneplane was designed for 20 s headways with 140-passenger vehicles. (140 pas / 20 s = 25,200 pas/hr). The goal of 12,000 passengers per hour, which is given in the Statement of Work, is met by using large vehicles at 40 s headways.

- A smaller vehicle is needed to allow more frequent service when there are not enough passengers to warrant a 140-passenger vehicle. A size of 45 passengers was selected for this purpose. Running a 45-passenger vehicle is more expensive per passenger than running a 140-passenger vehicle, but a small vehicle is less expensive than a large vehicle if there are only 45 passengers aboard each one. (Also note that less installed power is required if a corridor has *only* 45-passenger vehicles).

5.3.2.3.3. CALCULATIONS

This section contains more detailed information comparing vehicle/train sizes. The following categories are detailed:

energy costs
power systems capital costs
magway capital costs
other costs
systems operations factors

The most significant of these categories is the last one, systems operations factors. Some of the costs are significant, but they are not viewed as drivers of fundamental design decisions in this particular tradeoff.

5.3.2.3.3.1. ENERGY COSTS

Energy costs are not a significant factor in this tradeoff, as is shown below. Figure 4 shows the calculations of energy costs.

The **aerodynamic drag factor per train** was calculated by summing the drag induced by each of the surfaces of the first vehicle with a partial drag for all the other vehicles. The partial drag included all surfaces except the frontal area. This rough calculation could change by a few percent depending on how the coupling of vehicles was designed.

The **aerodynamic drag factor per passenger** is the aerodynamic drag factor per train divided by the number of seats per train. In the next row this is normalized for the single 140-passenger vehicle.

The **total drag factor per passenger** was calculated at 134 m/s, when aerodynamic drag accounts for 54% of total drag (65% for the small vehicle). Other components of total drag are assumed to remain constant while the aerodynamic portion decreases.

Number of vehicles in train	1	1	2	4	10
Size of vehicle(s)	45	140	140	140	140
Total train mass (kg)	25,000	50,000	100,000	200,000	500,000
Power usage factor according to acceleration and grade (normalized)	0.5	1.0	2.0	4.0	10.0
Aerodynamic drag factor per train	0.79	1.00	1.66	3.12	7.40
Fraction of total drag that is aerodynamic at 134 m/s	65%	54%	49%	48%	46%
Total drag factor per train (normalized)	0.66	1.00	1.81	3.52	8.60
Power capacity according to drag (MW)	3.96	6.00	10.9	21.1	51.6
Power systems cost according to drag (M$/block)	3.40	3.60	4.09	5.11	8.16

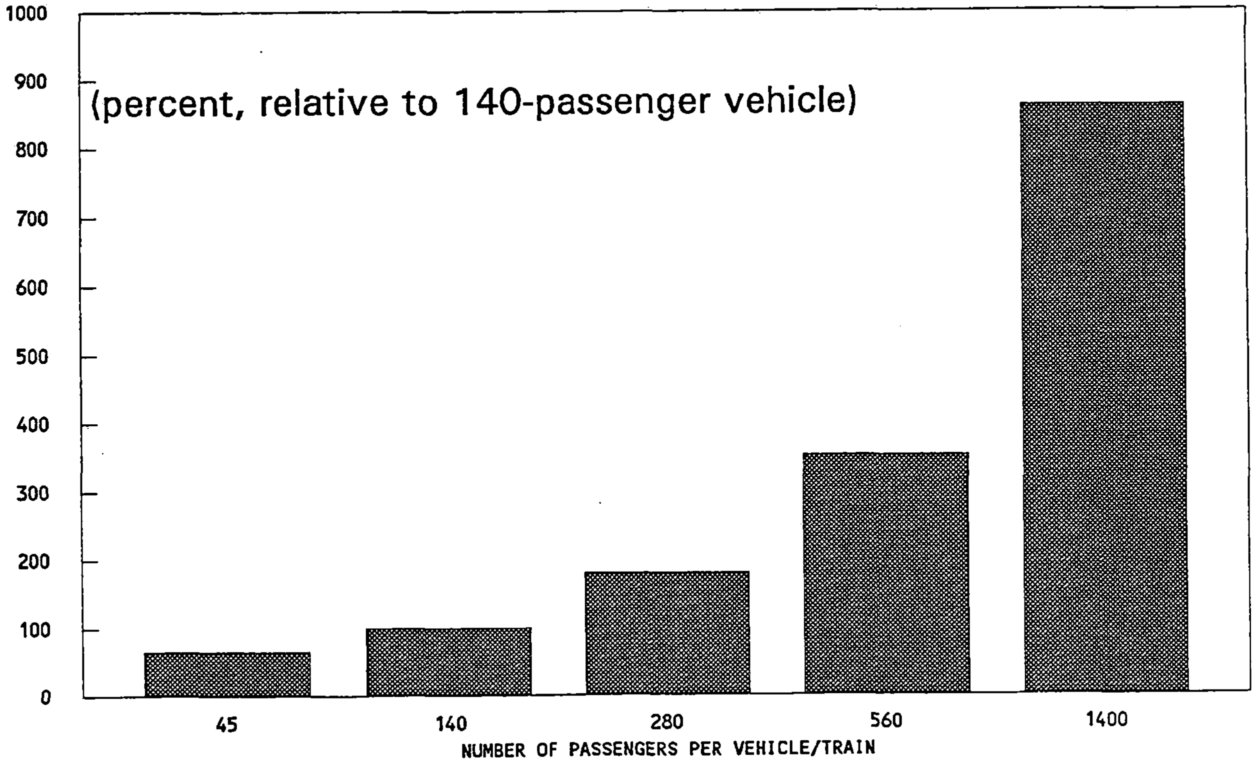


Figure 5 Power requirement shown for different vehicle sizes

Number of vehicles in train	1	1	2	4	10
Size of vehicle(s)	45	140	140	140	140
Total train mass (kg)	25,000	50,000	100,000	200,000	500,000
Weight per span factor	50%	100%	200%	200%	200% (limit)
Magway cost factor	75%	100%	140%	140%	140% (limit)

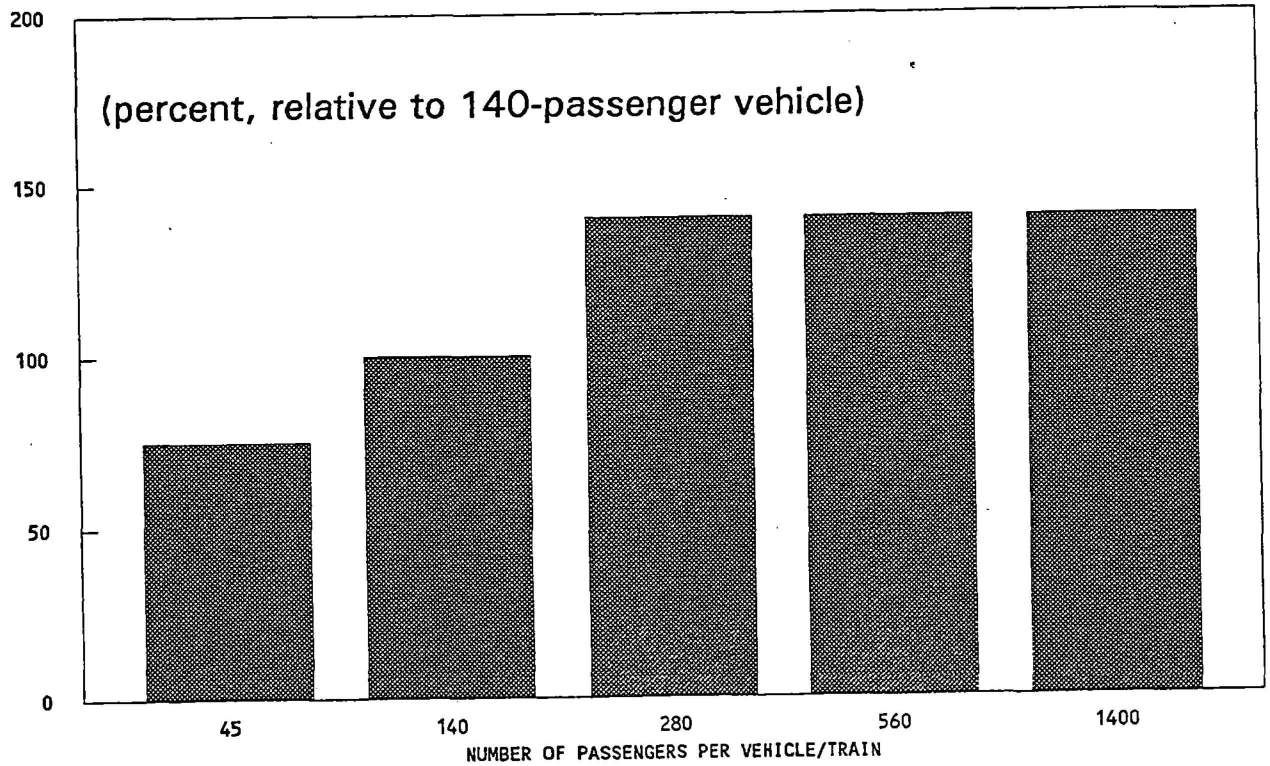


Figure 6 Magway capital cost shown for different vehicle sizes

The energy usage is proportional to the total drag factor per passenger for systems having the same passenger throughput. In other words, trains of 10 or more vehicles would use 86% of the energy (per passenger) of single vehicles at 134 m/s.

Since the average velocity is always less than 134 m/s, the savings is in practice not even this great. Average velocity is estimated at 110 m/s for Eastern US routes. The energy consumption for trains is about **91%** of that for single vehicles for operation at 110 m/s, on a per-passenger basis. Energy accounts for a minority of operating costs, and a small minority of life cycle costs (see 5.3.11.). In conclusion, a 9% savings in energy is not a large consideration in the choice of single versus multiple-vehicle consists.

5.3.2.3.3.2. POWER SYSTEMS CAPITAL COSTS

The capital cost of the power systems is a significant factor in this tradeoff. Figure 5 show the calculations to support this.

Power is used for three purposes: to overcome drag and maintain a constant speed, to accelerate, and to climb the grade. While the power required to accelerate and climb the grade is proportional to the mass of the vehicle/train, the power required to overcome drag is proportional to the drag of the vehicle/train. The exact proportion of installed power capacity required for each of these purposes depends on the route. For a straight route with zero grade and no curves, 100% of the power is used to overcome drag while at cruising speed. For very curvy hilly routes with constant changes in speed, a majority of the power capacity may be needed for acceleration and grades.

The **power usage factor according to acceleration and grade** is proportional to the mass of the vehicle/train. It is the extra power needed to accelerate the extra mass, normalized to the single 140-passenger vehicle. These values represent extreme limits.

The **power usage factor according to drag** is the extra power needed to overcome any extra drag associated with the vehicle/train, normalized to the single 140-passenger vehicle. These values represent a conservative "straight route" configuration. Actual values will be somewhere between the power usage factor according to acceleration and according to drag.

The **power capacity according to drag** assumes that 6 MW is required on average for a single 140-passenger vehicle. The row shows the power usage factor according to drag multiplied by 6 MW.

The **power system cost according to drag** is the cost of the power equipment as rated in the previous row. The cost is assumed to be $3M plus $0.10/W for the purposes of this study.

The table shows that there is a significant cost advantage in limiting the train size to two vehicles or less. As this only shows the cost according to drag, the actual costs for longer trains is even more than shown, depending on the route layout.

5.3.2.3.3.3. MAGWAY CAPITAL COSTS

Magway capital costs are a significant factor in this tradeoff. Figure 6 shows estimated costs of different vehicle sizes and train lengths.

Single Vehicles	Trains
Single-body dynamic control system is feasible.	Dynamic control system may be complex, expensive, and impossible to develop for multiple interacting bodies.
Stations can be distributed over a metropolitan area. (2 dimensional) *	Stations can only be along a single corridor. (1 dimensional) *
Feasible small off-line stations.	Off-line stations would be large and may be prohibitively expensive.
Vehicles can turn around quickly in a small area.	Impossible to turn around in normal daily operation.
Vehicle can leave a station in any direction because they can turn around.	Train must leave station in the direction it is headed, or be designed to be bi-directional.
No backward-facing seats.	Some seats in a bi-directional train would face backwards, or else they must be reversible.
Fewer stops between origin and destination. (*)	More stops between origin and destination. (*)
Greater average speed.	Lower average speed.
Less waiting time for pick-up due to dynamic scheduling and lower headways.	More waiting time for pick-up.
Can be dynamically scheduled to respond to instantaneous needs. (*)	Operates only in accordance with projected needs, or else schedule changes must be effected. (*)
More competitive with the automobile due to service qualities and points of access. (*)	Less competitive with the automobile. (*)
Even power distribution.	Highly uneven power distribution.
Can make up a higher fraction of a typical intercity trip.	Requires significant use of other forms of transportation to make up a typical intercity trip (car or bus).

Figure 7 Operational comparison of single vs multi-vehicle consists

The **magway cost factor** is an estimate of the extra cost of magway that can support the extra weight of a train. In Magneplane's single-vehicle concept, only one bogie is on a span at a time. If two or more vehicles are coupled, two bogies (but never more) would be on a span.

This table shows that trains of any length incur a significant cost over single vehicles.

5.3.2.3.3.4. OTHER COST FACTORS

Other cost factors not included above are also significant in this tradeoff. For example:

- dynamic scheduling gives the ability to transport only the number of seats as there are passengers, and this could result in a higher average load. Dynamic scheduling is more feasible with smaller vehicle sizes.
- the fact that single vehicles would allow non-stop service more often than trains indicates a great savings in power required to accelerate out of magports.

5.3.2.3.3.5. SYSTEM OPERATIONS FACTORS

Figure 7 lists some benefits of single vehicles over trains that are related to system operation. Items marked with (*) are explained here:

* Magneplane's off-line magports can be located at a considerable distance from the main corridor, which allows the system to serve an *area* rather than just a *line.*

* Single vehicles would stop fewer times between any passenger's origin and destination because people going to the same place would be assigned to the same vehicle, and the control system would minimize the total number of different destinations of passengers aboard any one vehicle.

* The more seats in a consist, the more essential it is to have a fixed schedule. The maximum number of seats-per-consist for which dynamic scheduling is still possible is a function of ridership patterns.

* The reason single vehicles are more competitive with the automobile is that they behave more *like* an automobile. They take you *from* your origin *to* your destination *whenever* you want to go. Long trains, on the other hand, take you from a hub to a hub on a schedule. Although the two methods may both get you there equally fast, the difference in **actual or perceived convenience** will determine many people's choice of whether to drive or take maglev. Single vehicles could therefore displace automobile usage much more effectively than long trains can.

These reasons are primary in Magneplane's decision to use single vehicles. Of course cost was also considered in choosing the particular sizes of vehicles.

We repeat the two most important items relevant to this discussion:

(1) Single vehicles are within the realm of a dynamic control system, which is a requirement for EDS vehicles. Magneplane does not couple vehicles physically for the same reason that airplanes are not chained together to increase the capacity of the air.

(2) Single vehicles can compete with the 90% of passenger traffic that currently uses the automobile, while trains (if pre-scheduled and stopping at hubs only) can only compete with the other 10%.

5.3.2.4. SERVICE METHOD

5.3.2.4.1. MOTIVATION

An overall approach and method of servicing the demand for travel must be evolved. The question is to determine the relationships and appropriate balance among these factors:

- *number of stops per trip*
- *density of magports*
- *service time*
- *number, size, and load of magplanes*

This tradeoff analysis only introduces the topic, and gives one example route with a suggested service method. It does not solve the problem for every possible case, as each route has different characteristics that must be taken into account.

The principal driving variables are the system cost and the convenience for passengers.

Please consider this argument: Assume that every magplane stops at every magport. (Alternatives to this strategy are introduced below.) If the density of magports is sufficiently high to call the system "conveniently accessible", then the trip time will be slow because of all the stops. If the density of magports is sufficiently low to call the system "fast", then it will not be conveniently accessible. Therefore a system in which every magplane stops at every magport cannot be both "conveniently accessible" and "fast".

We wish to create a system that is both conveniently accessible and fast. So, we cannot have a system in which every magplane stops at every magport. Another solution needs to be developed.

5.3.2.4.2. CONCLUSIONS

Alternatives to all-stop "basic service" (introduced above) are local/express scheduling, multiple express scheduling, and dynamic scheduling.

Local/express scheduling is done on many subways (for example New York and Philadelphia). Most stations are only served by local trains, and some are served by both local and express. We will not use this type of service because it requires that most passengers change vehicles at least once per trip.

Multiple express scheduling is exemplified by the suburban train service in Paris. Every train is an "express" train that makes only a handful of stops on the whole route. But every train has a different permutation of stops. When you arrive at the platform, you refer to a huge chart on the wall which lists each individual train for the whole day, and all of the stops that it will make. You scan down the column of your destination and find the train number of the next train that will stop at your destination. (It is sometimes possible to find a series of two trains that will get you there faster.) You may then have to wait for several trains to go by, but ultimately it is a lot faster than "basic service".

Dynamic scheduling works in a similar way, but the timetable is only built a few minutes or an hour in advance of the current time. Dynamic scheduling is responsive to each individual passenger.

Both multiple express scheduling and dynamic scheduling are adequate methods for Magneplane. We choose dynamic scheduling because it is more convenient and efficient, as it is optimized to current conditions rather than just to general conditions. (The system in Paris cannot use dynamic scheduling because they do not have off-line stops. They have to have a precisely engineered timetable while Magneplane's off line magports can accommodate loading delays and unforeseen service of groups.)

5.3.2.4.3. CALCULATIONS

For the following analysis, it is sufficient to use multiple express scheduling. The objective of the analysis is to find out, for any particular placement of magports and passenger demand, how many and what size of vehicles are needed to insure timely and fast service.

First it is necessary to define the corridor. Taking the Boston-Washington Amtrak corridor as a base, which has 18 stations in about 480 km, we find that a reasonable magport density is one per 25 km. With that density, a great majority of people who live within 25 km of the corridor live within 15 km of a magport. By the way, Amtrak does not actually serve all those stations very frequently, but we would like to.

Assume that the average cruising speed is 120 m/s. (As a reminder: our red-line speed is 150; top cruising speed is 134; average cruising is often about 120; and average non-stop optimized trip speed is often about 110.) One of the requirements of the Magneplane system is that it is competitive with airplane travel in terms of trip time. So, it is necessary to determine a minimum required average trip speed, which should be better than airplane service. For an estimate, assume that this is 80 m/s, or two-thirds of the average cruising speed. The Magneplane trip time would be one hour for a 300 km trip. A trip of the same distance in an airplane takes about an hour including loading. Grand total trip times for Magneplane would be less than airplanes at that distance because magport densities are greater than airport densities.

Here is an example to clarify the 80 m/s requirement. Suppose you get on a magplane in Boston headed for New York and time your whole trip including any stops until you arrive in New York. The total distance divided by that total time should be 80 m/s or more. During just the travel time, the vehicle would be averaging 110 m/s. During just the cruising time (excluding time spent slowing down for a stop or speeding up after a stop) the magplane would be averaging 120 m/s, reaching a peak of 134 m/s at some points.

Keeping these speeds in mind, it is now possible to determine the acceptable number of stops per unit distance. Assume that each stop "costs" 500 s (8.3 minutes) including the time lost while slowing down, standing, and speeding up. Now find the distance *b* for which the time spent traversing the distance at full speed with one stop is equal to the time spent traversing the distance at two-thirds speed. The algebra works out as follows:

$$\frac{b}{120m/s}+500s=\frac{b}{80m/s}$$

$$\frac{120b-80b}{120\times80}=500$$

$$0.00417b=500$$

$$b\approx120km$$

A vehicle travelling at an average of 120 m/s that stops every 120 km exhibits a trip average velocity of the required minimum 80 m/s. Therefore, it is permissible to stop once every fifth magport (round up to 125 km).

Now a non-optimized scheduling system working under the above parameters is described. Using the multiple express method of scheduling, every vehicle stops at exactly one magport in each consecutive group of five magports. Therefore every fifth vehicle (on average) stops at any particular magport. The pattern of stops is as irregular as possible. If vehicles run on the main corridor at 20 s intervals, then a vehicle leaves each magport at 100 s intervals. A particular passenger waiting at magport A wishing to get to magport B would have to wait never more than 500 s (8.3 min), since one of the next five vehicles leaving magport A would be planning to stop at magport B.

Moving now to s system of dynamic scheduling, several other assumptions have to be made. First, how far are people actually going? There are ten magports that belong to a set of two 125 km segments of corridor. Since a magplane is allowed to stop once in each of the two segments, assume that every complete trip is a non-stop ride from one of the first five magports to one of the second five. Passengers who are travelling farther than this will be ignored for now, as they won't disrupt the pattern of stops to be established in this analysis. Assume that each passenger is independent and each is equally likely to show up at any of the first five magports and equally likely to want to go to any of the second five. One measure of the average distance travelled is from the middle of the first set of five to the middle of the second set of five, which is 125 km. Again, the average trip speed including stops is 80 m/s. Assume that half of the cost of stopping is taken up by the origin and half by the destination. Therefore, the average trip time is 1563 s (26 min).

Now define a "service cycle" as a conceptual way to divide up the day into service blocks. In fact, the service cycle varies in time for each vehicle and all vehicles' cycles overlap. But for this analysis, assume that a service cycle consists of:

1. Passengers arrive at magports in a constant stream for a period of 26 min. (This happens while the previous cycle is in transit.)
2. Vehicles arrive at magports in a distribution which is sufficient to pick up some fraction of the waiting passengers.
3. Vehicles deliver all passengers to their destinations in a period of 26 min.

Referring to step 2, "some fraction of passengers", it is necessary to define the allowed flexibility of departure time. The ticketing/scheduling system will try to obtain the greatest average load per magplane trip. If this was the only factor (high flexibility), then no magplane would leave until it is full. Passengers may have to wait a long time for this to happen. On the other hand, if the allowed flexibility is too low (say 5 minutes), the system would require an enormous number of vehicles operating at a low average load in order to service everyone that quickly.

In order to make a good assumption of what flexibility of departure time would be an appropriate compromise between cost and convenience, take a look at a some real world examples. Suppose first that I plan a trip to another city well in advance. I might find out hours in advance exactly when my magplane will be leaving (assuming that enough other people have also planned in advance). No problem there. But suppose I find out at the last moment that I have to leave for another city as soon as possible. In this case, I would call Magneplane and order a ticket, saying that I could be there at 9:00 at the earliest. How acceptable, then, is a delay of another half-hour or hour - if they could tell me what the delay would be before I leave home?

Assume that the flexibility of departure time is 45 minutes. (For commuters, this is too long, but there are generally enough commuters in any one place to make more frequent service possible.) This 45 minutes means that the scheduling system has a 45-minute window for each passenger to create the optimal loading and routing. The details of such an algorithm are beyond the scope of the contract. If the system could not service a passenger efficiently in that time window, it would service her or him inefficiently - that is, in a vehicle with low load. The 45-minute figure does not mean that anyone will be waiting on a platform for that long. Also note that passengers could possible pay more to shorten their window of flexibility.

Since the service cycle is 26 minutes and the flexibility of departure time is 45 minutes, the fraction of passengers to be picked up in any one cycle is the quotient of these, or 58%. So, if 100 people arrive at a magport in a service cycle, 58 will be served in that cycle.

As promised, the number and mix of vehicles will be determined. These values are based on the all of the above considerations and the passenger demand. For the first round, assume that the passenger throughput is 12,000 passengers per hour each direction. 12,000 passengers will leave the 125 km segment going East every hour. (The same number will leave to the West.) Therefore 2,400 passengers heading East arrive at each magport every hour, or one person every 1.5 s. In one service cycle, this is 1,040 passengers. If 58% of them must be serviced, that is 603 passengers serviced per cycle per magport. Those 603 are necessarily going to one of the five magports in the 125 km segment to the East. For this analysis, ignore those who are going to another magport in the same segment. Those going farther than one segment away are included, because their magplane will stop in the adjacent segment and continue on (as was established by the rule of the average trip speed being two-thirds of the average cruising speed).

Since 603 passengers are going to one of five destinations, or intermediate destinations, there are 121 passengers going to each, all of which must be serviced. For them, one could use a large vehicle operating at 121/140 = 86% average load. This is probably acceptable, judging from the fact that airplanes can make a profit at only 33% load. Magneplane could also use lighter 45-passenger vehicles when there are 45 or fewer passengers needing service to one destination. The number 121 is only an average, so the average vehicle size should be 121. Refer to the Hypothetical Route Report ("Determining Vehicle Mix") for a discussion on how to determine the appropriate number of vehicles and size mix.

5.3.2.5. TAKE-OFF VELOCITY

5.3.2.5.1. MOTIVATION

The Magneplane system attains full magnetic levitation at some velocity, the take-off velocity. Below that point, some or all of the weight of the vehicle must be supported by the landing gear, and above that point, all the weight is supported by magnetic lift.

The point at which full magnetic levitation is achieved is controllable by varying the height of the vehicle on its landing gear. In other words, the take-off velocity is not absolutely fixed, but can be decided somewhat independently in light of optimizing several factors.

Mechanical lift (ie landing gear) is at the expense of mechanical drag, which is the same for all speeds. Magnetic lift is at the expense of magnetic drag, which is higher at low speeds.

There is a natural magnetic lift height for all speeds. At zero speed, there can be no magnetic lift. At low speeds, the natural lift height is low (and the drag is high). At high speeds, the natural lift height is up to a clearance between the vehicle skin and the magway surface of 0.15 m (and the drag is low).

A tradeoff study is needed to determine the appropriate velocity at which to retract the landing gear and rely solely on electromagnetic lift. This would probably be the same velocity at which to extend the landing gear in deceleration.

The velocity chosen by this analysis would not be a sharp line, but it would be a transition range, during which the vehicle would settle from the landing gear height to the natural magnetic lift height. (Yes, the height would go *down* during take-off.)

5.3.2.5.2. CONCLUSIONS

No numerical study has been done due to the lack of data. In particular, there are no data on the lifetime, costs, and operating velocities of the landing gear.

The advantage of choosing a high-speed transition point is in operating energy savings. If the landing gear extends the vehicle above the natural magnetic lift height for speeds up to about 60 m/s, there is a savings in energy due to the fact that the mechanical drag from the landing gear is less than the electromagnetic drag. Electromagnetic drag would be almost eliminated because of the mechanical separation distance between the levitation coils and the magway levitation sheet.

The advantage of choosing a low-speed transition point is in the cost and lifetime of the landing gear and potentially in ride quality. The expense of building a landing gear that is capable of normally handling speeds of 60 m/s or more may be unjustifiable. Testing is needed in this area.

For information about the drag associated with the different types of levitation, see the Concept Definition Report section 3.2.1.b.

Based on our best understanding of these issues, we have proceeded using an estimated optimal range of 30-50 m/s for the take-off velocity. At 30 m/s, some weight will be taken off the landing gear by magnetic lift; by 50 m/s, the gear will lose contact with the magway surface. For more details, see section 3.2.3.i.. There will be a significant reduction in height and increase in drag during the take-off procedure, but the ride quality will no doubt be better after take-off and the landing gear pads will last longer than they would for a 60 m/s take-off.

5.3.2.6. LANDING GEAR OPTIONS

5.3.2.6.1. MOTIVATION

On the basis of 30 years of experience with aircraft operations, Henry Kolm, inventor of the concept under study, is of the opinion that the maintenance of landing gear tires, bearings and brakes represents a substantial expense which is inevitable in airline operations, but which must be avoided in maglev operations if at all possible. Charles Haldeman and Michael Judd, aeronautical engineers at Lincoln Laboratory, concur with this opinion. So do key engineers at Beech Aircraft Corporation.

During WW-2, when aircraft of significant performance were first used on an operational basis, tires were found to be a severe maintenance problem. DC-3 (C-49) tires, for instance, survived only about 100 landings on paved runways. Larger tires of higher moment of inertia survived even fewer landings. Two solutions to the problem were tried:

> Landing on grass next to paved runways extended life several-fold, but was not always possible.
>
> Pre-rotating the wheels prior to landing with turbine disks proved disastrous. Tires become severely unbalanced after only a few landings, and pre-rotation caused destructive vibrations.

After WW-2, aircraft tires became smaller to reduce the moment of inertia, but increased tire life was soon consumed by heavier aircraft and higher landing speeds. Severe demands were also placed on tires, bearings and brakes.

A landing gear closely matching the performance requirements and space availability of a Magneplane is that installed on several Beechcraft turboprops, such as the Super King-Air model C-120 corporate aircraft. Each of four main-gear wheels, of which Magneplanes would need sixteen, is equipped with dual disks clamped by six hydraulic calipers and surrounded by a compressed air cooling manifold ring fed by turbine compressor air. These brakes are marginally capable of absorbing energy from a normal 60 m/s (120-knot) stop, assisted by reversible-pitch propellers. Failure is common, and typical repair cost is $15,000 per wheel.

It is obvious to an expert that brakes and tires capable of absorbing four times as much energy from a 134 m/s emergency stop are beyond the existing art for commercial vehicle service, would require major development, and would be substantially larger and heavier than currently available aircraft components.

Therefore some alternative is needed.

5.3.2.6.2. CONCLUSIONS

The use of skids instead of wheels is considered an integral part of the concept being defined. The choice is obvious to an expert inventor, though possibly not to a layman. Justification of every concept element by quantitative comparison with all conceivable alternatives is clearly beyond the scope of a concept definition study by reason of absurdity.

It is logical to use a combination of air-lubricated anti-friction skids for normal operations below levitation speed, and high-friction pads for emergency deceleration. Braking energy would be dissipated in a volume of aluminum very much larger than brake disks.

Low friction materials have coefficients of 0.05, and high-friction materials have coefficients of 0.65. The low-friction materials could thus operate safely even in the event air lubrication fails, and the high friction materials provide adequate deceleration for emergency requirements. The skids consume very much less space than wheels, and mechanism for extension and retraction does not present any unusual engineering problem. It has to be capable of operating rapidly, and of lifting the vehicle to several cm above levitation height in the event emergency deceleration is required.

Both low friction and high friction materials have been tested, although not under conditions resembling the conditions in question. Tests need to be performed in which the materials are dragged at 150 m/s over cold 6061 aluminum with various surface treatments, with speed, pressure and travel distance as the variable parameters. Wear and service life are the parameters to be measured. Variations in composition should also be explored.

5.3.2.7. REINFORCING MATERIALS PLACEMENT

5.3.2.7.1. MOTIVATION

The use of steel reinforcement bars (rebar) near the magway represent a typical construction technique, however, they may cause interactions which are not beneficial to the vehicle. In particular, the levitation coils are attracted to the rebar, thus potentially altering the lift.

5.3.2.7.2. CONCLUSIONS

To gain insight into these effects, a quadrupole levitation module was modelled at zero speed at various distances from layers of rebar. This is the conservative case, since, at high speeds, the rebar is shielded by the eddy currents induced in the magway sheets. However, it is realistic because the vehicle must be capable of stopping anywhere.

Rebar should be placed no closer than 0.5 m from the magway sheet, according to this analysis.

5.3.2.7.3. CALCULATIONS

Figure 8 assumes symmetry relative to the X=0 plane and shows a section through one of the two coils in a quadrupole levitation module, together with the field lines that result from its interaction with four layers of rebar beneath it. Each magnetically permeable plane beneath the coils represents a rebar mesh of 0.01 m diameter steel bar in a square grid with 0.1 m center to center distances between bars.

The computed attractive force between the module and the steel is shown in Figure 9 for one, and for four layers of rebar, as a function of distance between the plane of the module and the first layer of rebar. The force is normalized to $\mu_0 I_v^2$, where I_v is the amp-turns in one coil in the module and, for example, has a value of about -0.02 for a separation distance of 0.5 m. Our lift computations for the module are typically normalized in this same fashion and the corresponding value for Magneplane is 1.9. Hence, for a 0.5 m separation, the effect of the rebar is -0.02/1.9 or about 1% of the lift. As a result, we have restricted the use of rebar in our preliminary evaluation of magway construction concepts to be more than 0.5 m from the surface of the magway sheet. A more detailed evaluation of this type of interaction will be necessary at a later design stage, when the form and location of steel reinforcing materials are better defined, if they are used.

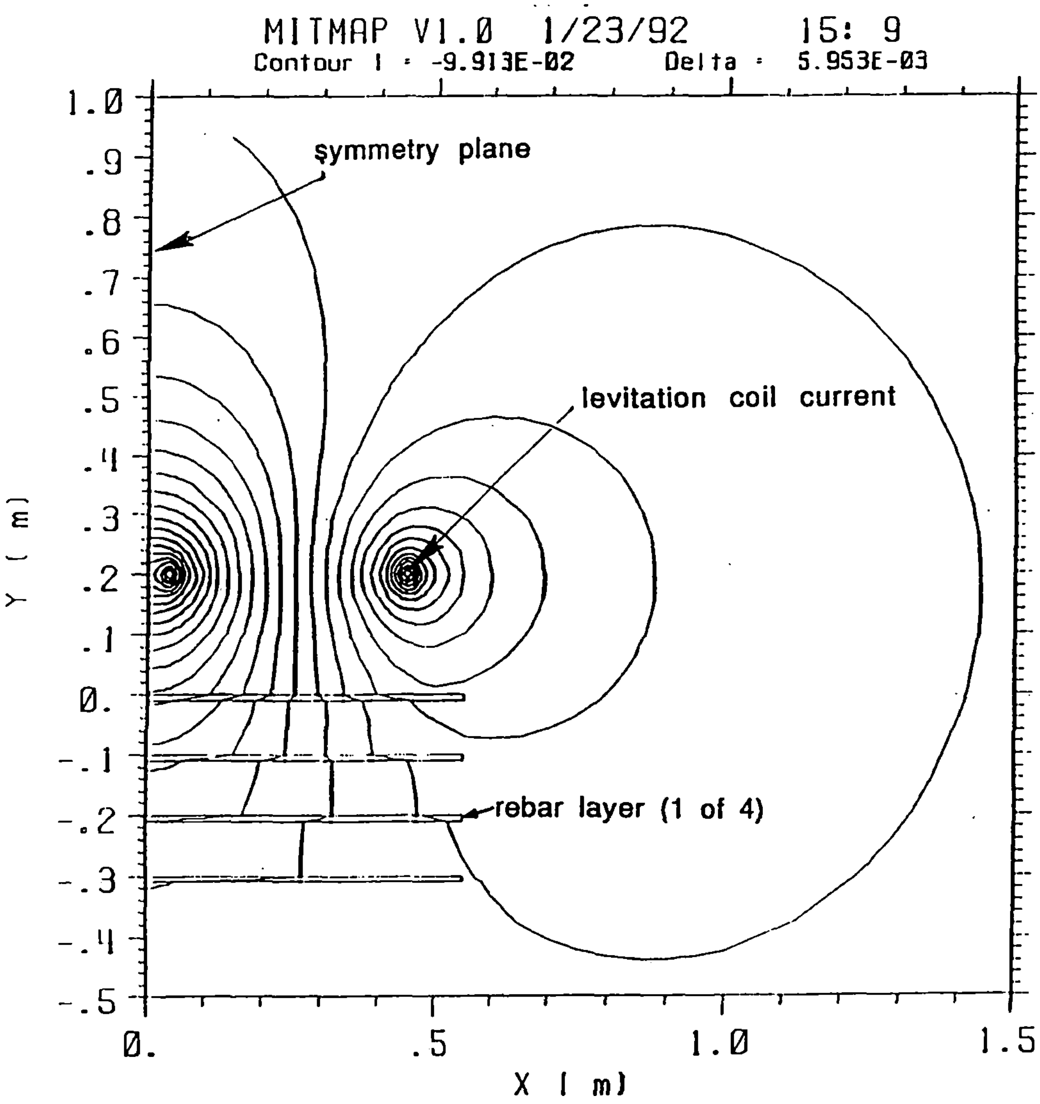


Figure 8 Field lines with levitation module and rebar

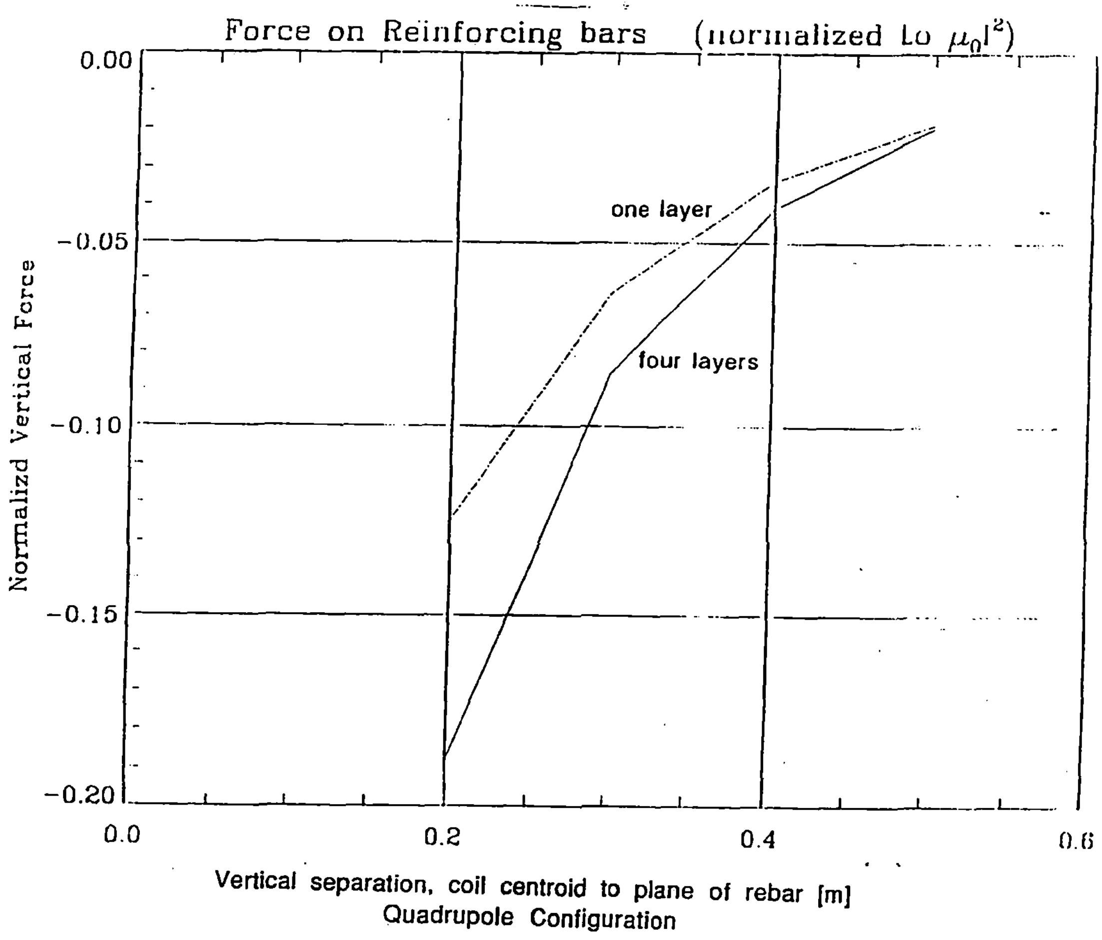


Figure 9 Force on reinforcing bars

5.3.2.8. SUPERCONDUCTING COIL CHARGING PROCEDURE

5.3.2.8.1. MOTIVATION

A method must be developed for charging the superconducting magnets. This procedure will be used when a vehicle is first put into service after maintenance. The charge does not need to be reapplied while in operation.

5.3.2.8.2. CONCLUSIONS

The method described in this section is considered proprietary. Our method (see method C below) will allow superconducting coil systems used for levitation, propulsion or guidance on maglev vehicles to be charged to their operating current level without the use of current leads passing into the cryogenic vessel to the coil at low temperature from the power supply at ambient temperature. This would alleviate one of the major sources of heat load into the cryogenic vessel containing the coil system. It would also reduce the overall size of the coil/cryogenic container envelope, simplify its mounting to the vehicle, increase reliability, and allow coil charging, discharging, & recharging to be more automated for maintenance personnel.

5.3.2.8.3. CALCULATIONS

Figure 10 is a schematic illustrating two relatively standard methods for charging a superconducting coil system, as well as the method proposed in this section for use in maglev applications.

5.3.2.8.3.1. METHOD A (STANDARD): PERMANENT CURRENT LEADS ATTACHED

In method A, the superconducting coil is located within its cryogenic container or cryostat and connected to a power supply outside the cryostat via a pair of current leads passing through the cryostat boundary. These current leads are usually specially designed to reduce thermal conduction along the leads from ambient conditions into the cryostat because each watt of heat load into the cryostat represents a significant power requirement for the refrigeration or liquefaction system supplying the cryogen for the coil system. Alternately, in an "open" cryogenic system, a significant volume of liquid cryogen would have to be carried to support the heat load for this part of the total requirement for the length of the mission. For example, a well designed pair of current leads will still produce a heat load of about 2 watts to the cryogen per thousand amps of current carrying capacity per lead pair. The power required by a refrigerator to support this part of the total heat load at low temperature is about 2 KW.

The persistent switch shown is optional for a maglev system, in that one may choose to have none, charge the coil system with the power supply, and leave the power supply connected and "on" throughout operation. This is unlikely, however. A more likely scenario would involve a persistent switch as in methods A & B.

The persistent switch is typically a length of superconducting wire (possibly in coil form) connected across the terminals of the coil and located within the cryostat. It also has a heater which can be activated through relatively small current leads which pass through the cryostat boundary to a small power supply outside. To charge the main superconducting coil system, the switch on the main power supply is left open while the heater power supply on the persistent switch is activated to a current level that raises the heater output until the persistent switch superconducting wire is above its critical temperature so that it is not superconducting. The level of resistance in the persistent switch at this point is selected when it is designed so as to be consistent with the desired charging vs time scenario. The main power supply switch is now closed and the main power supply current raised to the desired operating current level. The heater power supply is then turned off and the persistent switch is designed to allow the temperature of its wire to drop back below its critical temperature so that it is again superconducting. The current from the main coil power supply may now be turned down to zero without significant change to the current flowing through the superconducting coil because it is short circuited by the superconducting wire in the persistent switch. The current in the circuit will decay over time depending on the inductance of the circuit and resistance (typically, only the resistance of the joints is significant and can be made quite small, that is, of the order of 1e-9 ohms, thus yielding a very long current decay time constant.

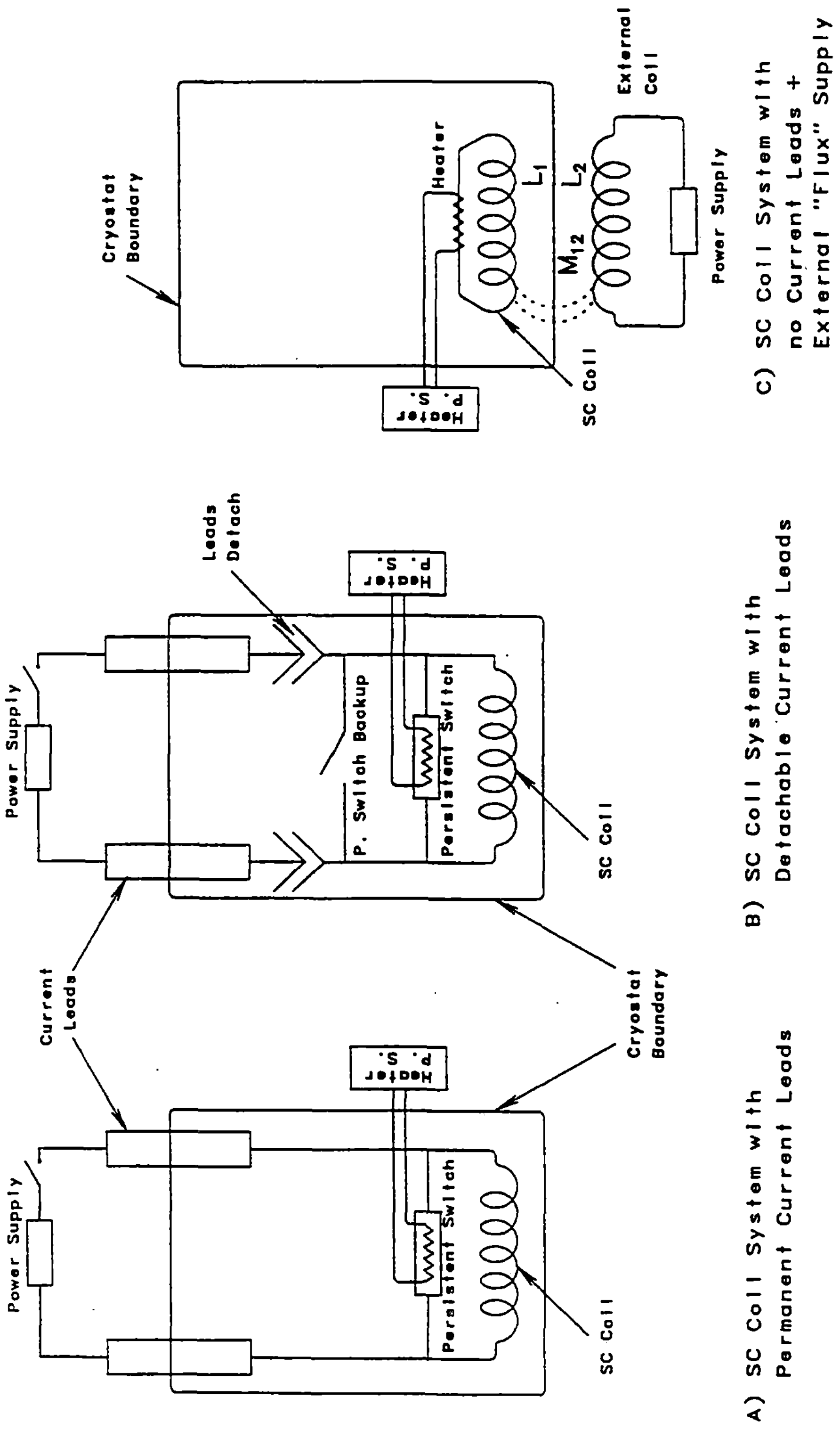
5.3.2.8.3.2. METHOD B (STANDARD): DETACHABLE CURRENT LEADS

The approach schematically shown in B is operationally identical to that in method A for charging the superconducting coil when the leads are connected to the coil. However, two additional features are shown in the schematic.

A back-up switch for the persistent switch is shown for reliability purposes (and may be used in any of the options). This may be another switch of the same type or a switch which is closed mechanically and has a high resistance so that it does not interfere with persistent switch operation, but provides protection for coil overvoltage in the event the persistent switch fails open while the coil is charged.

The other, more significant, feature is that the current leads are made to be detached after coil charging, persistent switch closure (transition to superconducting state) and main power supply turn-off. This requires complex mechanical connections within the cryostat that can be detached from outside and that can allow complete removal of the leads or moving them far enough to significantly reduce the heat transfer down the leads into the cold cryostat. In this way, the heat load during coil operation can be reduced, but the lead detachment and retraction process increases maintenance complexity for the system, increases cost, and reduces reliability.

The approach described for method A & B above has been demonstrated in laboratory and commercial systems.



A) SC Coil System with Permanent Current Leads

B) SC Coil System with Detachable Current Leads

C) SC Coil System with no Current Leads + External "Flux" Supply

Figure 10 Schematic of three options for charging the superconducting coils

]

5.3.2.8.3.3. METHOD C (PROPRIETARY): NO CURRENT LEADS & EXTERNAL FLUX SUPPLY (A TYPE OF TRANSFORMER)

The approach in method C is the baseline approach for this system and has no current leads coming through the cryostat boundary from the main superconducting coil or circuit. The terminals of the superconducting coil are connected together (short circuited) within the cryostat, but a length of the wire in the coil has a heater in close proximity to it. Outside the cryostat, another coil system, which may be conventional or superconducting, is brought near the superconducting coil. Both coils are assumed to be initially uncharged or in a zero current condition.

The current from the heater power supply is increased until the temperature of the main coil superconducting wire near the heater is above its critical temperature and, therefore, resistive. This becomes a resistance in series with the main coil. The current in the external coil is now raised to the necessary DC level by its power supply. During this time a small current will be induced in the main superconducting coil and will decay in time depending on circuit parameters. The heater power supply is now turned off and the main coil portion of wire allowed to regain its superconducting condition. Note that operation at this point is somewhat different than a persistent switch because the wire is not required to carry any significant current while recovering its superconducting condition as it must in cases using a persistent switch. Finally, the external coil power supply or a switch is used to discharge the external coil. This induces a current in the main superconducting coil in the cryostat by transformer action.

The principles underlying this method are straight forward and have been demonstrated in other applications. For example, it is the method used to induce the plasma current in a Tokamak (at the MIT Plasma Fusion Center and elsewhere), where the plasma is analogous to the main superconducting coil in this method and the ohmic heating transformer (coil) is analogous to the external coil system in this method. As another example, an analogous process has been used at the MIT Plasma Fusion Center to induce a large current through a single turn superconducting coil to deduce the resistance of the joint.

Method C, as described above, offers the following advantages relative to the "standard" methods A & B, described above, when applied to maglev systems:

1) The absence of current leads simplifies the design, reduces coil construction cost, reduces heat load to the cryogenic subsystem, reduces weight and size of the coil system envelope, and increases reliability.

2) A reduced heat load either decreases the power required by and weight of the "closed" cycle cryogenic system or reduces the size and weight of the cryogenic reservoir required for an "open" cycle cryogenic subsystem.

3) Improved maintenance and operation results because the external coil system can be packaged to interface properly with the main coil to automatically give the proper inductive coupling (transformer action) and can be set up with controls for "turn-key" operation.

4) The concept would be attractive for conductors which are particularly suitable for high current operation (eg- CICC), because it would avoid the larger current lead losses or complexity associated with operation of these conductors in methods A & B.

5) The method does not require the use of a CICC, but if one is used, then it may be advantageous to heat a section of the conductor or the entire conductor for the proposed process by using the working fluid from the cryogenic system. This would be tapped off at a stage in the cryogenic system that is at a temperature high enough to use for heating the conductor in place of the electrical heater described above.

This proprietary method is currently the baseline for the system and we are proceeding with a conceptual design of a "turn-key" system that would allow all coils in a bogie to be charged simultaneously after cool down to operating temperature without the use of current leads entering into the cryostats.

5.3.2.9. SUPERCONDUCTOR

5.3.2.9.1. MOTIVATION

A material and configuration for the superconducting coil conductor must be chosen.

5.3.2.9.2. CONCLUSIONS

The superconductor configuration selected for both the levitation and propulsion coils on the vehicle is a cable-in-conduit-conductor (CICC) as illustrated by the sample in the photograph in Figure 11. It consists of multiple strands (eg-27 in the figure) of multi-filament Nb_3Sn, which are formed into a cable, then enclosed in a steel conduit. The conduit serves as the channel for the working fluid which is supercritical helium. This eliminates the need for the usual cold helium vessel that surrounds the entire coil and that can be the source of a high heat load due to induced eddy currents if the cold vessel vibrates during operation.

5.3.2.9.3. CALCULATIONS

Analytical & experimental investigations in the fusion program have demonstrated the advantages of the Cable-in-Conduit-Conductor (CICC) approach from the operational stability standpoint. A preliminary study concerning the advantages of using this type of conductor in maglev applications has also been performed (R.J. Thome, et al, "Application of Cable-in-Conduit-Conductor to MAGLEV Magnet Systems," Final Report prepared for VNTSC under Contract no. DTFR53-91-C-00042, July, 1992). The study showed that CICC conductors have an order of magnitude higher energy margin for stability against disturbances than epoxy impregnated windings. Furthermore, it was shown that Nb_3Sn has a much higher energy margin than NbTi at a given temperature. In view of these results we have selected the CICC approach as the baseline conductor configuration for this program.

The operating current density for a superconducting magnet must be selected to be a fraction of the critical current density so as to allow for stability of the conductor to operational disturbances which could take the form of temperature excursions due to cryosystem fluctuations or losses generated by the conductor under transient conditions. The referenced study showed that Nb_3Sn has a higher energy margin for stability than NbTi for any given operating field or temperature level at a specified current density, hence, Nb_3Sn was selected as the baseline conductor.

The temperature and the magnetic flux density are not uniform throughout the windings in the respective coil systems. In our case, the magnetic field experienced by the levitation winding at full current will range from zero to 3.3 T and the temperature will be range from 6K to a maximum of 8 K. For the propulsion coil, the maximum field is 5.05 T and the maximum temperature is also 8K. If the maximum field point and maximum temperature point in either of the windings coincide, then this would be the point of lowest margin relative to the critical current surface for the conductor. In these designs, the operating fraction of critical current density on this basis was selected to be 40%. This should be ample margin to allow for operational uncertainties at this stage of the design process, especially since the maximum temperature and field points can be designed to occur at different points in the system.

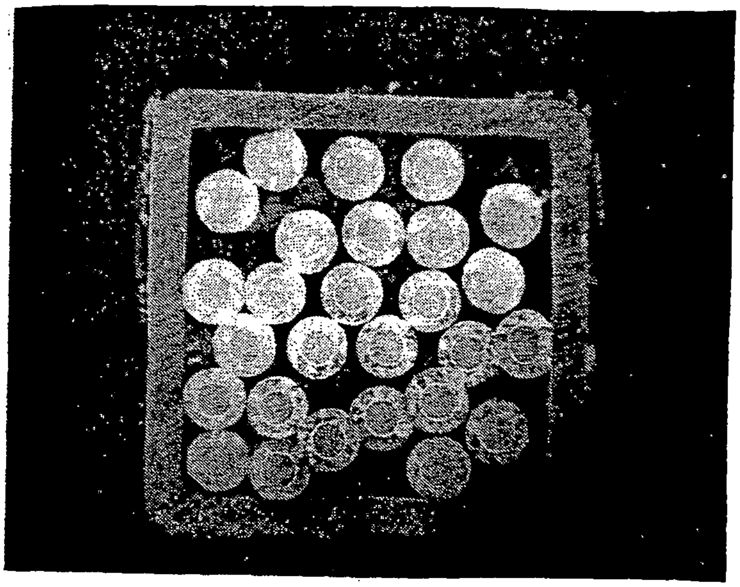


Figure 11 Sample 6000 ampere cable-in-conduit conductor consisting of 27 strands of multifilamentary copper-stabilized superconductor in a stainless steel sheath (full size is 0.2 in^2)

5.3.2.10. DISTRIBUTION OF LEVITATION MODULES

5.3.2.10.1. MOTIVATION

One issue considered during this program was the advantages and disadvantages of concentrating the lifting forces for any particular vehicle in a limited number of levitation modules vs distributing these forces along the length of the vehicle in a larger number of levitation modules. As expected, this trade-off is affected by how the relative weight of the levitation magnets, radiation shielding and cryogenic dewars scale with the number of individual levitation modules used and with the amount of lift required.

5.3.2.10.2. CONCLUSIONS

Centralized levitation was chosen, one bogie at each end of the vehicle, for all vehicle sizes.

5.3.2.10.3. CALCULATIONS

The relationship between the number of levitation modules per vehicle, vehicle weight and required lifting force can be derived in the following way. The amount of lift that can be generated by a levitation module can be shown to be proportional to the number of amp-turns in the coil, that is:

$$F_L=\mu_0(N_tI_t)^2K_L \qquad (1)$$

where:

N_tI_t=number of amp turns in coil
K_L =dimensionless function of coil geometry, speed and guideway characteristics

The weight of the coil can be expected to be proportional to the number of amp-turns for a fixed coil geometry and overall scale:

$$W_c=K_c(N_tI_t) \qquad (2)$$

where:

K_c=weight per amp turn for a fixed coil size and geometry

The weight of the dewar for the coil is not a strong function of the amp-turns in the coil and, to first order, is essentially constant once the coil overall size and geometry are fixed. Thus, if there are N_{cd} coil/dewar modules, the total weight of the levitation modules is given by:

$$W_{cd}=N_{cd}[K_c(N_tI_t)+W_d] \tag{3}$$

If the vehicle weight is W, then the number of modules required is related to the lift per module by:

$$W=N_{cd}F_L \tag{4}$$

Combining the above relationships to obtain the ratio of the total weight of the levitation modules to the weight of the vehicle leads to:

$$\frac{W_{cd}}{W}=\frac{K_c}{K_L(N_tI_t)}\left[1+\frac{W_d}{K_cN_tI_t}\right] \tag{5}$$

Since K_c and K_L are essentially constant, Equation 5 implies that N_tI_t, the amp-turns per module, should be large to reduce the ratio of levitation module weight to vehicle weight. For a fixed vehicle weight, Equations 1 and 4 then imply that it is desirable to reduce the number of levitation modules to a minimum, which, for all practical purposes, is probably four. This is the basis for the present design.

Concentrating the lifting forces in a relatively small number of levitation modules per vehicle offers other advantages to the overall design. These include an anticipated reduction in heat load to the cryogenic system for fewer levitation modules, potential savings from the reduction in the amount shielding and other materials used as the number of levitation modules decreases, and reduced manufacturing costs.

Centralized modules may require more electromagnetic shielding than distributed modules, however, since the local magnetic fields are more intense. On the other hand, the concentrated coils and shields allow passenger exposure to be reduced by limiting access to the bogie region of the vehicle.

5.3.2.11. DIPOLE OR QUADRUPOLE

In general, the far magnetic field from a current distribution decays as $r^{-(n+2)}$ where r is the distance from the point of field measurement to the currents and n is the order of the multipolar distribution (ie: n=1 is a dipole, n=2 is a quadrupole, etc). Hence, from the standpoint of minimizing the stray fields, it is best to use as high an order, n, for the current distribution as is practical. In this design, we have chosen n=2, a quadrupole, as the baseline for the levitation module configuration since it is straightforward to construct, has good lift characteristics and an adequate decay of stray field with distance for this application.

5.3.2.12. OPERATING TEMPERATURE

5.3.2.12.1. MOTIVATION

An operating temperature for the superconducting coils must be chosen.

5.3.2.12.2. CONCLUSIONS

The operating temperature of 8 K for the Magneplane superconducting magnet systems was chosen because of the high stability margin retained by the type of conductor selected as the temperature increases and because of the initial assessment of the potential gain for the cryogenic support system discussed in 5.3.2.12.3..

5.3.2.12.3. CALCULATIONS

Figure 12 and Figure 13are plots from J.L. Smith, et al, "Survey of the State of the Art of Miniature Cryocoolers for Superconductive Devices," NRL Memo Report 5490, Dec, 1984. They show points corresponding to presently available cryogenic support systems.

Figure 12 is a plot of cryocooler weight versus refrigeration capacity in watts at the operating temperature. It illustrates the major decrease in cryosystem weight possible at any refrigeration capacity as the low end operating temperature increases. For example, a simple interpolation implies a specific weight of about 160 Kg/watt of refrigeration capacity at 4 K and a reduction to about 50 Kg/watt of refrigeration capacity at 8-10 K.

Figure 13 shows points corresponding to commercially available units in terms of their specific power required vs operating temperature. The specific power is the ratio of the power required by the compressors divided by the refrigeration capacity. In general the points are considerably higher than the ideal Carnot efficiency, but are roughly parallel to it, thus indicating a strong decrease in power required to provide a given refrigeration capacity as the low end operating temperature increases. For example, at 4 K, the lowest value corresponds to about 1500 watts of power input per watt of refrigeration capacity, whereas at 8-10 K, a simple interpolation would imply about 600 watts input per watt of refrigeration.

Both plots imply that a major reduction in the weight and power requirement for the on-board refrigeration system could be achieved if the magnet operating temperature were raised above the usual

4.2 K, frequently used for superconductors. A temperature of 8 K was selected as a baseline because calculations indicated that the Nb_3Sn conductor used in the design would provide adequate design margin at this level and allow the benefits to the refrigeration system to be achieved.

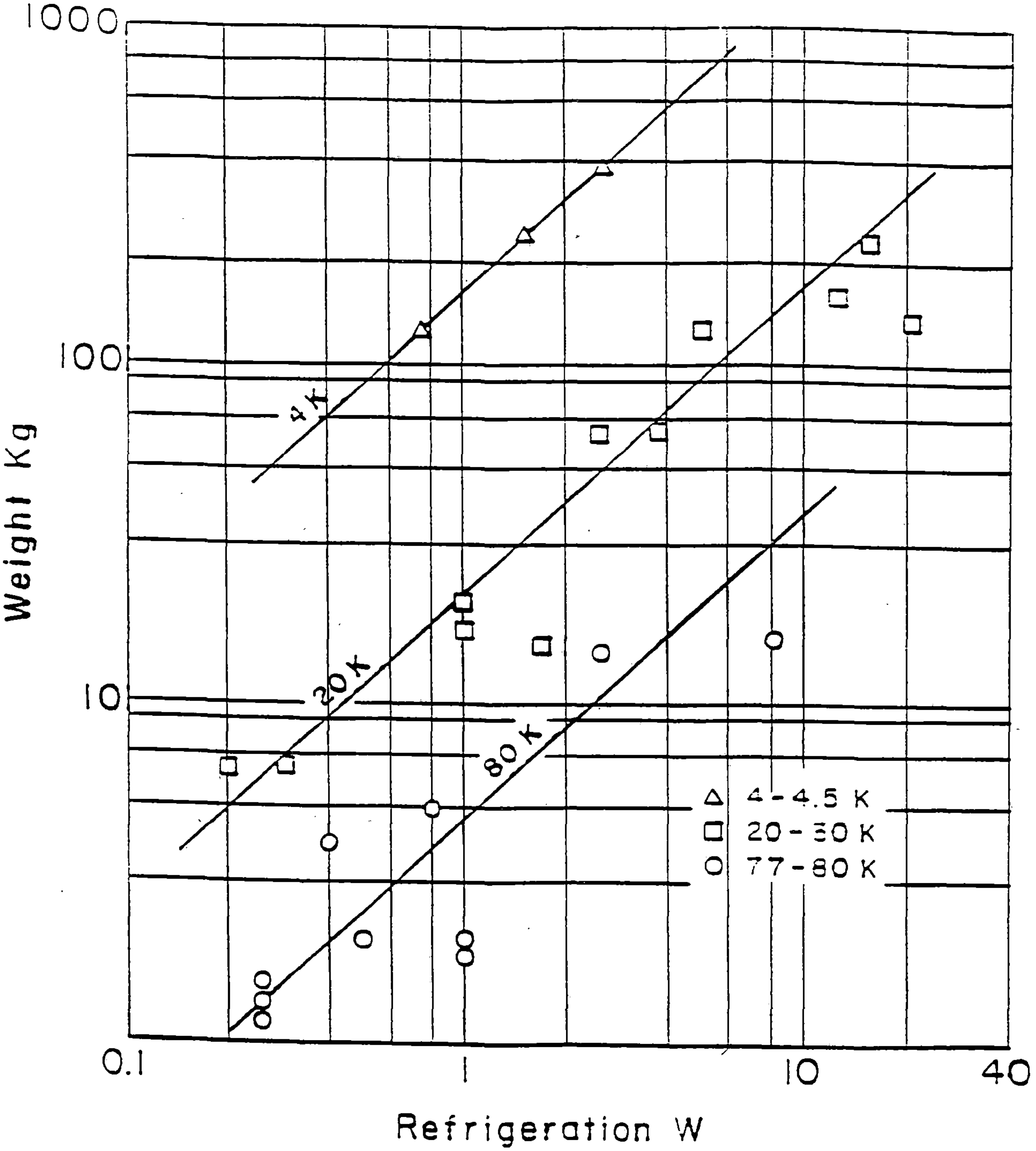


Figure 12 Weight of commercial cryocoolers vs refrigeration capacity in watts.

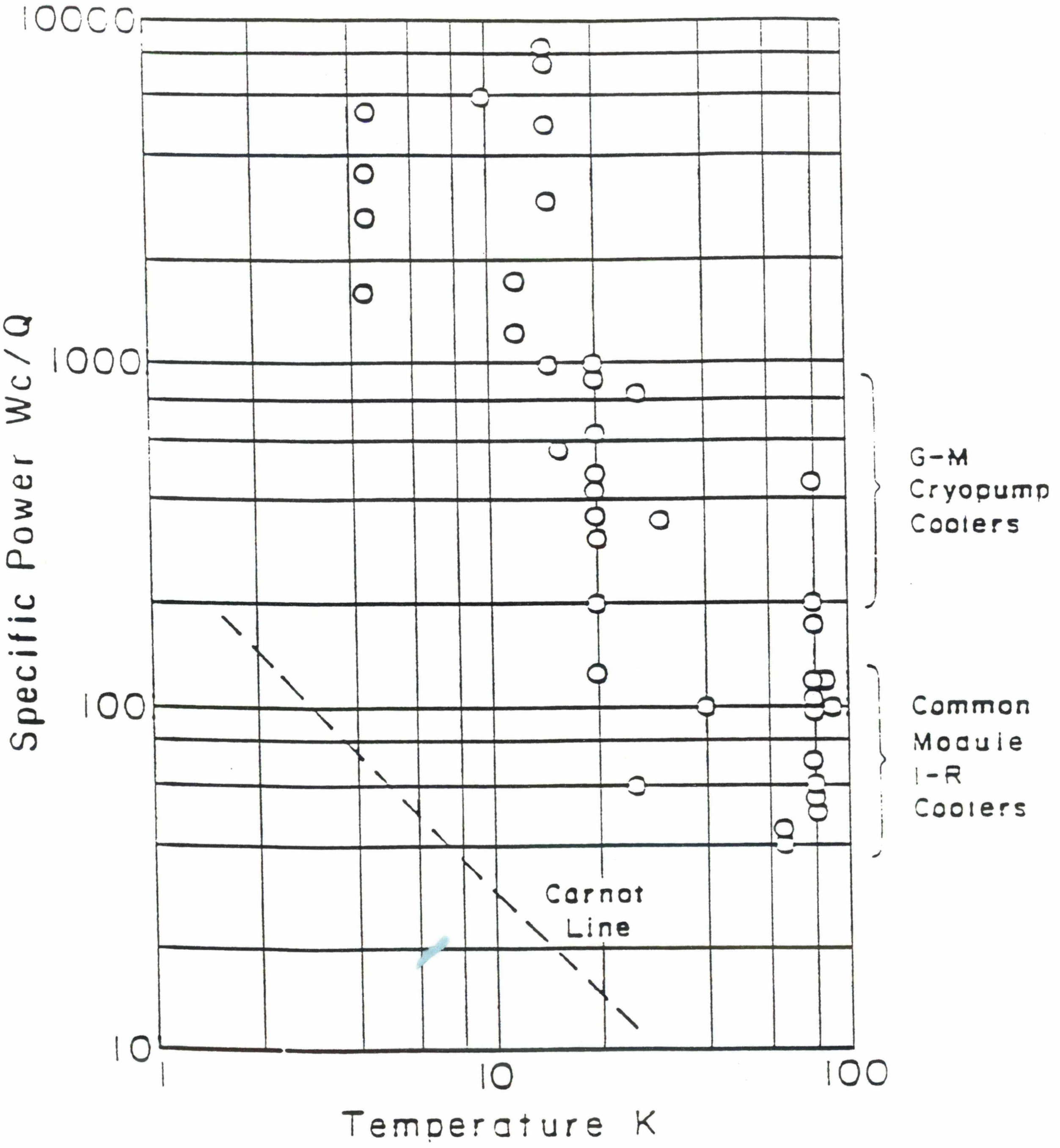


Figure 13 Specific power (power input derived by refrigeration capacity) vs temperature for commercial cryocoolers

5.3.2.13. MAGWAY LEVITATION MATERIAL CONFIGURATION

5.3.2.13.1. MOTIVATION

The configuration of magway levitation materials must be chosen. Three configurations were studied: continuous sheets, loops, and ladders.

5.3.2.13.2. CONCLUSIONS

A continuous aluminum sheet was chosen.

5.3.2.13.3. CALCULATIONS

The analysis of sheets vs loops vs ladders was carried out both with single coil levitation modules and quadrupole coil levitation modules travelling over the magway surface.

5.3.2.13.3.1. SINGLE COILS OVER SHEETS, LOOPS & LADDERS

Figure 14 shows the cases that were studied for a single coil levitation module traveling at constant speed at a height of 0.2 m above each of ten different magway configurations. The latter consisted of continuous sheets of two different widths, four "loop" magway cases, and four "ladder" magway cases. The differences for the discrete magway systems were in the number of transverse crossover sections per unit coil length.

The lift to drag ratio for the ten cases considered are shown in the bar chart in Figure 15. It indicates that sheets are best, but that the width of the sheet is an important variable. It also shows that ladders are substantially better than loops for lift to drag ratio.

5.3.2.13.3.2. QUADRUPOLE COILS OVER SHEETS, LOOPS & LADDERS

Figure 16 shows a quadrupole lift coil module and nine cases including a continuous magway, four "loop" cases and four "ladder" cases. Results for lift to drag ratio are summarized in Figure 17 and show the same trends as for the single coil module discussed earlier. The quadrupole moving over the continuous sheet has a lift to drag ratio that is slightly higher than that for the single coil, but also has the advantage of lower stray fields, hence, it was chosen for the baseline.

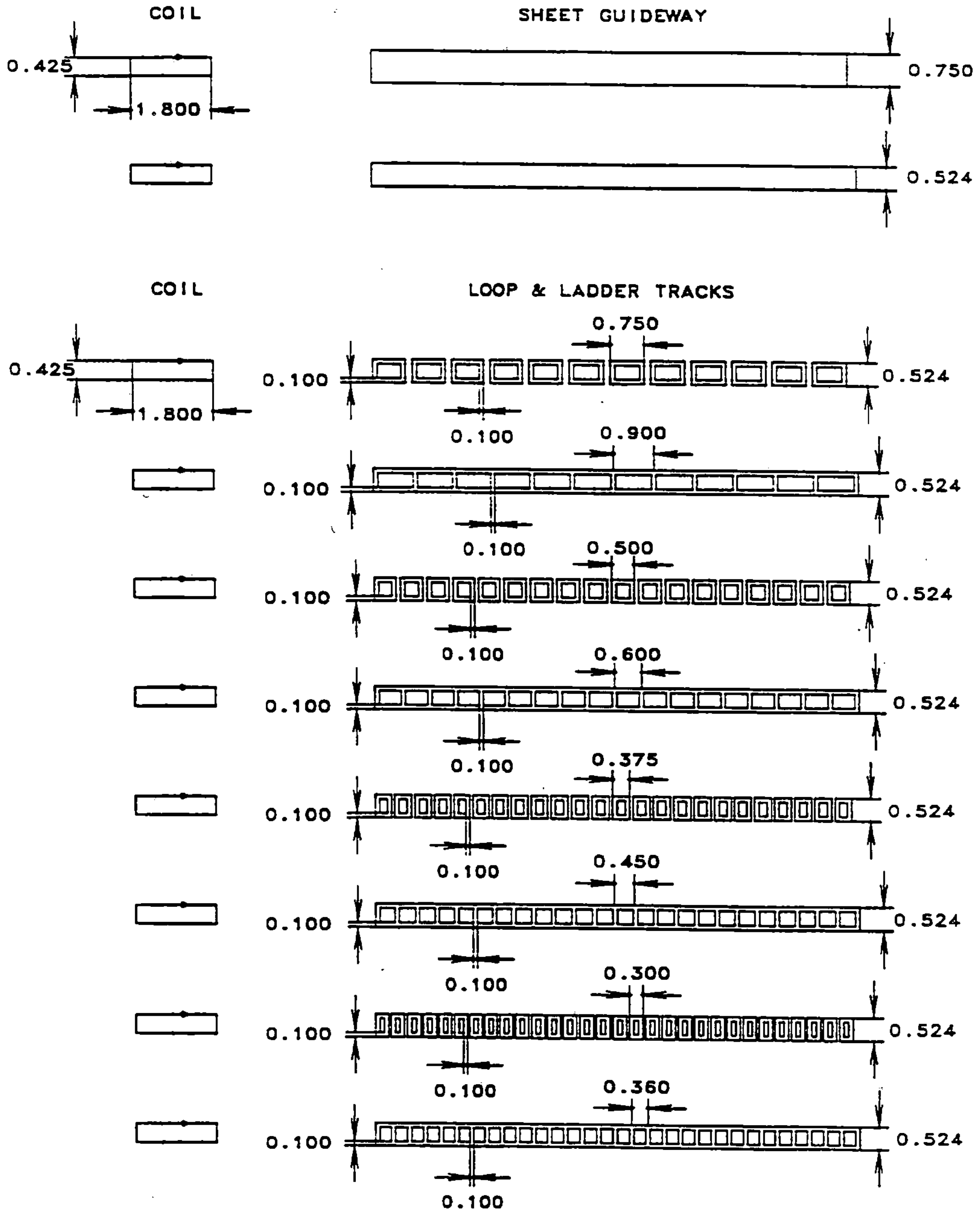


Figure 14 Interaction of a dipole levitation coil with magway sheets, loops, and ladders

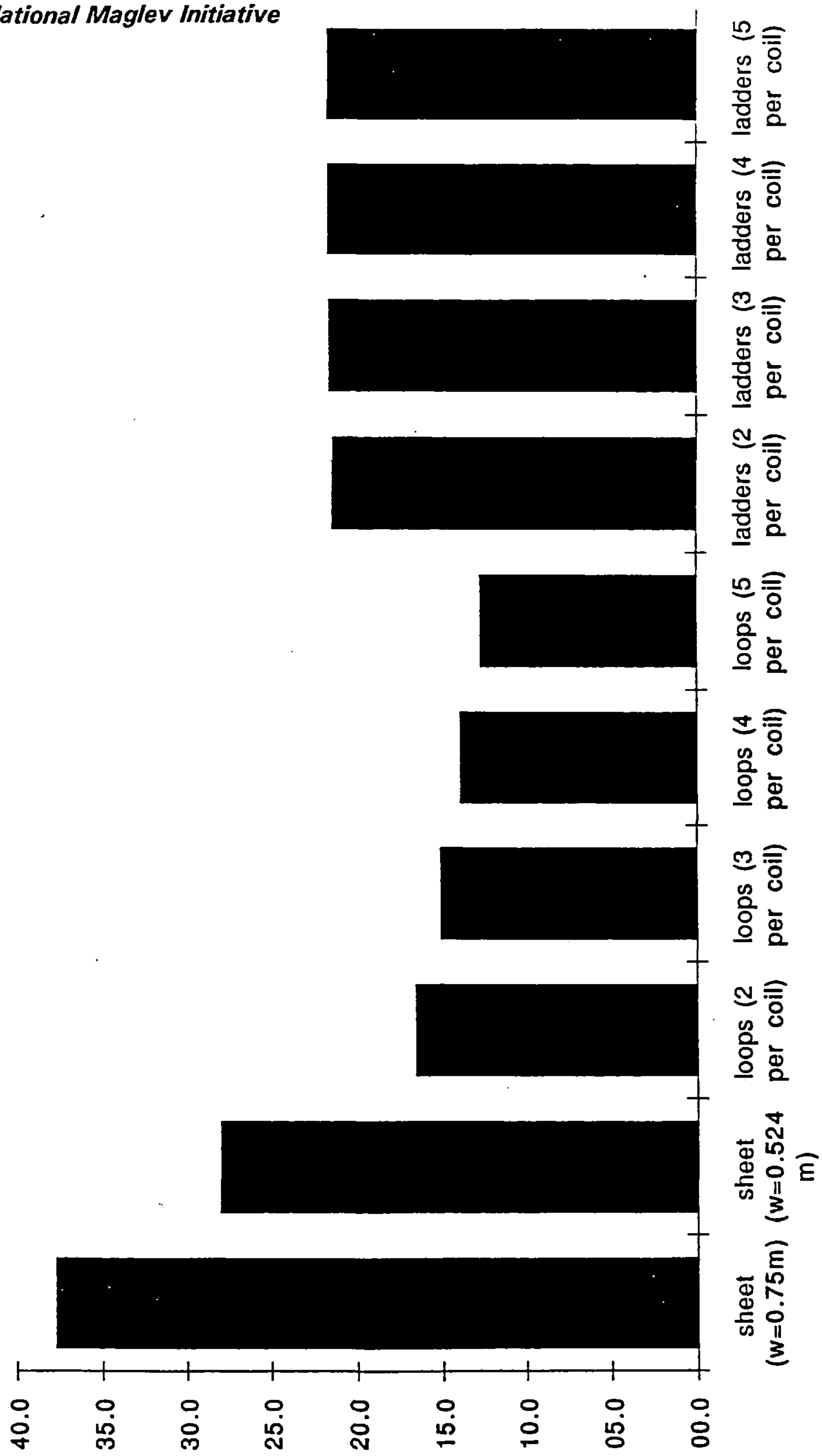


Figure 15 Lift to drag force ratio for a single coil with a speed of 150 m/s for selected magway configurations

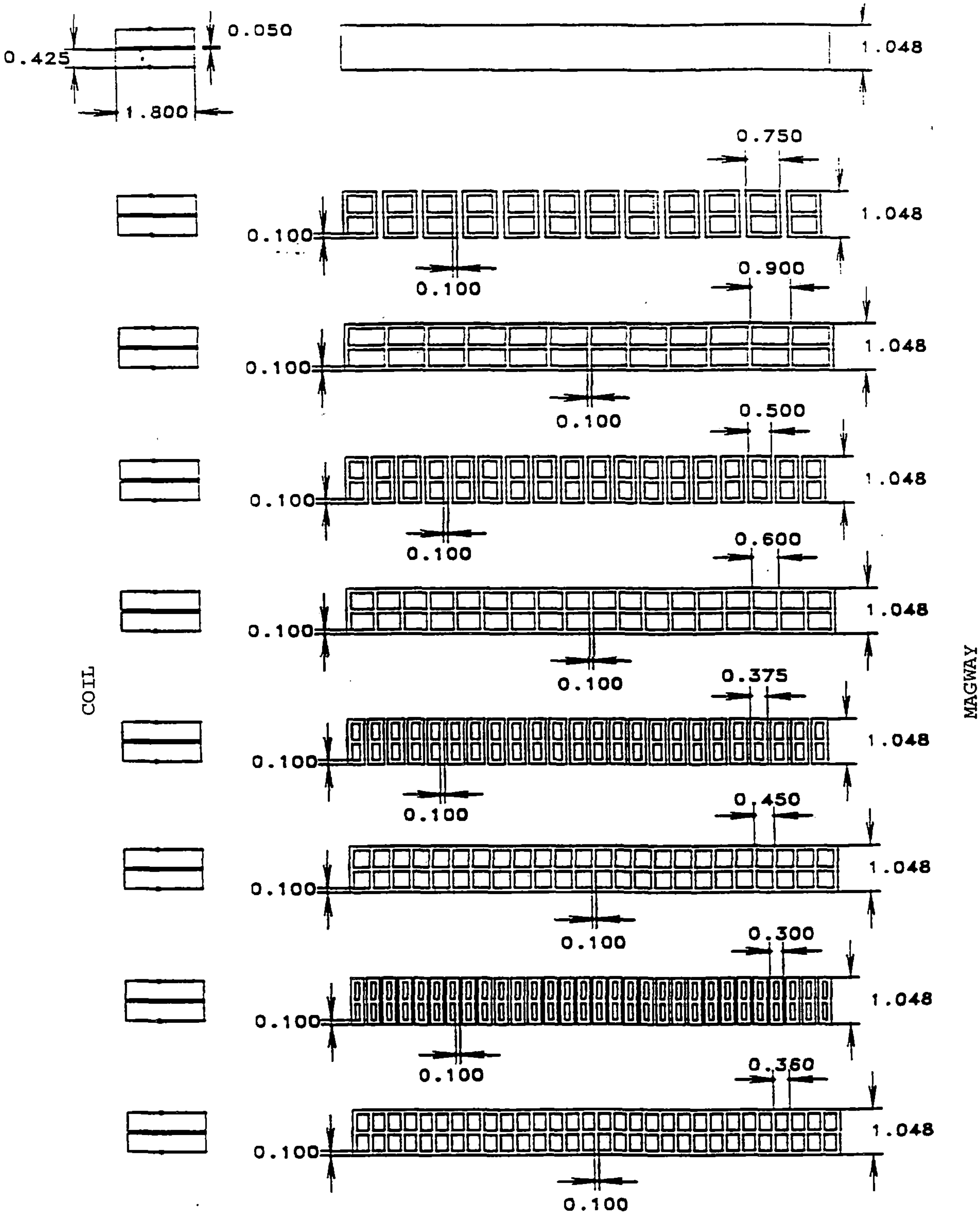


Figure 16 Interaction of a quadrupole levitation coil with magway sheets, loops, and ladders

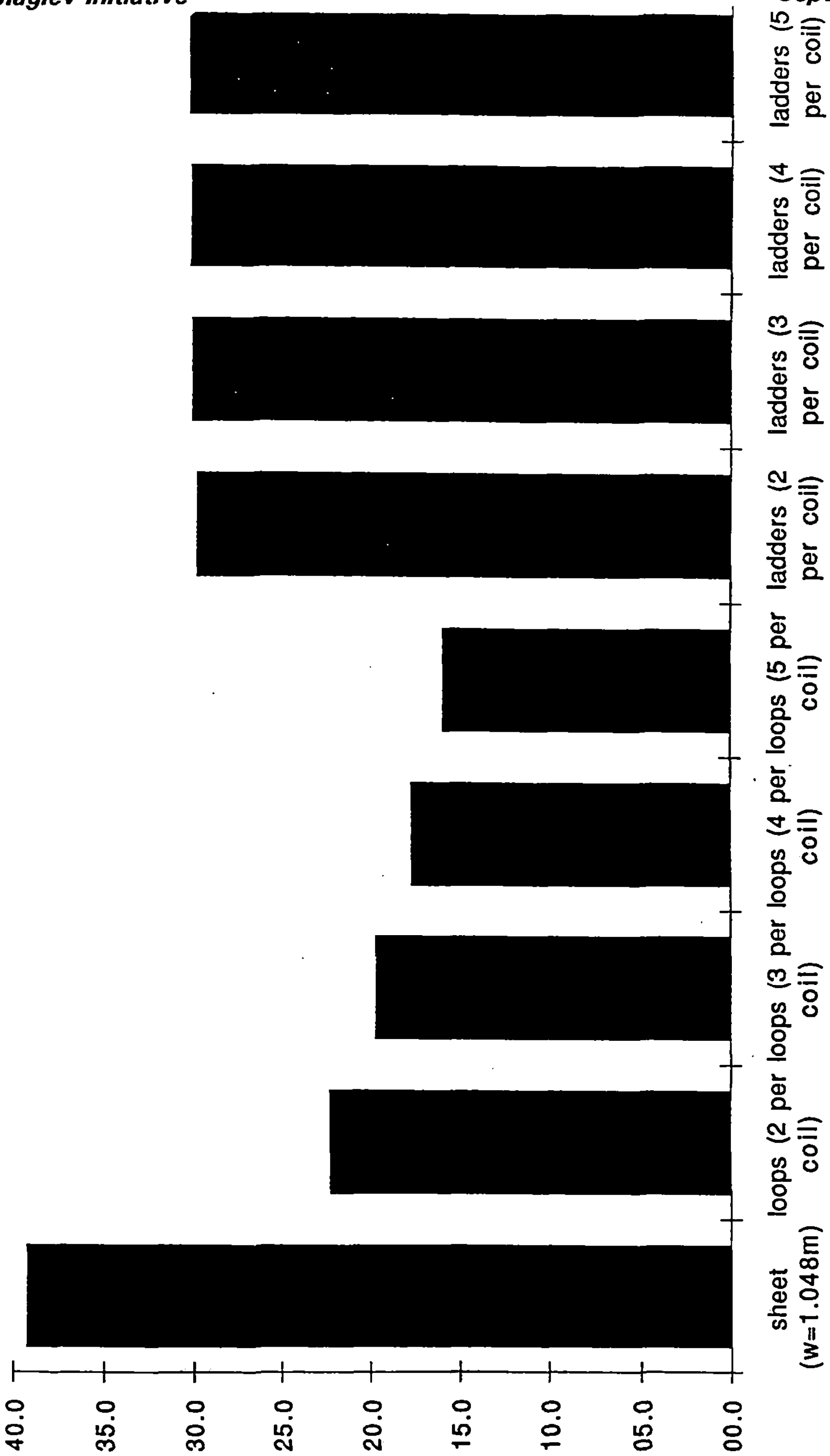


Figure 17 Lift to drag force ratio for a quadrupole levitation module travelling at 150 m/s over selected magway configurations

The weight per unit length for the magway configurations used in this study are summarized in the bar chart in Figure 18. The advantage of the discrete systems is a factor of two to three in weight, however, this was judged to be an insufficient gain relative to the loss in lift to drag ratio and the potential dynamic problems associated with the force variations inherent in the discrete systems.

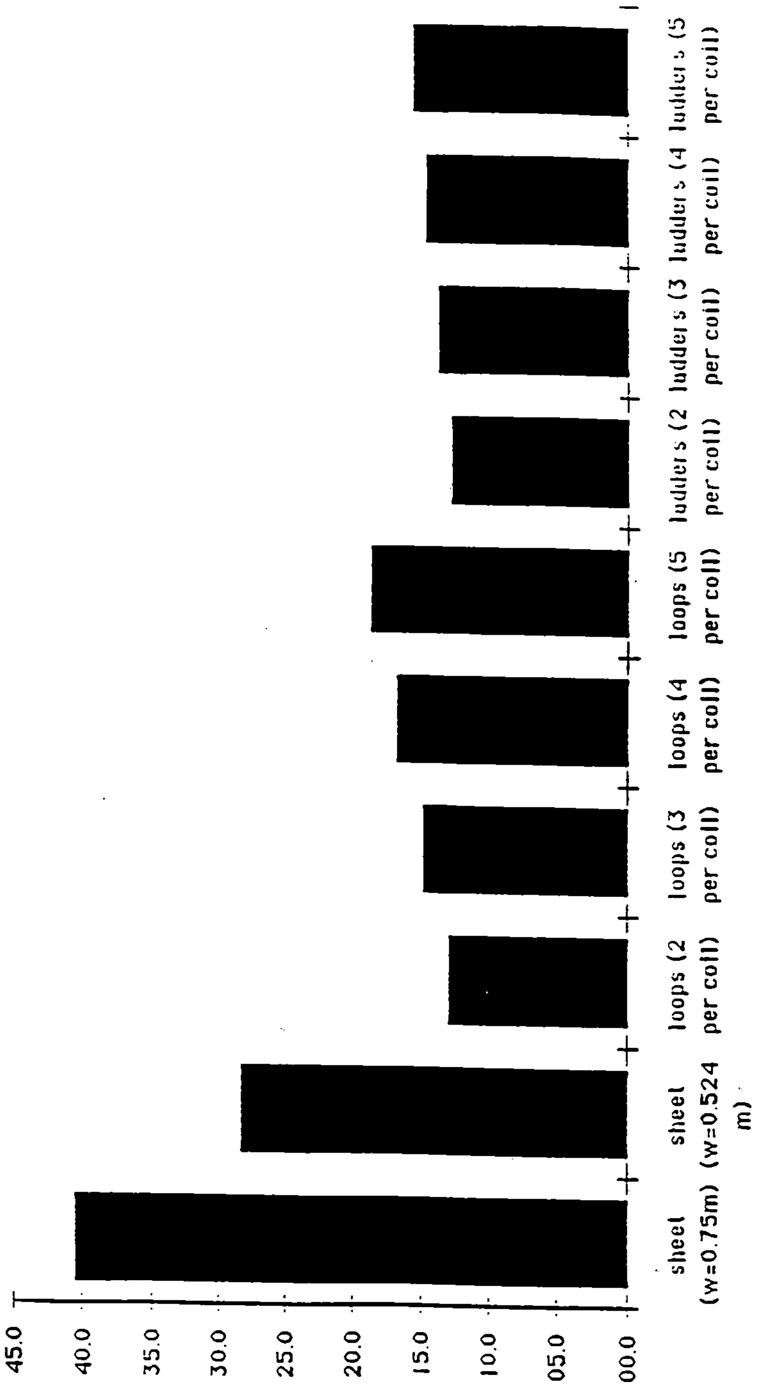


Figure 18 Unit weight (kg/m) of selected magway configurations

5.3.2.14. LEVITATION SHEET THICKNESS AND JOINTS

5.3.2.14.1. MOTIVATION

The thickness of the levitation sheet must be chosen. Also, the magway sheets must necessarily be segmented because of material length availability and the need to provide for thermal expansion joints. Therefore the type of joint needs to be specified. The choice of both the thickness and the joints have magnetic implications.

5.3.2.14.2. CONCLUSIONS

The levitation elements in the magway consist of two sheets of aluminum, each 0.02 m thick. The selection of this thickness was based on an evaluation of the lift and drag characteristics of a quadrupole levitation module for several sheet thicknesses over the range of operating speeds.

Several joint types were analyzed. Straight transverse cuts that leave square ends on the levitation plates were found to be acceptable.

5.3.2.14.3. CALCULATIONS

5.3.2.14.3.1. SHEET THICKNESS

Figure 19 and Figure 20 show the lift and drag, respectively, as a function of speed for a quadrupole levitation module traversing sheets of different thicknesses. The forces in each plot are normalized to $\mu_0 I_v^2$, where I_v is the current in one coil in the module. The figures show that the lift increases and that the drag decreases as the sheet thickness increases.

The lift to drag ratio is given in Figure 21 as a function of speed for several sheet thicknesses. It shows an increase in lift to drag ratio as sheet thickness increases, but that the incremental improvement decreases with each additional centimeter. The Magneplane team has selected 0.02 m as a baseline thickness for the magway sheets because it provides the major part of the benefit to be gained. However, we will consider using thicker sheets in selected sections of magway if the additional material can be beneficial from a cost or performance standpoint.

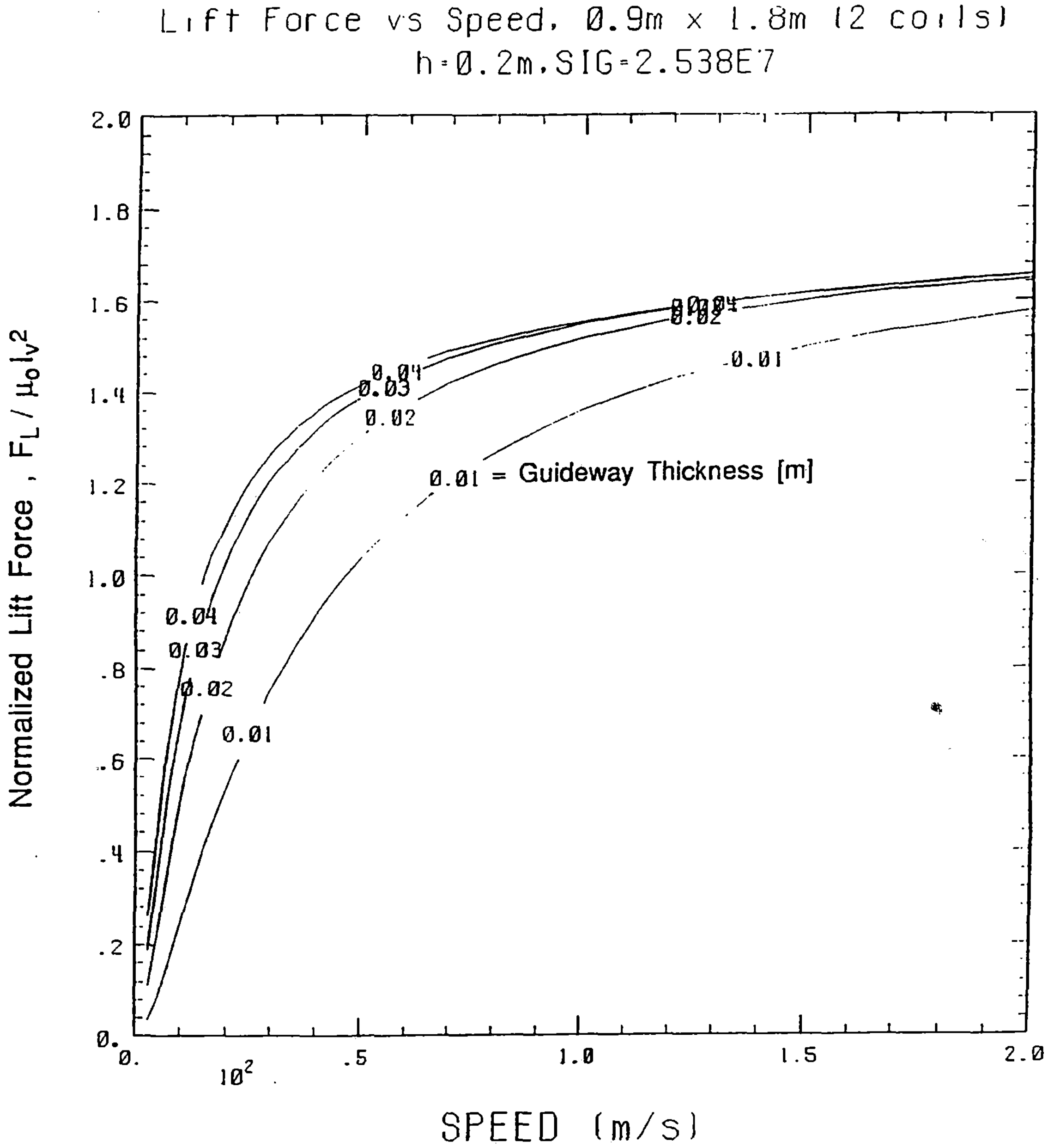


Figure 19 Normalized lift force vs speed for selected magway thicknesses

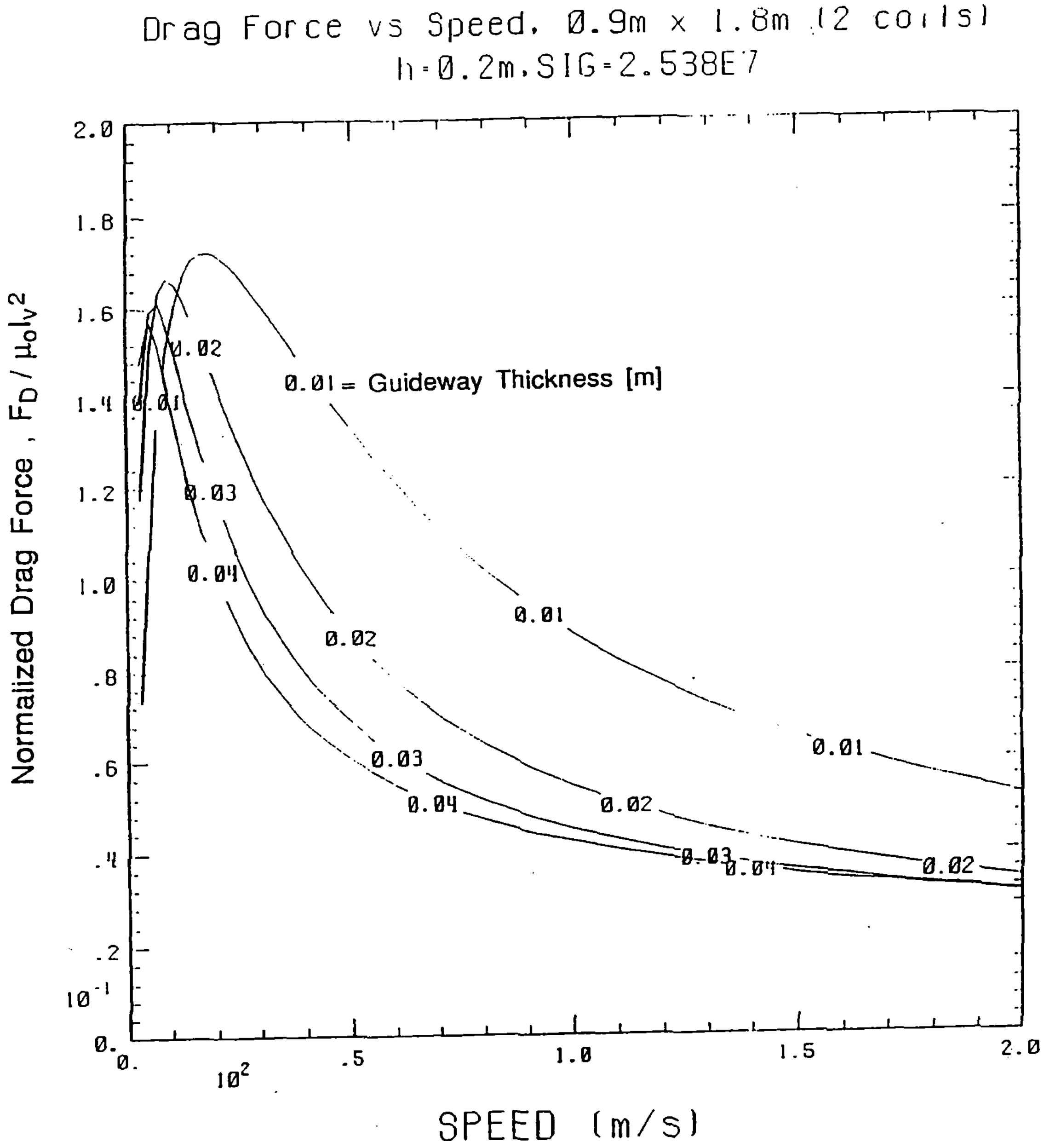


Figure 20 Normalized drag force vs speed for selected magway thicknesses

5.3.2.14.3.2. JOINTS

Several possible joint configurations were investigated for their impact on lift and drag. A typical computed result is shown in Figure 22 which shows the eddy currents induced in a magway sheet as a quadrupole levitation module approaches and passes over a transverse cut.

The model consisted of a quadrupole levitation module travelling at a height of 0.2 m and a speed of 140 m/s over a magway sheet 2 m wide and 0.02 m thick. The joint geometries considered included straight cuts across the sheet, cuts at an angle, and dovetail cuts facing toward or away from the direction of motion. Selected models also incorporated shorting straps across the cut or plates of selected lengths underneath the cut.

Each model resulted in a computed transient for the lift and drag force experienced by the module as it passed over the joint. Large variations were experienced among the different configurations. The best result in terms of simplicity of application in the system and relatively low force variation was for a straight cut, perpendicular to the direction of motion, with a 1 m long, 0.02 m thick, backing plate under the cut. The latter is not required to be electrically connected to the magway sheet on either side. For this case, the percentage variation in lift and drag as the cut was traversed was 3% and 30%, respectively. This is considered acceptable at this stage of the design process. In the future, we will continue to search for means to reduce these values in a cost effective manner, including the possibility of staggering the cuts so that all levitation modules do not traverse the cuts simultaneously.

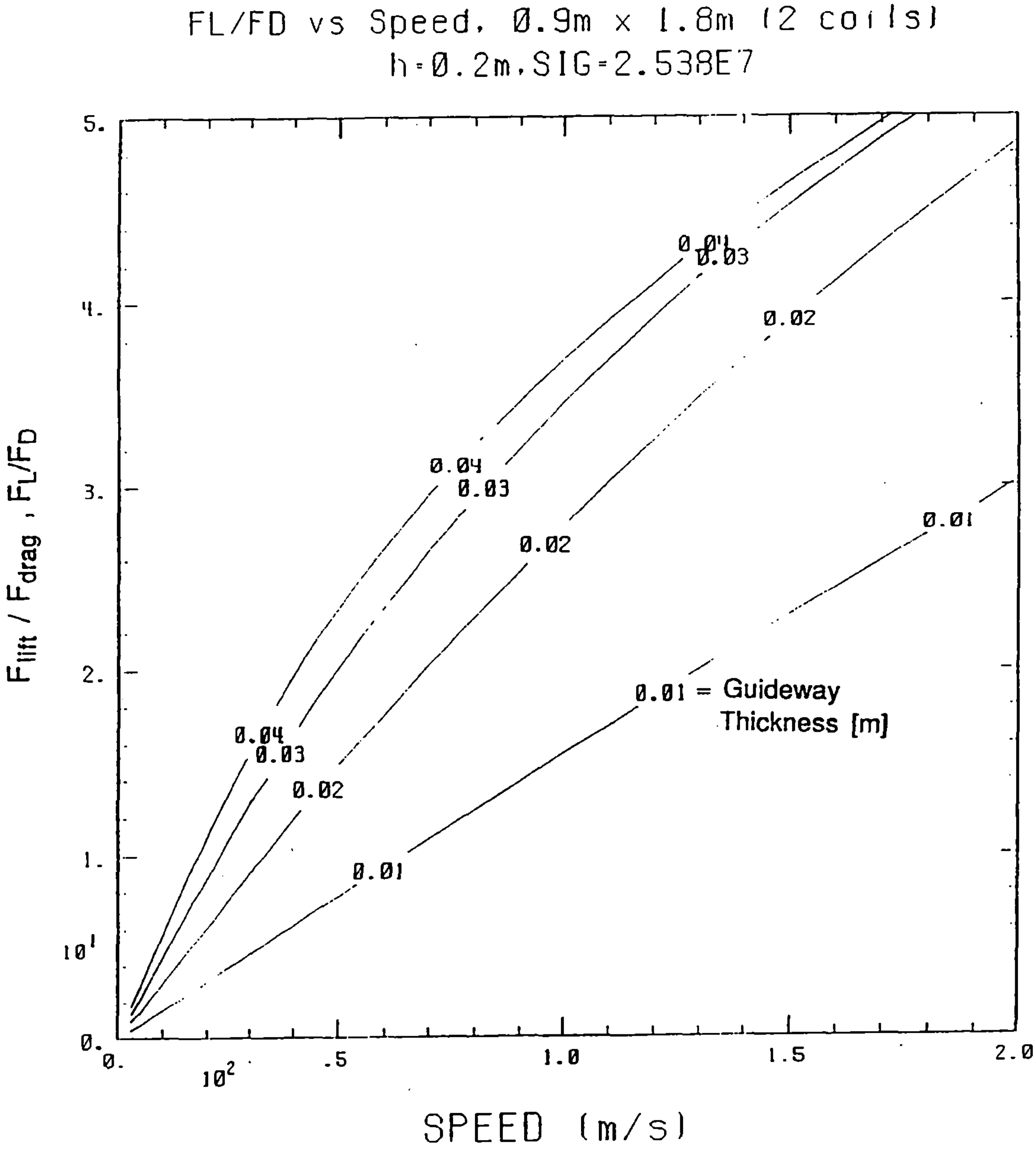


Figure 21 Lift to drag ratio vs speed for selected magway thicknesses

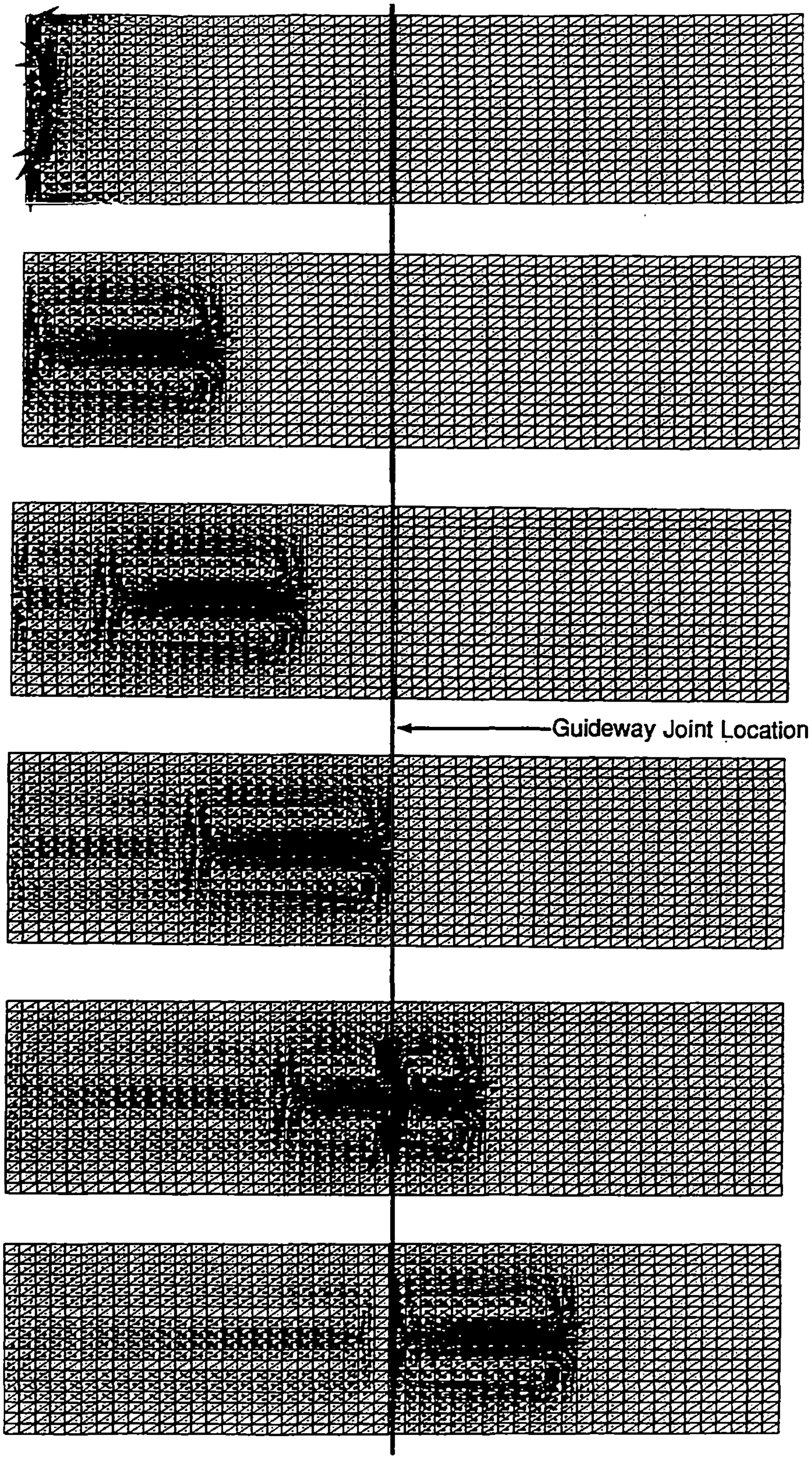


Figure 22 Currents induced in a magway sheet with a joint being traversed by a levitation module

5.3.2.15. NUMBER OF LEVITATION AND PROPULSION MODULES

5.3.2.15.1. MOTIVATION

In the Magneplane concept, the superconducting coils that perform the levitation function and propulsion function are independent, thus allowing considerable flexibility in selection of their geometry and location on the vehicle.

Both the number of levitation modules and number of propulsion modules must be chosen.

5.3.2.15.2. CONCLUSIONS

Eight levitation modules and twelve propulsion modules were chosen. The levitation coils are in pairs on each of the four corners of the vehicle. The propulsion modules are in two sets of six, one set on each end of the vehicle.

5.3.2.15.3. CALCULATIONS

5.3.2.15.3.1. LEVITATION COIL MODULES

A recent study[1] considered the general requirements for a levitation module and showed that:

> 1)The maximum lift per unit weight for a levitation module could be achieved if it were designed for the maximum product of conductor current density, j, times maximum field level, B, at the winding divided by winding weight density, ρ. This was deduced from electromagnetic considerations alone, independent of conductor properties. It is a general guideline for design of levitation modules.
>
> 2) Operating the levitation modules at a higher temperature could be beneficial from the standpoint of cryosystem weight or efficiency.

---

[1] R.J. Thome, et al, "Application of Cable-in-Conduit Conductor (CICC) to MAGLEV Magnet Systems", Final Report, VNTSC Contract no. DTFR53-91-C-00042, July, 1992.

3) A Nb_3Sn conductor in CICC form at a low maximum field (2-4T) provides a much higher jB/ρ than NbTi while providing substantially higher stability margin for operation. The latter translates to a more robust design.

The results of the above study led us to a levitation module design at a modest field level (ie. 3.3 T). Furthermore, for any levitation module geometry, the levitation force is proportional to I_v^2, where I_v is the amp turns in the module. The weight of the coils in the module are proportional to I_v, but tend to be dominated by the cryostat weight. This tends to favor using the minimum number of levitation modules and the decision to use four on each end (total of eight per vehicle) as our baseline.

5.3.2.15.3.2. PROPULSION COIL MODULES

The thrust developed by the synchronous windings interacting with the superconducting propulsion coils on the vehicle is proportional to the current in the magway, I_g, and the total amp-turns in the coils on the vehicle, I_p. Because the magway must be excited for a block length, and the propulsion coils on the vehicle are relatively small, the cost effective trend is to design such that $I_p >> I_g$.

The amp-turns in the coils on the vehicle could be conceptually located in a single coil or distributed along the entire length of the vehicle provided the coil size is chosen to be compatible with the wavelength of the magway winding. For redundancy purposes, it is also desirable to have at least two electrically and cryogenically independent propulsion coils or sets of coils.

The trade-off to determine the length over which the vehicle coils are to be distributed involves several factors, assuming a given thrust requirement and clearance between vehicle and magway. A short distribution will lead to a concentration of amp-turns on the vehicle and, in turn, higher field propulsion coils which:

1) will have more concentrated local fields and be more difficult to shield so the tendency is to locate them in bogies;

2) will concentrate the thrust load on a fewer number of magway windings, thus leading to the requirement for additional local support along the entire magway length;

3) will have greater internal electromagnetic loads on the superconducting windings, thus leading to a higher structural weight within the cryostats;

3) will have less total cryostat surface area and, in turn, a smaller overall heat load on the cryogenic system which is beneficial from the weight and on board power standpoint;

4) will concentrate the "speed voltage" that is generated over a shorter length of magway windings; and

5) will have poorer coupling to the magway windings if the distribution is too short, because the propulsion coil winding center will have to be higher to concentrate the amp-turns.

In view of the above, we have selected six propulsion coils on each end of the vehicle as a reasonable compromise (twelve total per vehicle). They occupy about 23% of the total length of the 140 passenger vehicle and experience a maximum field at the superconducting magnet windings of about 5 T.

5.3.2.16. BLOCK LENGTH SELECTION

5.3.2.16.1. MOTIVATION

This discussion describes how block size can be traded off against capital cost and energy consumption for a simple model of the Magneplane system.

The capital cost of the system can be decreased by increasing the block length because this reduces the total number of converters. Longer blocks have higher resistive losses associated with the LSM winding which increase the operating cost.

Life cycle cost is minimized by performing two tradeoffs

1. block size vs. capital cost
2. block size vs. operating cost

5.3.2.16.2. CONCLUSIONS

The results of the two tradeoffs are shown in Figure 23 which illustrates that the optimum block size is in the range of 1 to 2 km.

5.3.2.16.3. CALCULATIONS

The following assumptions were made to simplify the analysis.

1. Installed power cost at each block is proportional to converter rating.

2. The cost of energy is constant.

3. Vehicle speed is constant.

4. All blocks are the same length.

5. One converter powers each block

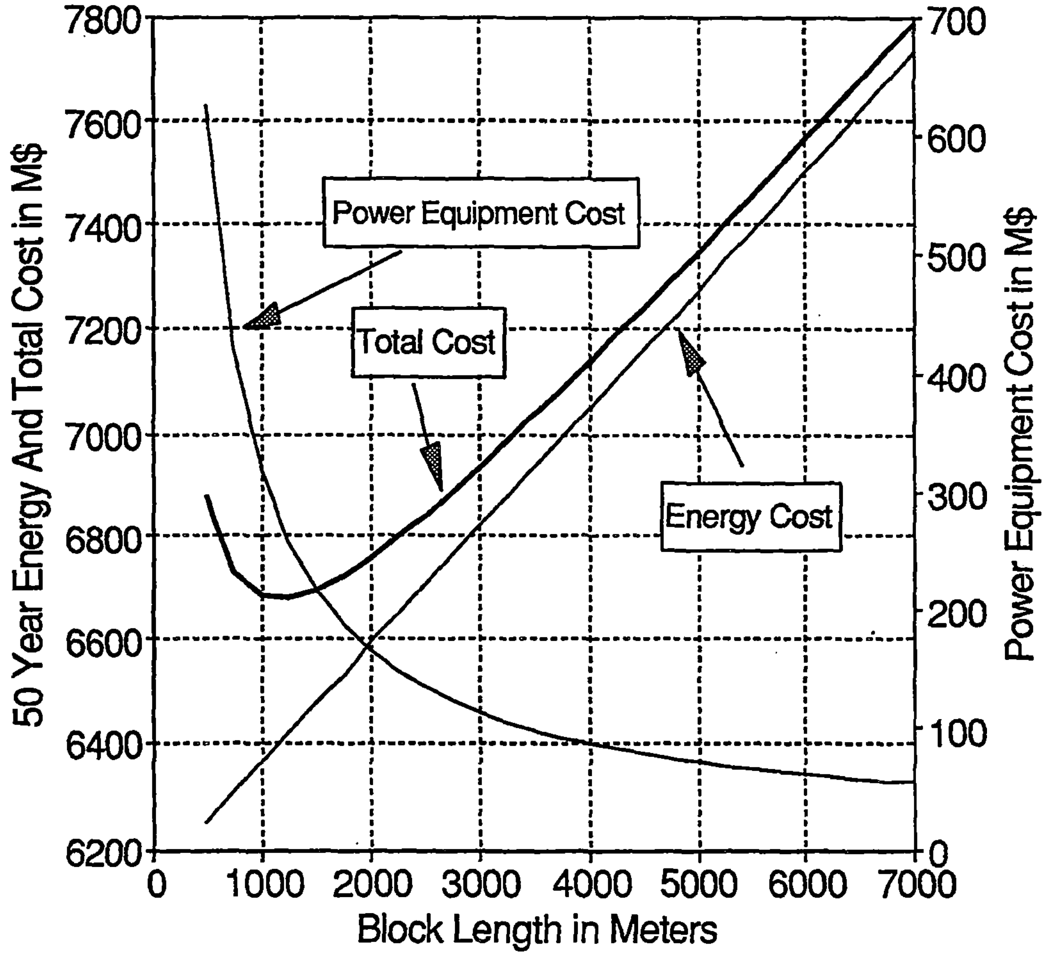


Figure 23 Power equipment and energy costs versus block size

While these assumptions are approximations to real cost, they illustrate certain fundamental features of system design.

The cost variables are

C_{EU}: Unit cost of energy in \$/w-s
C_{CU}: Unit cost of capitol in \$/w

The power supplied to each block is the vehicle power plus the I^2R loss in the magway. Reactive power is ignored.

The following definitions apply to the equations:

H : headway distance in meters
L_B: Block length in meters
L_S: System length in meters
T_L: Operating Life in seconds

$N_V = \frac{2L_S}{H}$: number of Vehicles in system

$N_B = \frac{2L_S}{L_B}$: number of blocks in system

Notice that N_V and N_B are defined for a two-way system and that N_B is also the number of converters required.

The block power is

$$P_B = P_V + P_L$$

where the following definitions apply

P_V: Thrust x speed of vehicle in watts

$P_L = 3I^2RL_B$: Magway power loss in watts

I: Phase current of magway

R: Magway resistance in Ω/ϕ/m

The **total energy cost,** (C_E) is based on the concept that the power P_B must be supplied to each vehicle over the life of the system. This cost is

$$C_E = T_L N_V P_B C_{EU} \quad : \text{total energy cost}$$

$$= T_L \frac{2L_S}{H}(P_V + 3I^2 R L_B) C_{EU}$$

The **capital cost** is based on the concept that each block requires a converter rated at P_B. This cost is

$$C_C = N_B P_B C_{CU} \quad : \text{capital cost}$$

$$= \frac{2L_S}{L_B}(P_V + 3I^2 R L_B) C_{CU}$$

Analytic Optimization: The total life cycle cost of the system is

$$C_L = C_E + C_C$$

which can be analytically optimized on block size using the formulation described above.

Expanding the terms gives

$$C_L = \frac{T_L 2L_S}{H}(P_V + 3I^2 R L_B) C_{EU} + \frac{2L_S}{L_B}(P_V + 3I^2 R L_B) C_{CU}$$

The partial derivative with respect to block length is

$$\frac{\partial C_L}{\partial L_B} = \frac{T_L 2L_S}{H} 3I^2 R C_{EU} - \frac{2L_S P_V C_{EU}}{L_B^2}$$

Setting this to zero and solving for L_B gives

$$L_B = \sqrt{\frac{H P_V C_{CU}}{T_L 3I^2 R C_{EU}}}$$

	Block Size in km					
	1	2	3	4	5	units
Reactance	4.5	8.9	13.4	17.9	22.3	Ohms
Resistance	0.10	0.20	0.30	0.40	0.50	Ohms
Line-Neutral Voltage	5.4	9.9	14.6	19.4	24.2	kV
Line-Line Voltage	9.3	17.2	25.3	33.6	41.8	kV
Resistive Loss	0.3	0.7	1.0	1.4	1.7	MW
Efficiency	95.6	91.5	87.8	84.4	81.2	%

Figure 24 Block size versus LSM voltage

Numerical Example: Examples of the analysis are based on the following system structure and values

H = 7102 M: based on 9600 pph at 134 m/s
L_S = 1.6×10^5 m: 100 mile baseline system
T_L = 1.1826×10^9 s: 18 h/day, 50 year op. time
P_V = 4.8×10^6 w: no grade vehicle power at 134 m/s
I = 770 A: current for above
R = $1\times10^{-4}\Omega/\phi/\text{m}$: standard winding resistance

C_{EU} = 2.4×10^{-8}\$/J: 8.52 ¢/kWh
C_{CU} = 0.2 \$/W: Based on \$200 k/MW

The optimum block length can be computed from the formula and parameters presented above. For this example, the optimum block length is about 1160 meters.

LSM Winding Voltage Consideration: Another consideration in selecting block size was the need to reduce the winding voltage to levels below 20 kVac line-to-line. Practical experience with high voltage insulated systems suggests that severe reliability and cost penalties would be imposed at higher voltages. Figure 24 shows the LSM winding voltage and others factors at the design point for the propulsion system. The per kilometer equivalents of the baseline winding inductance and resistance values were used. The table shows that a 2 km block size will reduce the LSM winding voltage below 20 kVac.

It should be noted that the LSM winding voltage is determined almost entirely by the winding inductance. Increasing the conductor cross section will lower the resistive losses but is not effective in decreasing the required terminal voltage.

5.3.2.17. ON-BOARD POWER OPTIONS

5.3.2.17.1. MOTIVATION

The method of providing on-board vehicle power impacts the design, reliability and safety of the vehicle. Three alternative methods were considered in the selection process.

1. Gas Turbine Auxiliary Power Units (APU)
2. Inductive Power Pickup from the LSM winding
3. Ram air turbines

5.3.2.17.2. CONCLUSION

An inductive power pickup scheme has been selected after considering the impact on system safety, vehicle design and overall system reliability.

5.3.2.17.3. CALCULATIONS

The use of a ram air turbine was ruled out early in the selection process because the available power drops off very rapidly below the design speed of the vehicle.

The APU and inductive pickup schemes were considered in detail during the selection process.

A comparison of the two approaches is shown in Figure 25. Although the APU system uses conventional technology it requires on-board fuel. In addition to the potential safety issues, the fuel represents a compromise in the general design philosophy of the Magneplane system. The inductive power pickup was selected because of these reasons.

DUAL APU System

Weight

APU (2)	1000	kg
Fuel	500	kg
Total	1500	kg

Advantages

Redundant system
May Eleminate Battery Backup
Bleed air available for HVAC and Air Pads
Available Shaft Horsepower

Disadvantages

LNG Fuel required at 3 hour intervals
Fuel Safety
Crash worthiness
Noise generation
Reduced CRS efficiency
Requires Clean Air Input

Inductive Pick-up System

Weight

Coil	2000	kg
Battery	1800	kg
Total	3800	kg

Advantages

No Fuel
No Noise
Little External cooling required

Disadvantages

Extra Vehicle Weight
Needs Aux compressor for Air Pads
Wayside Power complexity

Figure 25 Comparison of APU and inductive pickup for vehicle power

5.3.2.18. LSM WINDING PITCH

5.3.2.18.1. MOTIVATION

The LSM pole pitch is an important parameter in the design of the propulsion system. At a given height LSM thrust is proportional to the product of LSM winding current and propulsion coil current. Proper selection of an LSM pole pitch minimizes these currents for a specified thrust requirement.

5.3.2.18.2. CONCLUSIONS

For a given level of LSM winding current the optimum pole-pitch p for any LSM gap z is:

$$p = \pi z$$

The baseline design uses an LSM gap of 0.25 m. The optimum pole pitch for this height is $\pi/4$ or 0.7854 m. A near optimum pole pitch of 0.75 m has been selected.

5.3.2.18.3. CALCULATIONS

The pole pitch of the winding was selected from analysis of the theoretical field pattern produced by a sheet of current with a sinusoidally varying current density. The magnitude of the flux density for this type of field can be expressed as

$$\beta = J\, e^{-z\,\pi/p}$$

In drawing a relationship between the discrete LSM windings and the ideal current sheet notice that the current density of the ideal sheet increases with the winding current and decreases with pole pitch. In other words

$$J = \frac{kI}{p}$$

so that the magnitude of the flux density becomes

$$\beta = \frac{kI}{p} e^{-z\pi/p}$$

The optimum pole pitch is found by setting

$$\frac{\partial B}{\partial p} = 0 = -\frac{kI}{p^2} e^{-z\pi/p} + \frac{kI}{p} \times \frac{z\pi}{p^2} e^{-z\pi/p}$$

$$\frac{kI}{p^2} = \frac{kIz\pi}{p^3}$$

$$or\ p = \pi z$$

The relationship between pole pitch and the magnitude of the LSM field is shown in Figure 26 for an LSM gap of 0.25 m. The "constant I" curve in the figure shows that a maximum occurs at a pole pitch of about 0.75 m.

The selection of a near optimum pole pitch contributes to the overall efficiency of the system and reduces space harmonics in the travelling field.

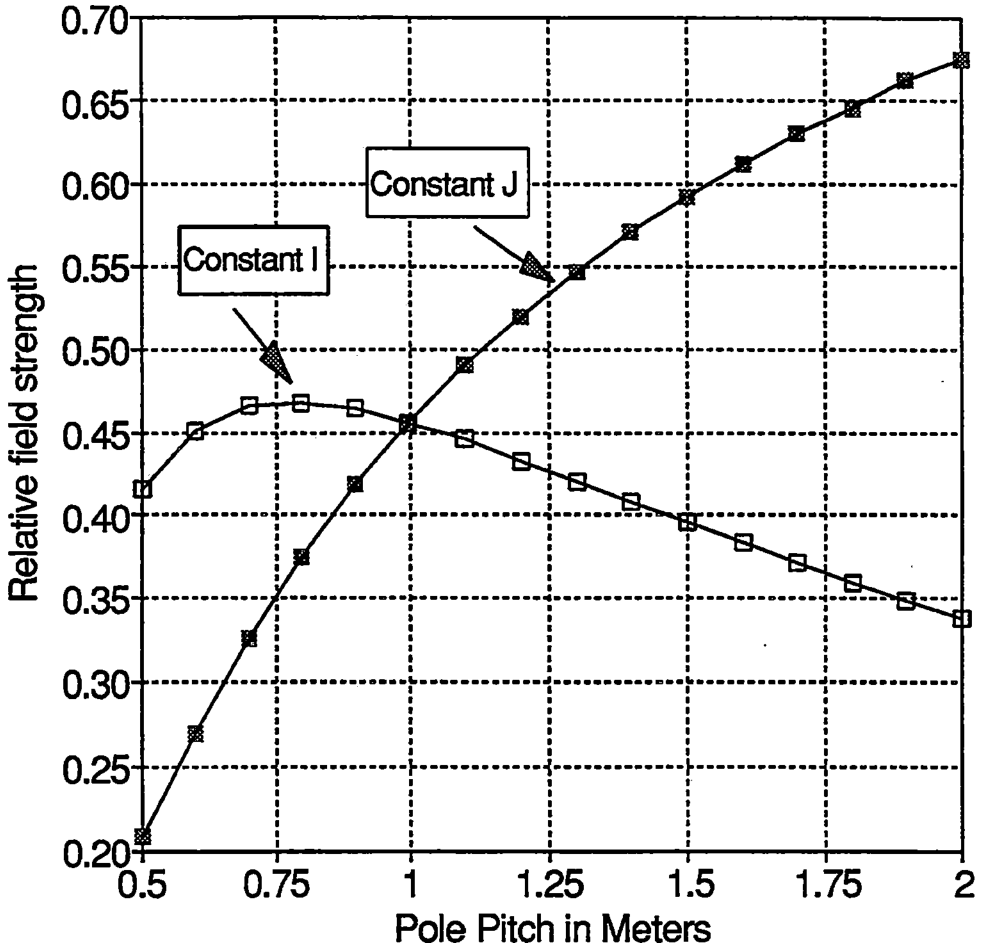


Figure 26 LSM field magnitude at 0.25 m LSM gap

5.3.2.19. LSM AND PROPULSION COIL CURRENT

5.3.2.19.1 MOTIVATION

LSM thrust is proportional to the product of the LSM current and propulsion coil current. The product is constant for a given value of thrust and the two currents can be traded-off against each other.

LSM winding current affects winding voltage, efficiency and power factor. The motivation for this trade-off was to reduce the LSM winding voltage to about 20 kV line-to-line for a 2 km block.

The first baseline design had voltages much higher than this. These were reduced to reduce system cost and improve the expected reliability of the LSM winding.

5.3.2.19.2. CONCLUSIONS

The LSM voltage is reduced to 20 kVAC line-to-line when the propulsion coil system provides 7.8×10^6 AT.

5.3.2.19.3. CALCULATIONS

The following Data from the baseline design was used to perform the tradeoff.

1. Design Thrust: 50000 N
2. LSM Current: 1075 A
3. Total Propulsion Coil AT: 7.8×10^6

The product of LSM current and propulsion coil current (normalized to one turn) is $1075 \times 7.8 \times 10^6$ or 8.38×10^9 A^2. All combinations of current producing 50000 N must have this product.

The tradeoff was performed for 6, 12, and 18 propulsion coils per vehicle since the number of propulsion coils was of interest. The results are shown in Figure 28.

The LSM voltage was approximated as IX where $X = 8.9\ \Omega$ for a 2 kM block at $f = 100$ Hz. The results are shown in Figure 27.

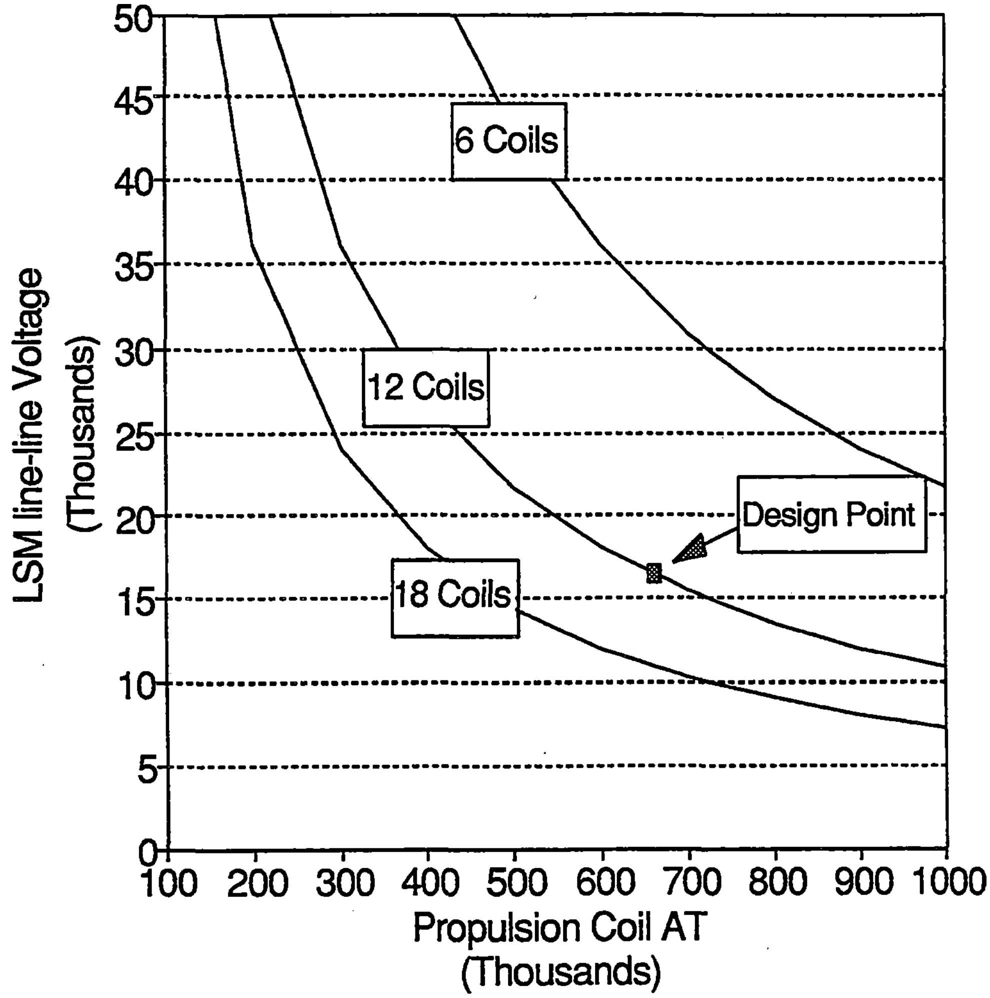


Figure 27 LSM voltage versus propulsion coil AT

4. LSM voltage is reduced to below 20 kVAC line-to-line when the propulsion coils carry more than 650,000 for 12 coils or 400,000 AT for 18 coils. The former was chosen as the design point.

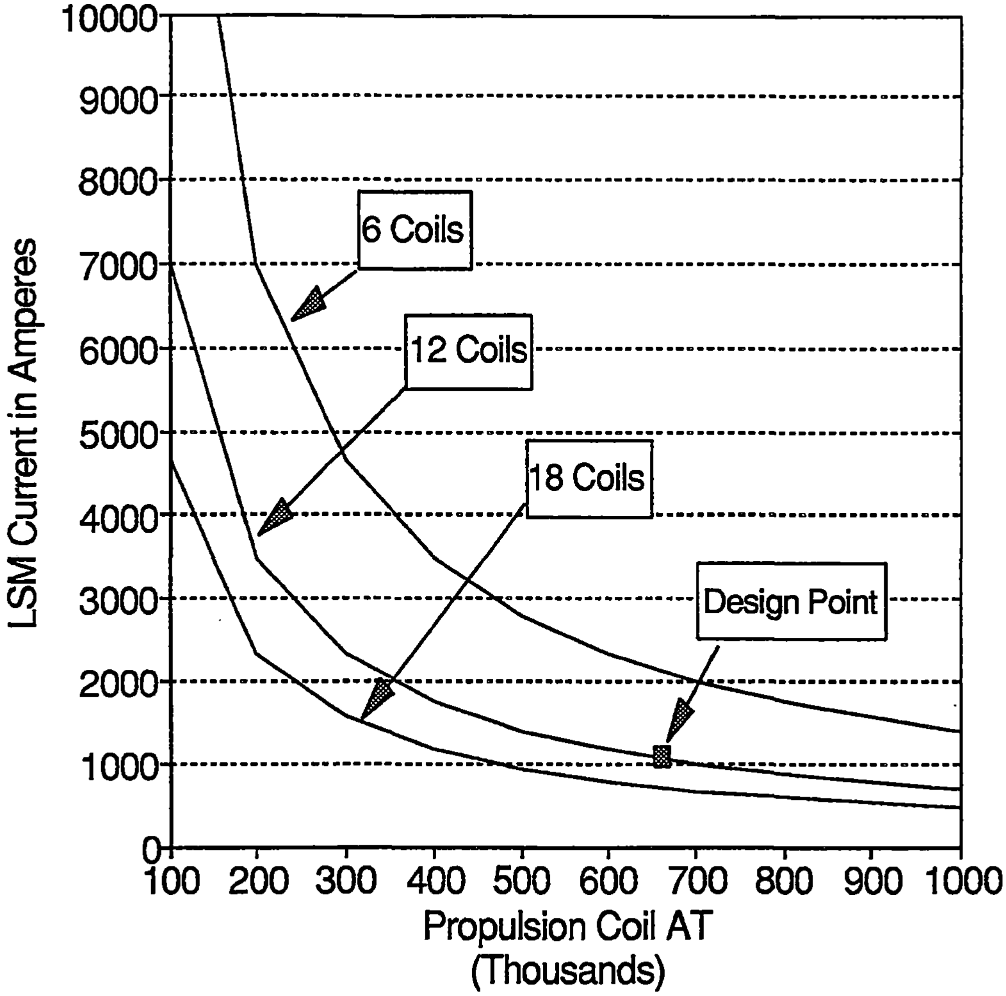


Figure 28 LSM current versus propulsion coil AT

The total propulsion AT is 7.8 x 10^6. The AT in each coil was modified for shielding purposes but this total number of AT was maintained in the final design using 12 coils.

5.3.2.20. CABIN SHIELDING METHODS

5.3.2.20.1. MOTIVATION

The optimal method for shielding passengers from high magnetic fields must be devised.

5.3.2.20.2. CONCLUSIONS

The baseline design incorporates a set of active shield coils with windings distributed to provide field cancellation within the passenger compartment. Concentrating the vehicle levitation and propulsion coils in bogies, alternating the polarity of adjacent coils, and using a non-uniform ampere-turn distribution in the propulsion coil set are additional mitigating approaches that have been used in the baseline.

Section 5.3.2.20.3. explains trade studies to illustrate the benefit of some of these approaches. It concludes with a study showing the impact of selecting field level exposure criteria at the 1, 5, & 50 gauss level for the baseline design.

5.3.2.20.3. CALCULATIONS

Early in the program, shielding studies focused on localized, active shields near the bogie coils of the type illustrated in Figure 31. This shows an outline of the coils and of a plane just below floor level over the bogie. Calculations proceeded to find the ideal ampere-turn requirement for shielding coils located in this plane and to estimate the power and weight required for aluminum coils operating at a typical, conventional coil current density level. Results implied the desirability of extending the shield coil locations up the walls of the vehicle, extending the shielding coils further along the floor, and limiting access over the bogie to a walkway for maintenance or storage only. They also showed the advantages of using a non-uniform amp-turn distribution in the propulsion coil set. Results are given below in Figure 29.

As Figure 29 shows, Case 1 requires the highest shielding coil weight and power. It is a flat shield arrangement (Figure 31) with an equal amp-turn distribution among the propulsion coils (i.e., 6 coils at 6.5E+05 AT per coil). Case 2 has the same propulsion coil current distribution, but uses a shield that limits access to a walkway over the bogie and has shield coils located up the sidewalls to about 1 m above floor level in the bogie area. It shows a weight and power reduction to about 63% of that for Case 1.

Case No.	Coil and Shield Configuration	SHIELDING COILS Weight (kg)	Power (kW)
1	6x650 "Flat Shield" (ref: M02)	7,670	73
2	6x650 1m High Shield (ref: M03)	4,840	46
3	390/4X780/390 1m High Shield (ref: M04)	3,730	36
4	390/4x780/390 2m High Shield (ref: M05)	3,410	33
5	390/4x780/390 Extended High Shield (ref: M07)	2,400	22

Figure 29 Shielding coil power and weight estimates for two bogies

The shield in Case 3 is the same as Case 2, but the amp-turn distribution has been altered to the baseline configuration of 3.9E+05 AT in each end coil and 7.8E+05 AT in the center four coils. This provides the same thrust as the previous cases. There is, however, a further reduction in shield coil weight and power by about 24%.

Case 4 is similar to Case 3, except the shield coils are placed up the walkway walls to a level of about 2 m. This results in an additional reduction of about 10% in shield coil weight and power.

The baseline configuration is given in Case 5 and consists of a shield that covers the bogie area and can be extended into and around the cabin, well beyond the bogie. It yields the best result, that is, a shield coil weight of 2400 kg and a power of 22 kW. The field profiles that result may be found in sections 3.2.1.i and 5.3.6. (Note: the baseline weight and power budget has been set at 3400 kg and 33 kW to allow a 50% contingency for special local shielding requirements in the vehicle.)

The impact of limiting the field exposure level for passengers in the vehicle to the 1, 5, or 50 gauss can be illustrated by considering the results given in Figure 30. The upper part of the first column gives the

	Option One		Option Two		Option Three	
	No Shield		Bogie Shield		Ext Bogie Shield	
Field Limit [gauss]	Delete Seats	Extend Length [m]	Delete Seats	Extend Length [m]	Delete Seats	Extend Length [m]
50	0	0	0	0	0	0
5	15	2.44	5	0.81	0	0
1	35	5.70	20	3.26	5	0.81
Vehicle Shield Characteristics						
Configuration						
140	Shield Wt = 0		Shield Wt = 3400 kg		Shield Wt = 2400kg	
	Shield Pwr = 0		Shield Pwr = 33 kW		Shield Pwr = 23 kW	
45	Shield Wt = 0		Shield Wt = 2300 kg		Shield Wt = 1600kg	
	Shield Pwr = 0		Shield Pwr = 22 kW		Shield Pwr = 16 kW	

Figure 30 Impact of field exposure limitation (bogies only)

limiting field value, then three options are considered with two mitigating approaches under each option, that is, delete seats or extend the length of the vehicle. Either approach removes passengers from the field level indicated.

Option One is the same as the baseline vehicle configuration, but with no shield, hence, there is no shield weight or power penalty for either the 140 or 45 passenger vehicles. Both vehicles can also seat all their passengers in areas with fields below 50 gauss. If, however, the field limit were 5 gauss, then either 15 seats would have to be deleted or the vehicles would have to be lengthened by 2.44 m. Similarly, if the limit were 1 gauss, then 35 seats would have to be removed or the vehicles lengthened by 5.7 m. It is clear that setting the field exposure level lower than necessary can have a strong impact on vehicle cost for the no shield case.

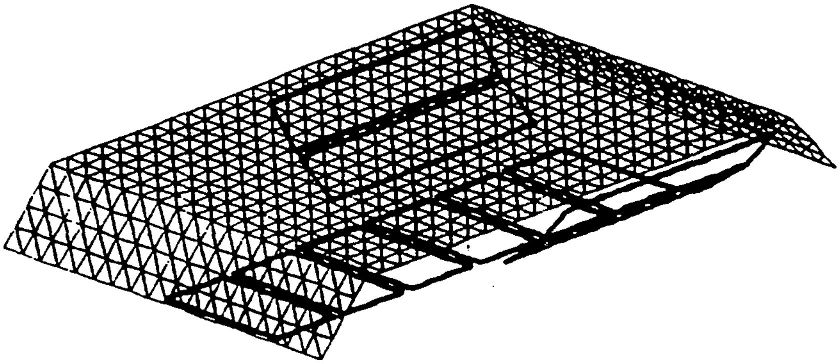


Figure 31 View of coils in bogie and "flat" shield

Option Two uses a shield coil arrangement that is limited to the bogie area and Option Three uses an extended shield that extends well into and around the cabin. The presence of the shield mitigates the need to remove large numbers of seats or alter the vehicle length significantly, even if the lower field limits are selected. However, there is a significant weight and power penalty for carrying the shield.

The baseline shield is that for Option Three, but with an Option Two budget for shield weight and power. The 50% contingency is available to allow local shielding where needed to satisfy the 1 gauss requirement and for shielding of sensitive equipment or sensitive areas.

5.3.2.21. PROPULSION CONFIGURATION IN CURVES

5.3.2.21.1. MOTIVATION

If a vehicle that is going very slowly through a curve or stops in a curve, the vehicle roll angle will decrease towards 0. Thus the vehicle may be oriented in such a way that its propulsion magnets are out of alignment with the LSM windings in the curved section of magway. An approach must be developed to deal with the contingency of stopping in a curve. Alternative configurations include variation of the magway elements in curves and/or a variation in the on-board magnet bogie configuration.

5.3.2.21.2. CONCLUSIONS

The baseline system uses a modification of the LSM winding width to achieve acceptable low speed performance on curves. This solution allows the vehicle to accelerate from an upright stopped position in a banked, curved section of guideway. The vehicle may achieve speeds of greater than 10 m/sec with the lowest coupling (highest misalignment). It will proceed at low speed until it leaves the curved section of magway. When the vehicle reaches a straight, unbanked section of magway the misalignment angle approaches 0 and normal LSM coupling is established. At this point normal operations resume.

5.3.2.21.3. CALCULATIONS

Figure 32 illustrates the problem using an earlier design in which the gap between magway sheets and the width of the LSM was the same in curves as it is along the straightaway. The top figure shows the vehicle negotiating a curve with a 35 degree bank angle at the design speed. In such a case, the propulsion coils are aligned with the LSM so that the vehicle has the design thrust throughout the curve.

In contrast, the lower figure shows the vehicle stopped in the turn. In this case, the propulsion coils are totally disengaged from the LSM because of the high bank angle of the magway. The levitation coils do not help in this situation because of their quadrupole nature. Since the propulsive force falls off roughly linearly with the angular misalignment of the vehicle centerline to the location of the LSM, there will be insufficient propulsive force in this configuration for the vehicle to leave the curve under its own power.

This situation is alleviated by using a wider LSM and larger levitation gap width in banked curve sections of magway. Figure 33 and Figure 34 show a typical magway section and a magway section for a 35 degree bank angle. Note that the LSM width in the banked, curved section has been increased from 1.4 to 1.7 m with the increased width on the lower side of the LSM winding. The "Semi-Gap" has increase from .7 to 1.0 m. The effect of this change is to provide LSM coupling to the on-board propulsion magnets over a wider range of misalignment angle as shown in Figure 35A.

In this case the available thrust decreases with misalignment but at 35 degree misalignment there is still in excess of 40 kN thrust capability. Although there is insufficient thrust to propel the vehicle over the drag peak, it will be possible to move the vehicle at reduced speed out of the curved magway section. When the misalignment angle is reduced the vehicle may resume normal operations.

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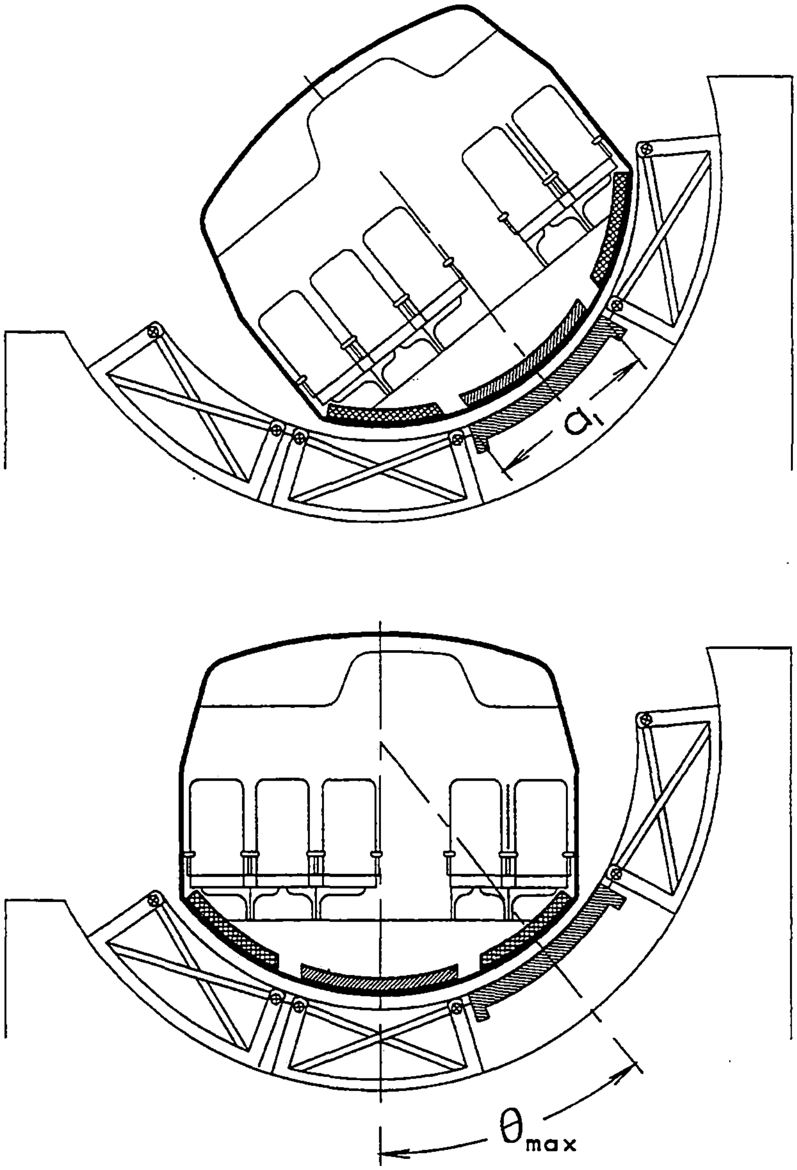


Figure 32 Curved, banked magway section for 35° coordinated curve (*top:* optimal coupling at design speed; *bottom:* effectively zero coupling at zero speed)

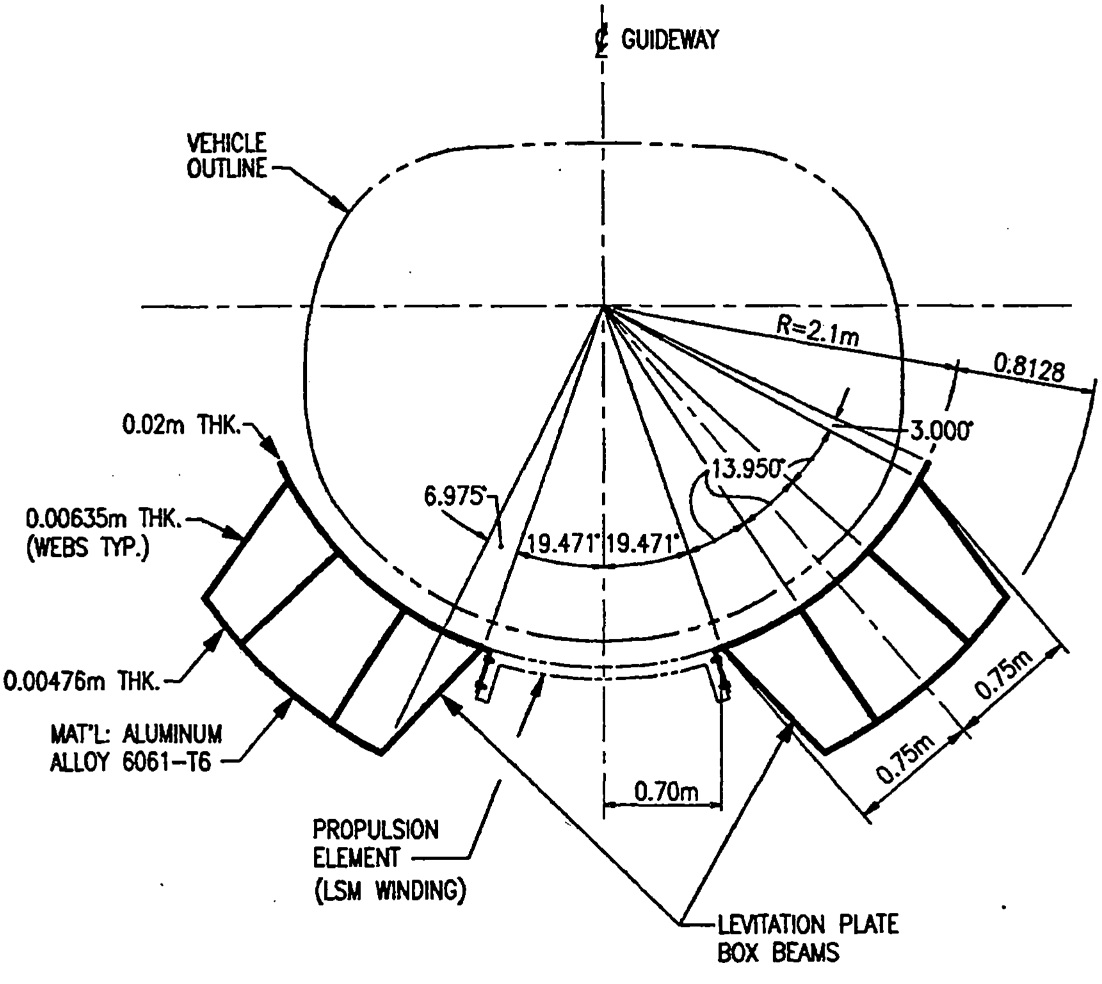


Figure 33 Typical straight magway section with 1.4 m wise LSM (0.7 m semi-gap)

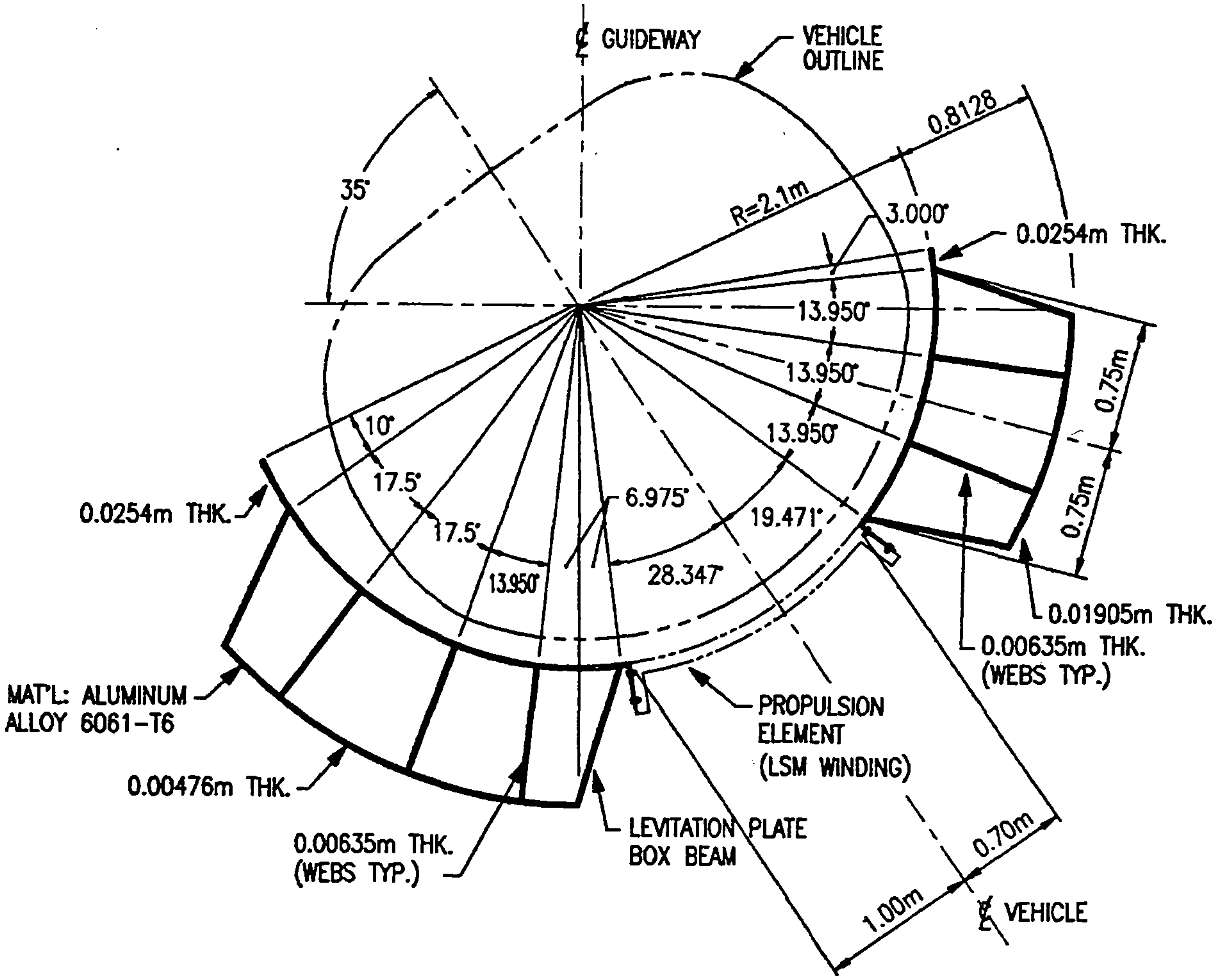


Figure 34 Typical banked magway section with 1.7 m wide LSM (1.0 m semi-gap *on lower side*)

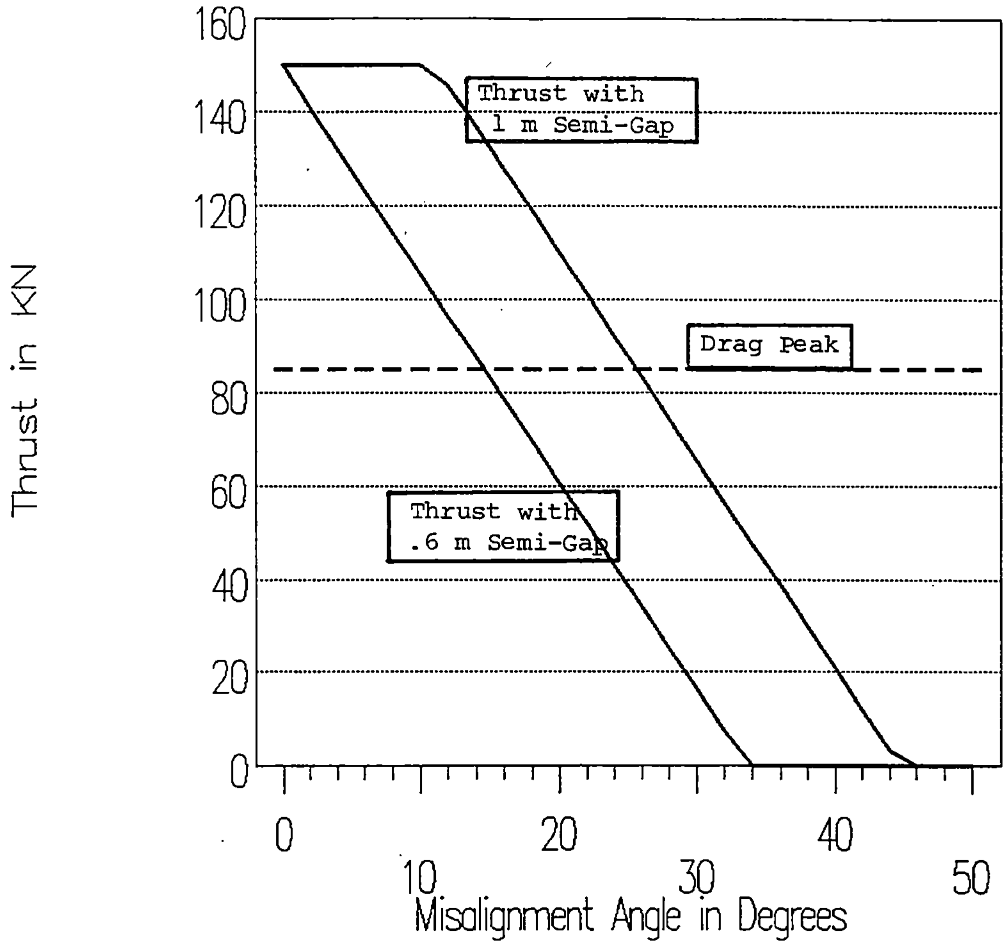


Figure 35A Thrust versus misalignment angle showing propulsion capability with 1.0 m semi-gap

5.3.2.22. SWITCH OPTIONS

5.3.2.22.1. MOTIVATION

A switch must be designed that will permit rapid reliable switching of vehicles to off-line magports.

5.3.2.22.2. CONCLUSIONS

The baseline switch for Magneplane as described in section 3.2.2.d. is totally electromagnetic and uses a combination of null flux coils and LSM windings over a single flat aluminum sheet in the main switching section. Transition sections use a dual sheet magway. The primary lift and guidance forces while switching occur through the interaction of the vehicle propulsion coils with the magway and null flux coils.

5.3.2.22.3. CALCULATIONS

A viable alternative that was developed early in the program is a mechanical switch that is shown in Figure 35. It is designed for 100 m/s operation. The switch consists of a sequence of nine metre long magway sections that are pinned together and mounted on carriages. The joints allow the switch to conform to the straightaway or the branch. The carriages travel on rails on concrete beams and have a length of travel that varies up to a maximum of 4.5 m at the last span. A hydraulic cylinder located on the concrete beam moves the magway sections between switch positions. An extendable tongue connector in the stationary levitation sheet beam is provided for each switch position to lock the last magway section in place when motion is complete. Stops are provided for the carriages in each switch position. Although this concept is considered feasible, it is believed to be more expensive and to require more cycle time than the baseline.

Figure 36 shows a Magswitch with a varying gap between magway sheets and a varying width LSM winding. This was also based on interactions for lift and guidance between the propulsion coils and the magway sheets. Analyses indicated the need to provide additional coils and to close the aluminum sheet under the vehicle in the main switch section, so the design activity evolved toward the present baseline case. Figure 37, Figure 38, and Figure 39 show other options that were considered for use as switching concepts early in the program.

Concept A in Figure 37 involves the activation of one of two LSM's in the switch area to select either the left or right branch of the switch. S1 or S2 thus provide both propulsion and guidance through the switch. Lift is maintained in the switch area by mechanically extending the lift coils on one side (or the other) of the vehicle to retain the operating clearance to the magway as the magway flattens and "falls away" from the vehicle on that side. Although the operational mechanics are conceptually valid, this alternative was not considered further because it was considered less attractive from the safety and reliability standpoint than the options discussed above.

Concepts B and C are shown in Figure 38 and Figure 39, respectively. In each case, four LSM windings are used in the magway and two are activated to select either the left or right branches of the switch.

In Figure 38, winding S1 or S2 provides propulsion and guidance, whereas winding S3 or S4 interacts with the levitation module to provide lift on the side of the vehicle with the increased clearance relative to the magway in the switch area. Estimates indicated that this concept would require excessive magway LSM current and power to perform the levitation function, hence, it was not considered further.

The concept in Figure 39 is similar to that in Figure 38, except that LSM windings S3 or S4 are used to provide attraction on the side of the vehicle on the inside of the turn. S1 or S2 provide propulsion, guidance and lift. Estimates indicated that this concept would also require excessive magway LSM current and power to perform the lift function with S1 or S2, hence, this concept was not considered further either.

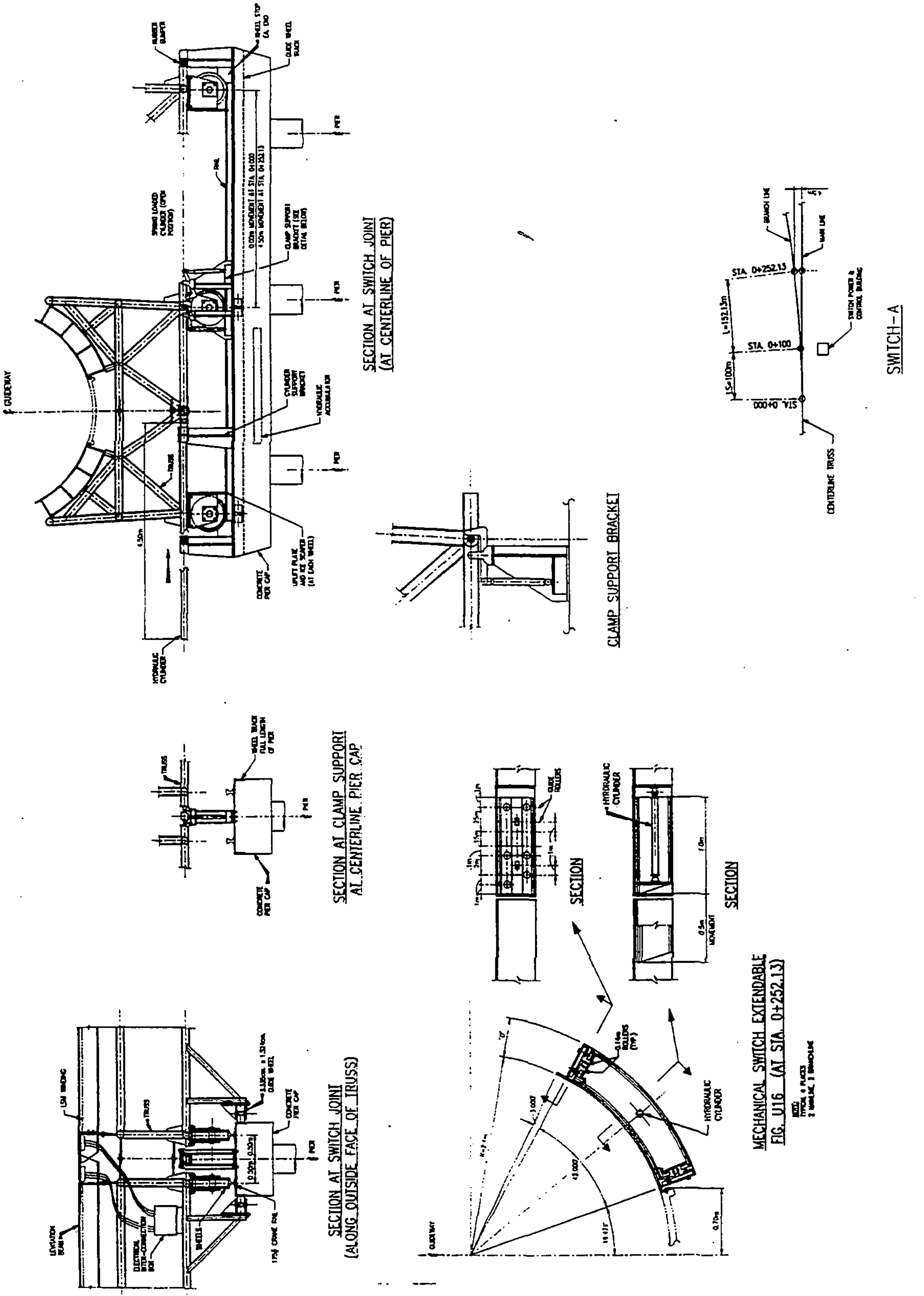


Figure 35 Mechanical switch alternative

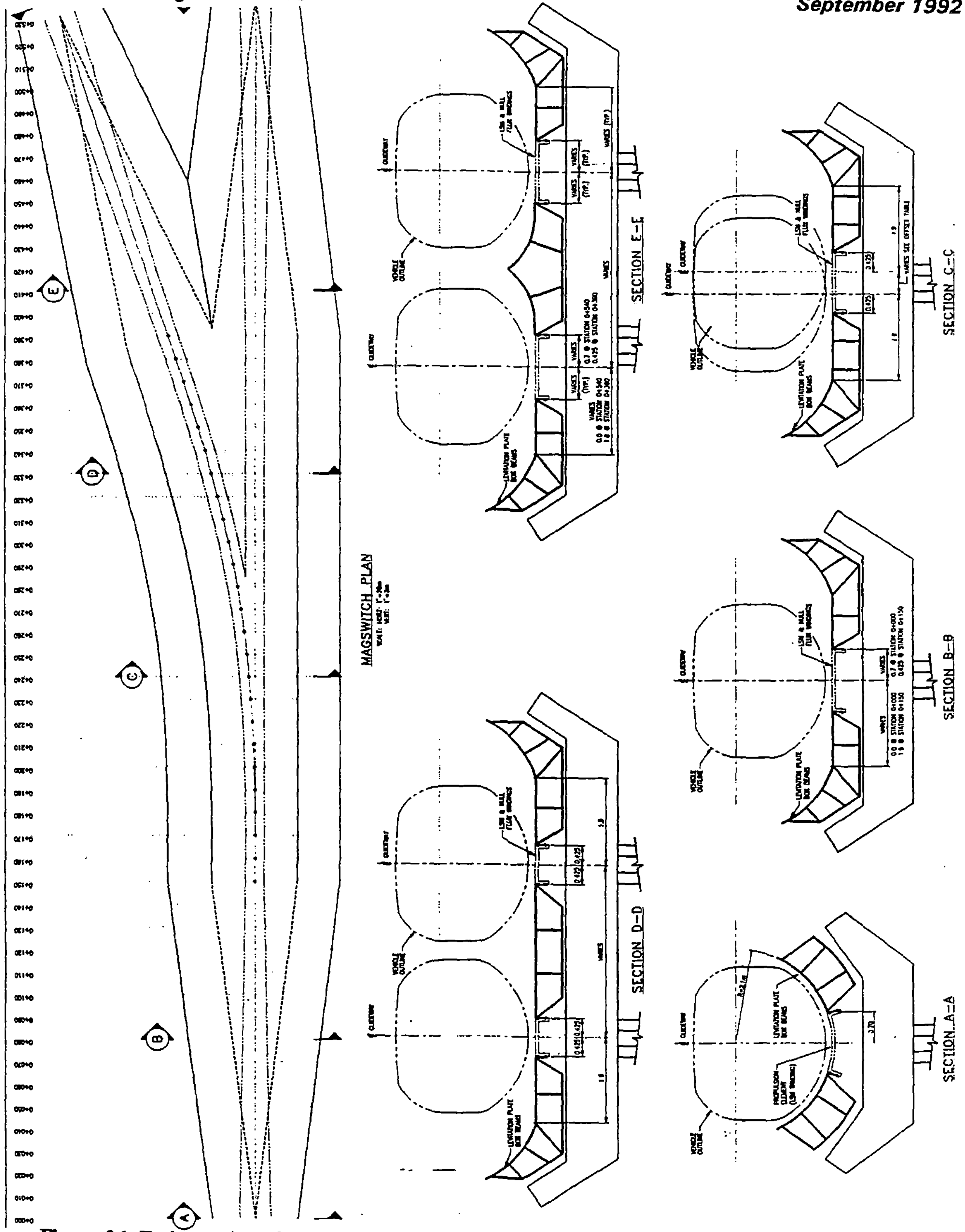


Figure 36 Early version of magswitch with dual sheet magway throughout

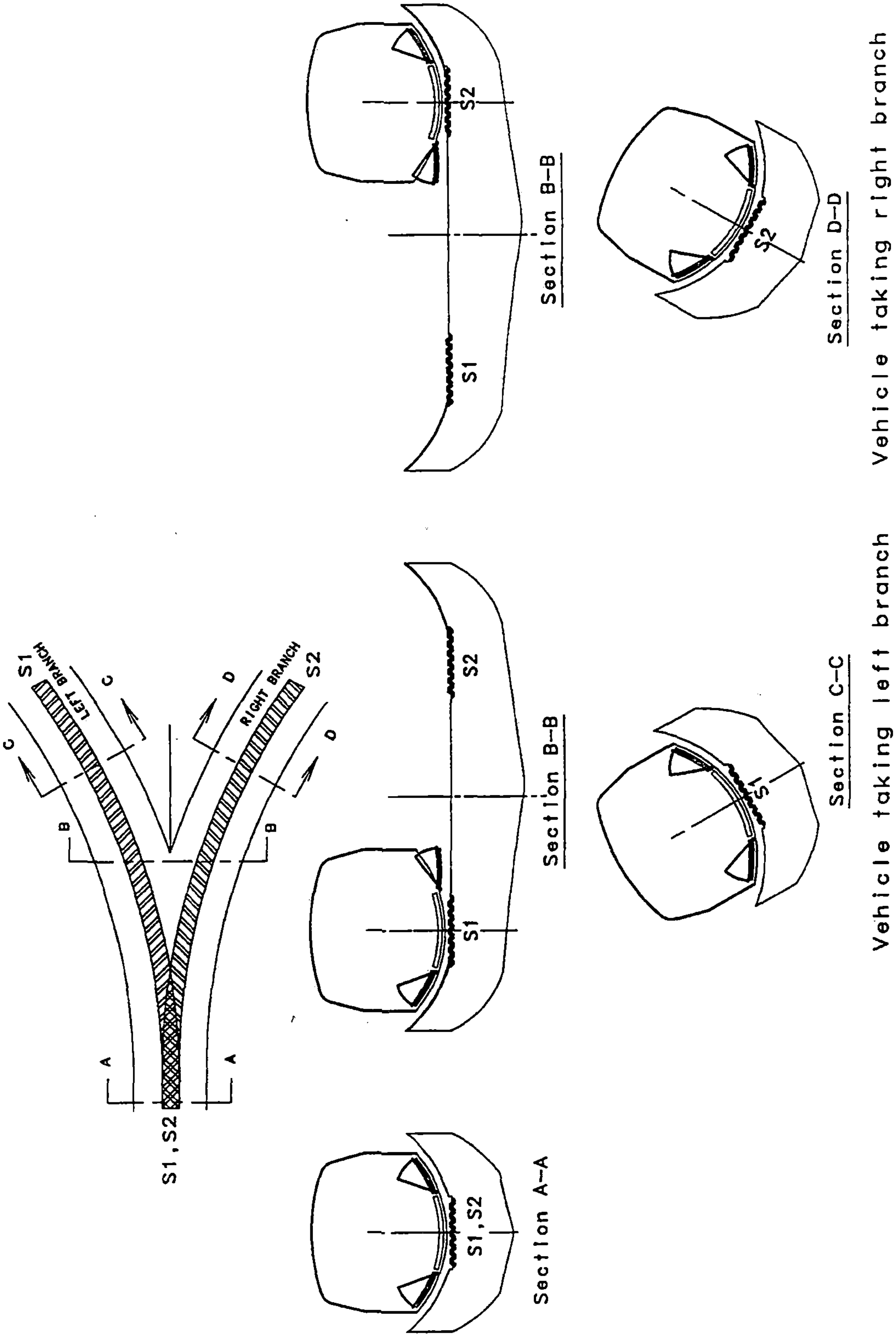
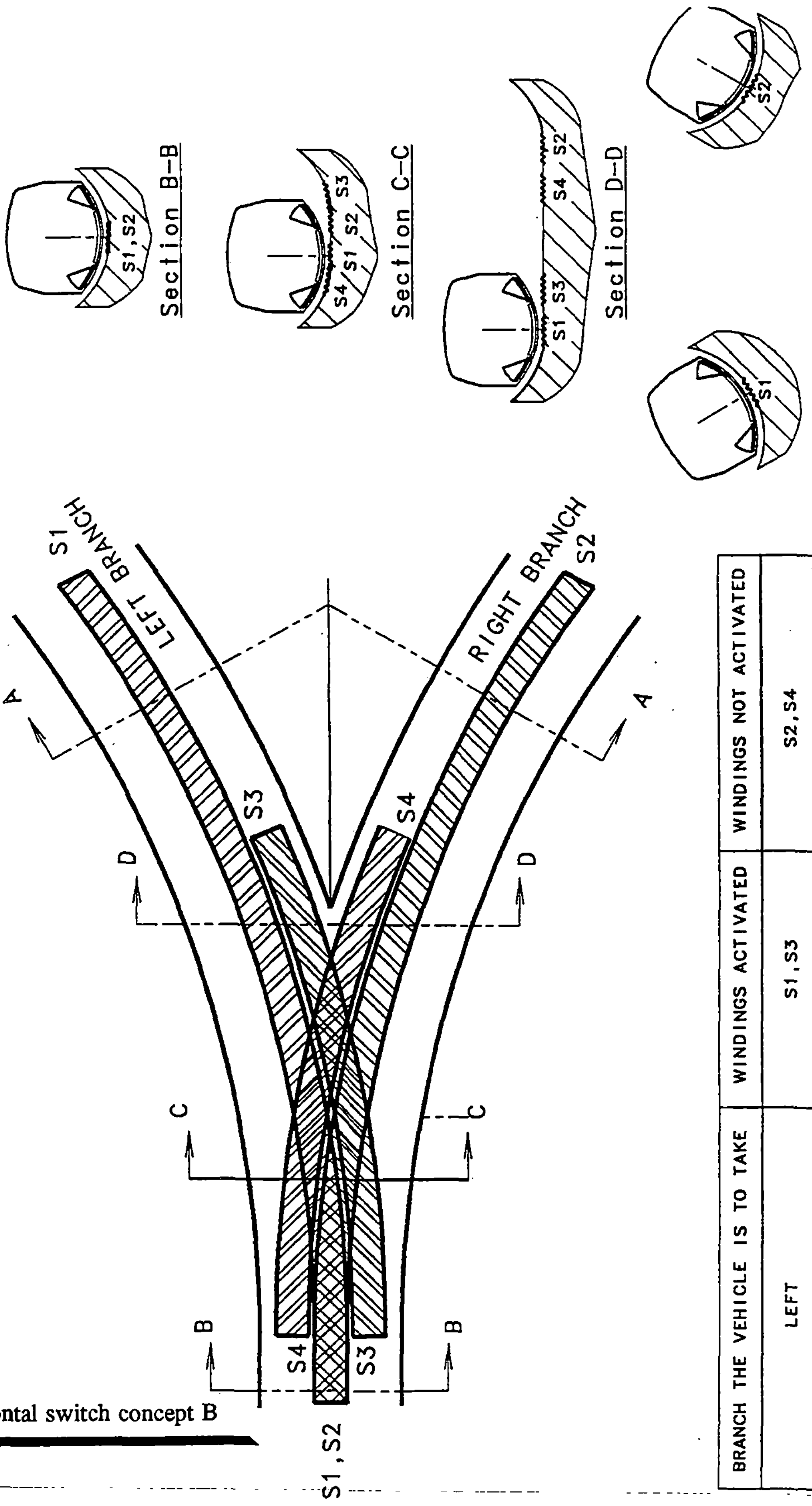
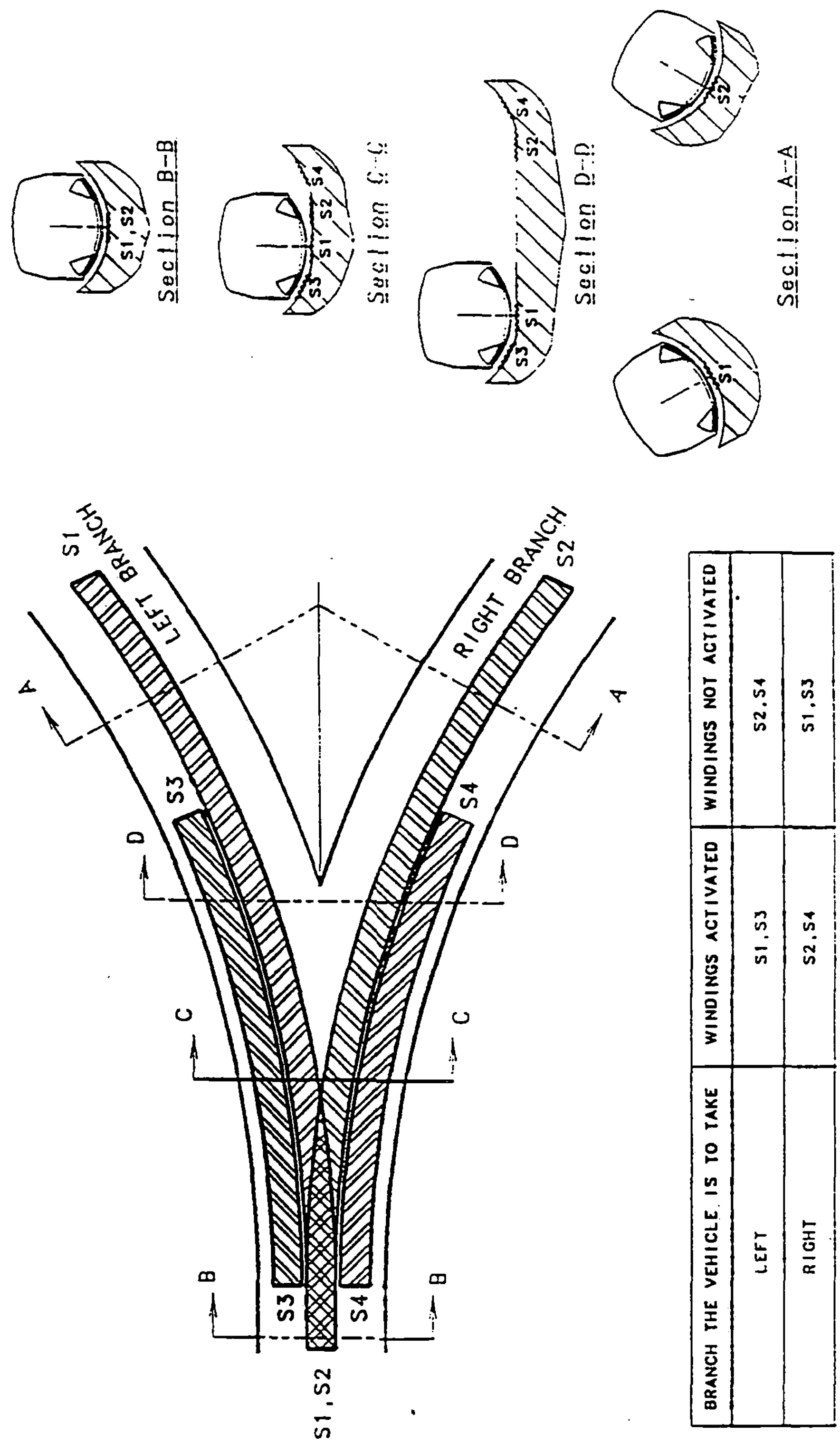


Figure 37 Horizontal switch concept A - extend lift coils



BRANCH THE VEHICLE IS TO TAKE	WINDINGS ACTIVATED	WINDINGS NOT ACTIVATED
LEFT	S1,S3	S2,S4
RIGHT	S2,S4	S1,S3

Figure 38 Horizontal switch concept B



BRANCH THE VEHICLE IS TO TAKE	WINDINGS ACTIVATED	WINDINGS NOT ACTIVATED
LEFT	S1, S3	S2, S4
RIGHT	S2, S4	S1, S3

Figure 39 Horizontal switch concept C

5.3.2.23. MAGWAY STRUCTURAL SYSTEM

5.3.2.23.1. MOTIVATION

Since the magway and its supporting structure comprise a majority of the cost of a Magneplane system, its cost effectiveness is critical to the program. The structural system must adequately support the magway trough at a variety of heights above grade and at a variety of spans between vertical supports as may be dictated by conditions along an actual route. The statement of work required that magways be designed for specific ranges of heights and spans.

5.3.2.23.2. CONCLUSIONS

The structural system consisting of aluminum box beams spanning between concrete supports is the most cost effective magway system based on an extensive structural study of many materials and configurations as described in the following sections. The optimum span length varies with magway height as shown in Section 5.3.2.25., however, the aluminum box beam system presently has a practical span limit of 14 m (45'). Where the magway is required to span longer distances, the steel truss support is shown to be the most cost effective, however, concrete beams may also be competitive depending on local situations and future market conditions.

Figure 40, Figure 41, and Figure 42 indicate costs per meter as a function of span length for a variety of heights for aluminum, steel and concrete double magways. Figure 43, Figure 44, and Figure 45 compare costs of the three systems on one graph for heights of 0.61 m, 5.18 m and 20 m.

5.3.2.23.3. CALCULATIONS

A variety of materials and configurations were initially considered for the structure used to support the magway trough. These concepts were given a preliminary screening for practicality considering several factors such as cost, aesthetics, and safety. Preliminary structural designs were done for three systems that passed the preliminary screening. Material quantities based on these preliminary designs were then used to provide estimated costs.

5.3.2.23.3.a. ALTERNATES CONSIDERED FOR PRELIMINARY SCREENING

1. **Aluminum box beams spanning between concrete supports.** See Figure 46 and Figure Figure 47.

This is perhaps the simplest configuration as it utilizes the strength of the stiffened levitation plates of the magway trough to span between concrete supports without any additional supporting structure. Both materials are relatively maintenance free as they do not require painting. The depth of the stiffeners (box beam) varies with the length of span, calculations were done for box beams spanning up to 18 meters (60 ft.), however, this span has a practical limit of approximately 14 meters. This configuration is a definite candidate for the "at grade" and tunnel magway with relatively short span lengths between supports (up to 10 meters). For elevated heights, it was initially felt that this system did not meet the design goal (DG) of having an independent support structure (reference 3.1.3(c) of SOW). However, in an in-progress design review meeting held on June 4 and 5, 1992, the COE personnel advised that aluminum box beams spanning between concrete supports would satisfy the intent of the referenced section and therefore the system would also be acceptable for elevated magways.

As a variation on this system, aluminum or steel supports are alternates to the concrete piers. The metal supports have the advantage of providing a means of "modularizing" the magway trough which includes both levitation plates and the LSM winding. The entire magway trough can be preassembled on the supports and then transported and erected as a unit onto concrete foundations or in the case of a tunnel, directly on the concrete floor.

2. **Aluminum box beams incorporated into an aluminum truss structure.** Figure Figure 50

   This configuration incorporates the aluminum box beams as the top chord of an aluminum structure. This system would have the advantage of low maintenance. It would be lighter weight than concrete or steel systems which would have the advantage of reducing footing costs. However, this system has the disadvantage that the truss length would be limited to the spacing of the thermal expansion joints which is presently determined to be 18 m (60'). This would obviously not meet the requirement of investigating spans up to 46 m (150'). Being restricted to the shorter spans, this system would basically be a variation of alternate 1 and would require a similar quantity of aluminum to provide the structural strengths to span between supports. As a result, this system was not pursued further.

3. **Prestressed concrete box beams.** See Figure 48 and Figure 49

   This system consists of precast or cast in place concrete box beams spanning between concrete column caps on concrete columns. The system has the advantage of low maintenance and pleasing aesthetics. A disadvantage would be its relatively heavy weight. This system lends itself to a variety of configurations and construction techniques. It is a strong candidate for both the single and double magway for all spans from 9 m (30') to 46 m (150').

4. **Steel truss under.** Figure 52 and Figure 51

This system utilizes a steel truss composed of tubular members to span between concrete column caps on concrete columns. This system can be fabricated in the shop and erected on location, is relatively light weight, can be designed to meet the deflection requirements, and can be configured to meet the varying alignments at switches, crossovers and stations. The disadvantage of requiring maintenance (painting) can be mitigated through the use of improved coatings. This system is a strong candidate for both the single and double magway for all spans from 9 m (30') to 46 M (150').

5. **Steel truss enclosed.** Figure 54 and Figure 53

This system employs either a rectangular or octagonal steel truss that surrounds and supports the magway trough and spans between concrete column caps on concrete columns. This structure would typically be enclosed using any of several siding materials such as aluminum, fiberglass or coated steel. This system would offer several advantages including: excellent security for the magway, prevention of ice and snow buildup, and generous space for utility corridors. It is inherently stiff due to its depth which would permit longer distances between supports. This system has the disadvantages of being difficult to transport as a completed module due to its size, and requiring further research to determine the optimum cross-sectional area and/or the amount of relief openings to mitigate aerodynamic effects. A preliminary design was accomplished for a rectangular cross section. As expected, this system's cost was appreciably more than other systems. For this reason, it is not considered a candidate for the typical cross-country system and did not receive further study or optimization based on span or height. It should be noted, however, that special circumstances may require an enclosed magway. For example, some urban areas may require the security or screening that it offers, or an area of extremely harsh climate may need protection from particularly heavy snowfall. In these special cases, the use of this type of system may be justified especially if a reduced speed is acceptable for the section.

6. **Steel tube.** Figure 55

In this system, a steel tube acts both as a supporting structure and enclosure. It would be stiffened internally as required. As in the previous system, this configuration would offer excellent security and weather protection. It would, however, be more difficult to provide the necessary openings since the enclosure itself is the structure. It also has the serious disadvantage of very limited access in the event of an emergency. For this reason, this system was not investigated further. However, in areas where an enclosed magway would be required the system may merit future consideration.

5.3.2.23.3.b. RESULTS OF PRELIMINARY SCREENING

The following systems were considered for further study and optimization:

1. **Aluminum box beam.** For "at grade" and up to 14 m span.

3. **Concrete box beam.** Single and double for all spans.

4. **Steel truss under.** Single and double for all spans.

The following systems were not pursued further for the reasons given:

2. **Aluminum truss.** Limited to 18 m, similar to alternate 1.

5. **Steel truss enclosed.** Preliminary design indicated high cost for typical magway, however, system should be considered if local conditions require an enclosed magway.

6. **Steel tube.** Safety concern due to limited access or egress in the event of an emergency, however, system should be considered if local conditions require an enclosed magway.

5.3.2.23.3.c. PRELIMINARY DESIGNS AND COST ESTIMATES

A preliminary structural design was done for each of the three selected systems for a variety of spans and heights as requested by the COE in their letter of 16 March 1992. The design was based on the structural criteria as outlined in Section 3.2.2.a. Specifically, designs were accomplished for the single and double concrete box beam and the single and double steel truss configurations for the following spans and heights:

For 9.14 m (30') spans, these heights: 0.61 m (2'), 0.91 m (3'), 5.18 m (17'), 7.62 m (25'), 9.14 m (30'), 20 m (65.6')

For 22.86 m (75') spans, these heights: 0.61 m (2'), 0.91 m (3'), 5.18 m (17'), 7.62 m (25'), 9.14 m (30'), 20 m (65.6')

For 36.58 m (120') spans, these heights: 0.61 m (2'), 0.91 m (3'), 5.18 m (17'), 7.62 m (25'), 9.14 m (30'), 20 m (65.6')

Designs were also accomplished for the aluminum box beam for spans of 4.6 m (15'), 9.14 m (30'), and 13.72 m (45') at heights of 0.61 (2') up to 20 m (65.6') and for a single steel truss spanning 4.73 m (150') at a height of 22.86 m (75').

The results of the above designs, including both quantities and costs, are shown in Figure 56 and the 18 following pages.

The estimating approach is given in Section 5.3.11.2. A listing of some items pertaining to the magway system is given here for convenience:

- As directed by the COE, civil costs such as land costs, demolition, and civil reconstruction are not to be included.
- Other site specific civil costs are not included since (1) there would be little difference between the contending maglev concepts, and (2) the information can be obtained from the Parsons, Brinkerhoff, Quade and Douglas reports. (Nor would this affect the span

length/height tradeoff studies since items such as fencing and access roads are assumed to be continuous along the route.)

- The magway costs include the magway trough (LSM winding and levitation plate box beams), support structures, column caps (cross beams), columns (piers) and footings.
- Pricing is based on 1991 dollars per COE direction.
- Amounts shown in the tables are generally in English units to be consistent with historic civil/structural estimating data bases. The totals, however, have been converted to dollars/meter.

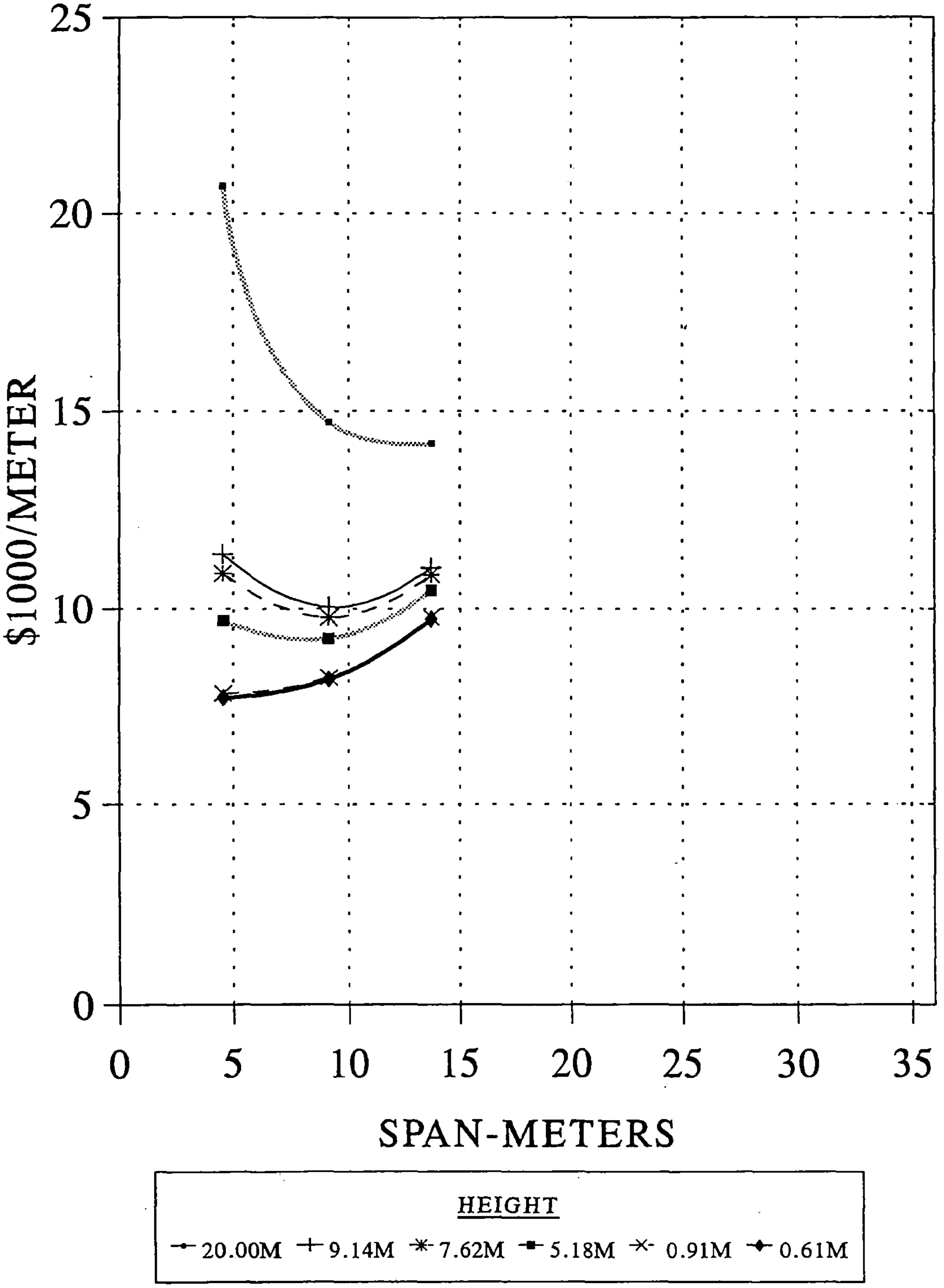


Figure 40 Aluminum box beam - double

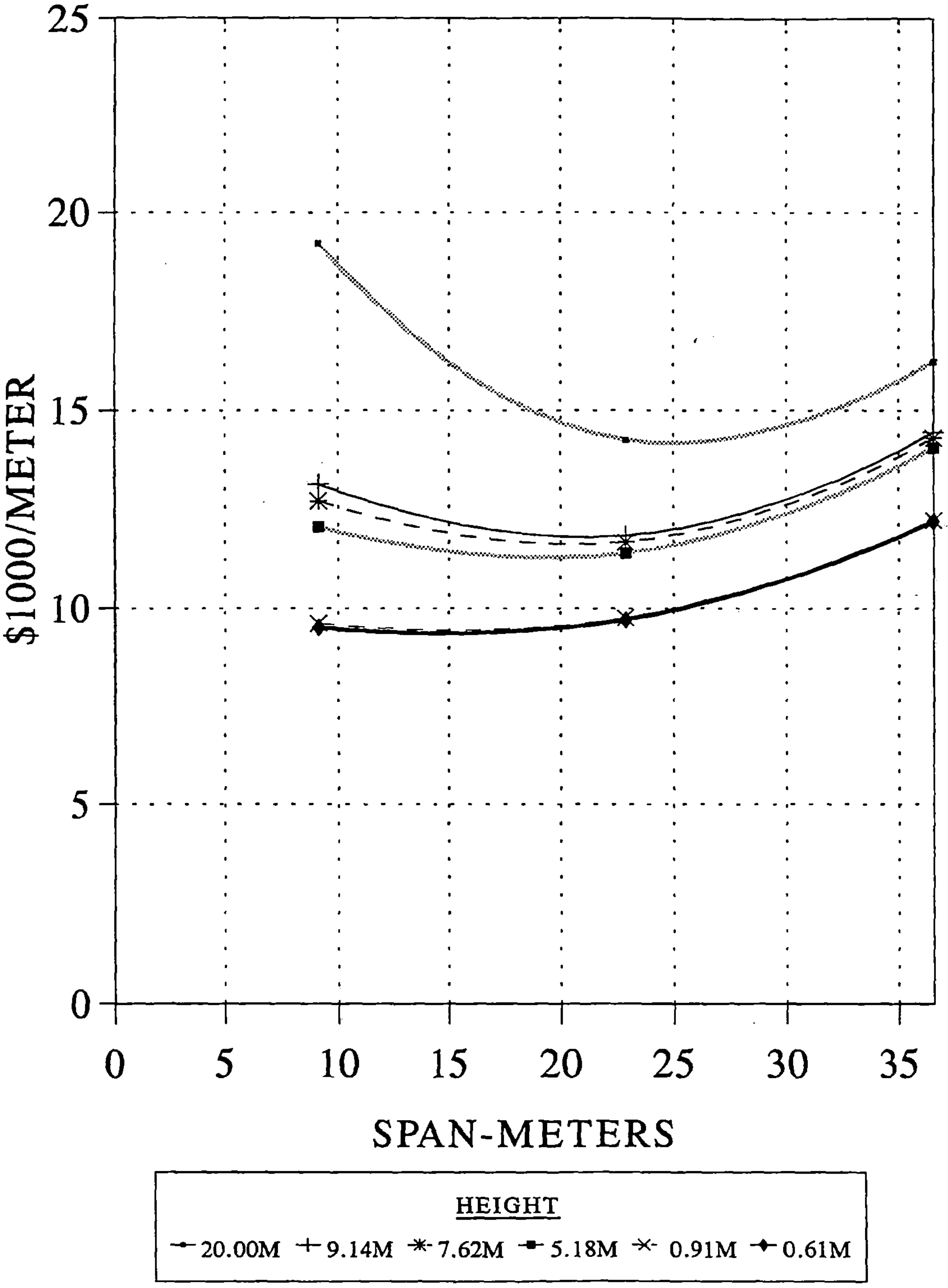


Figure 41 Steel truss - double

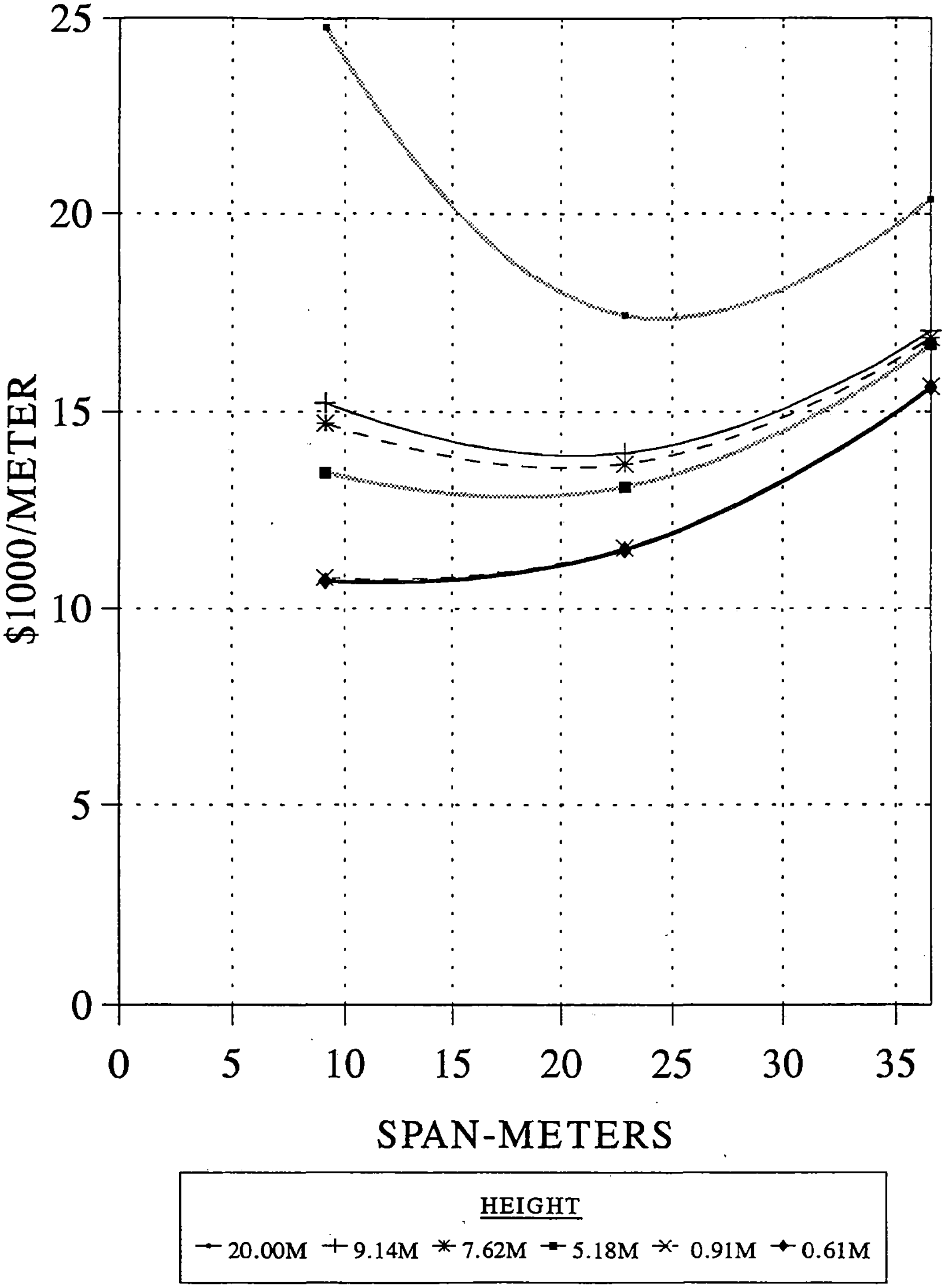


Figure 42 Concrete beam - double

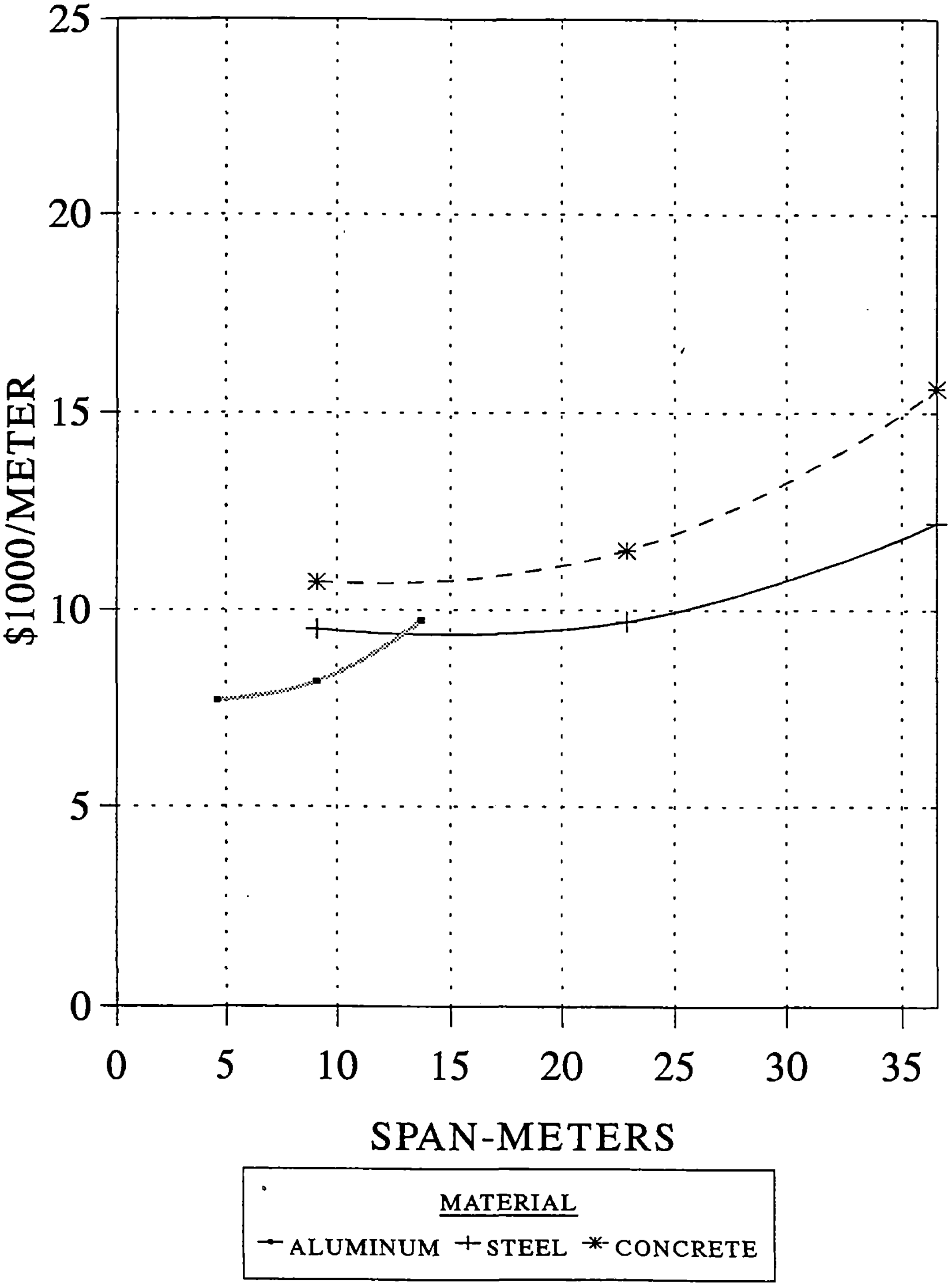


Figure 43 Comparison of magway system costs for a height of 0.61 m

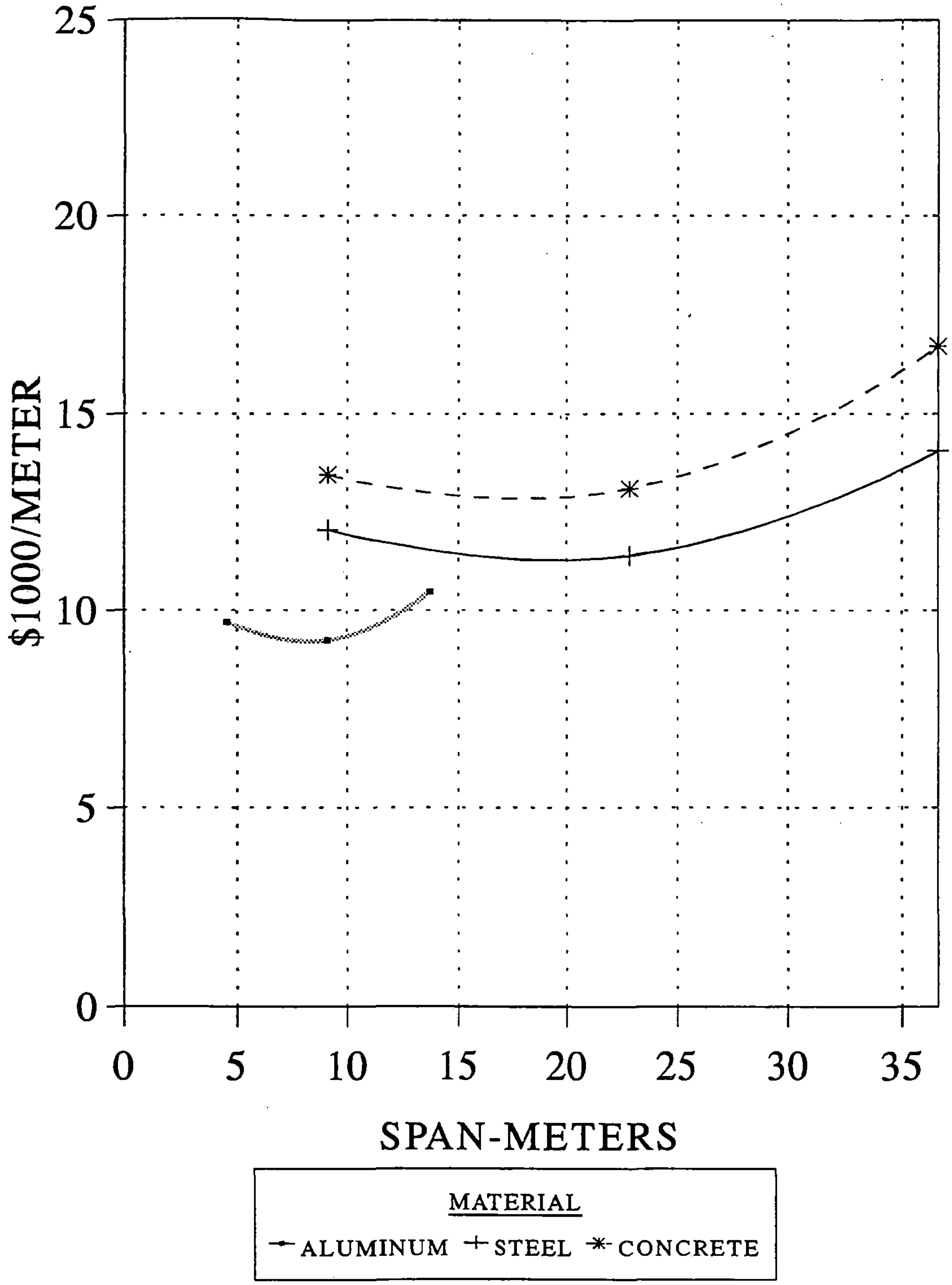


Figure 44 Comparison of magway system costs for a height of 5.18 m

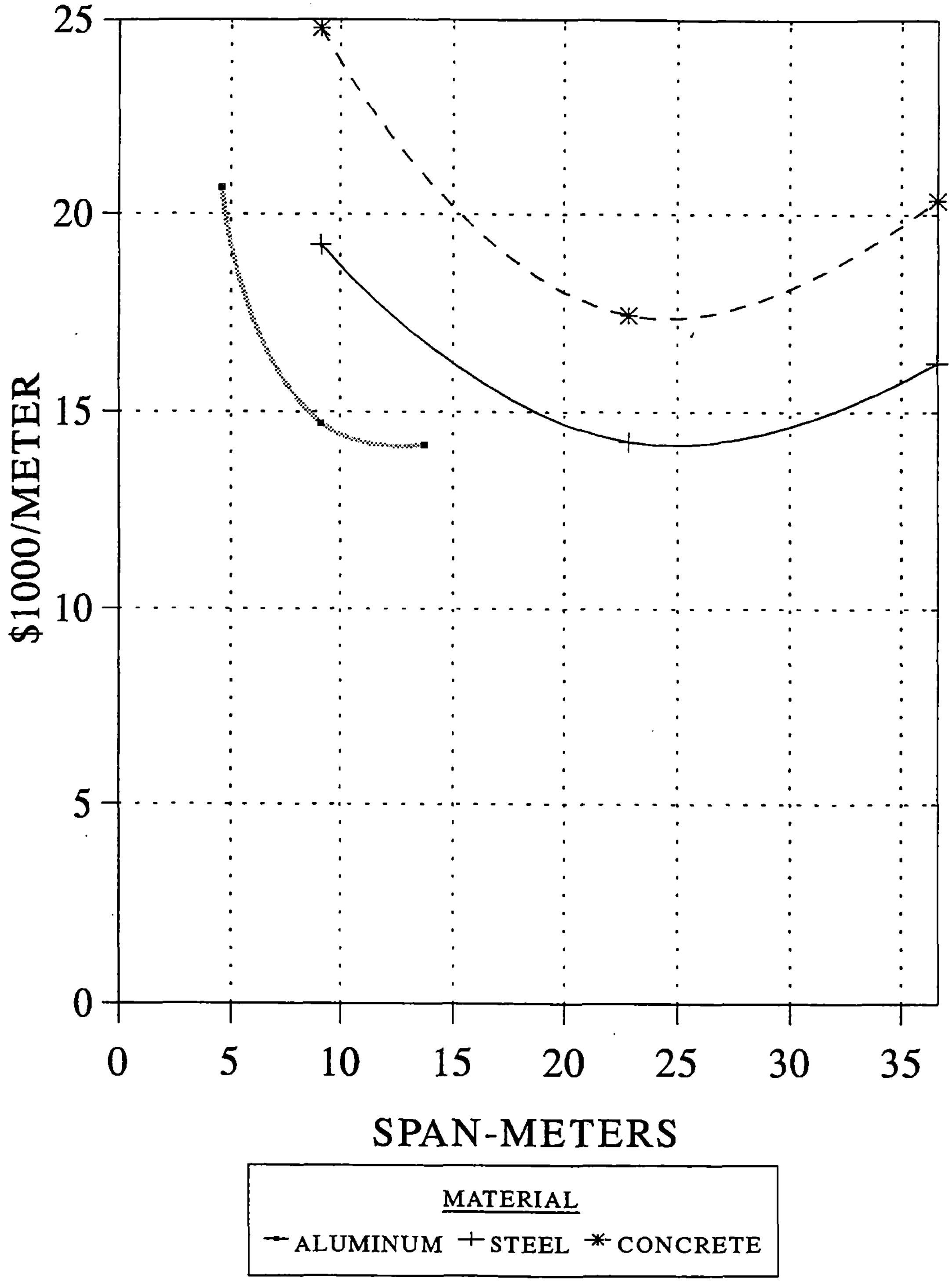


Figure 45 Comparison of magway system costs for a height of 20 m

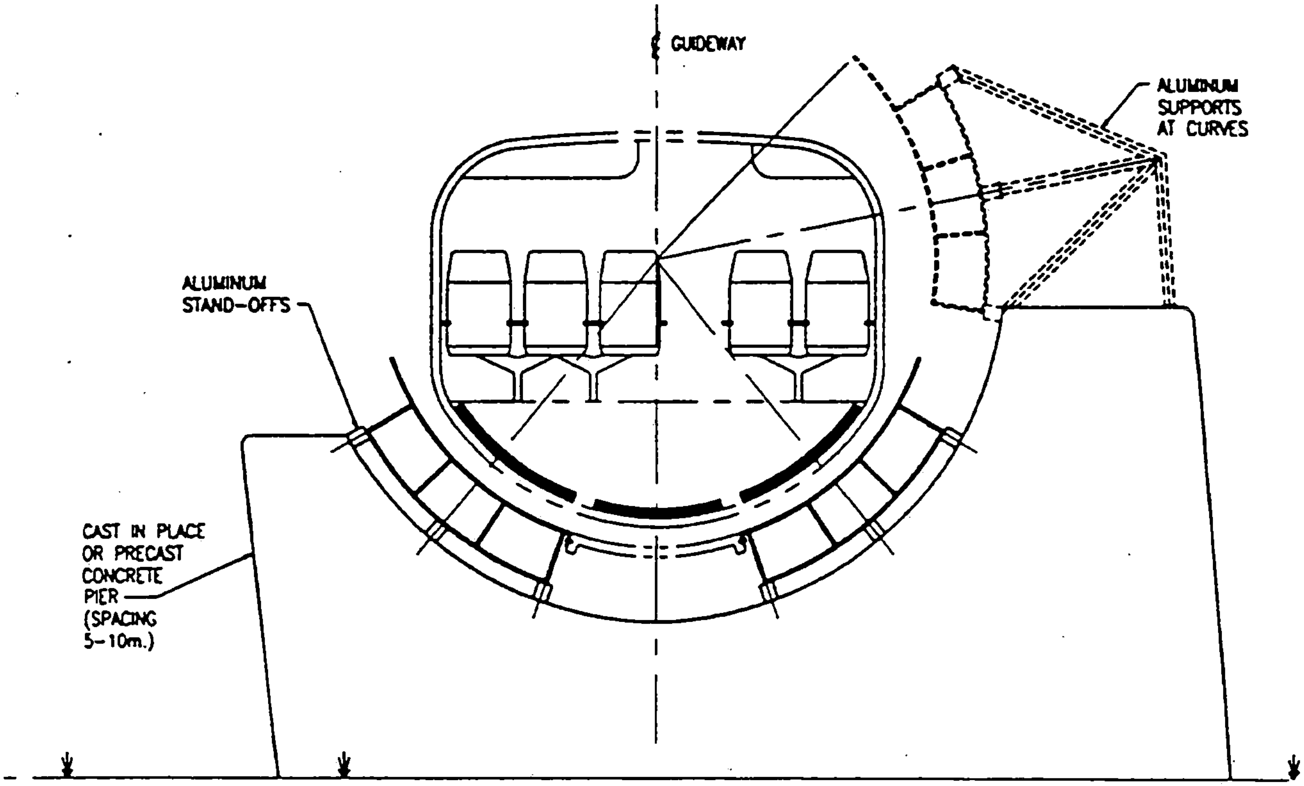


Figure 46 At-grade aluminum box beam concrete support

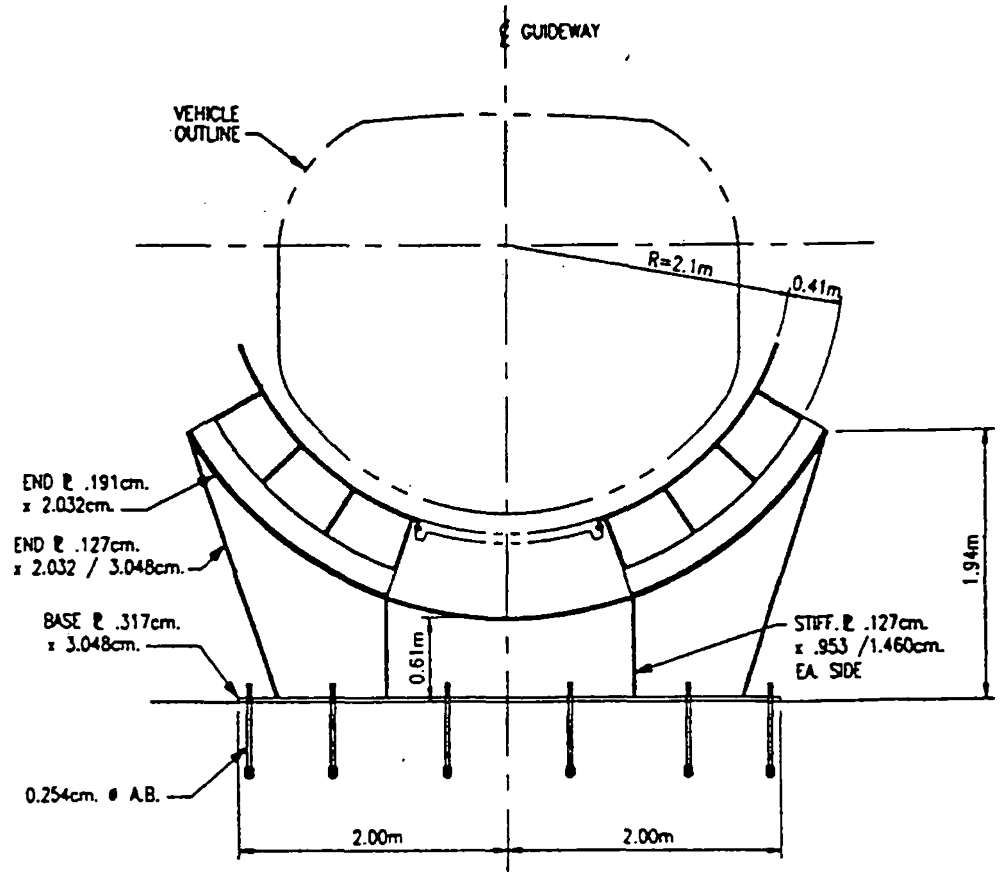


Figure 47 At-grade aluminum box beam with metal supports

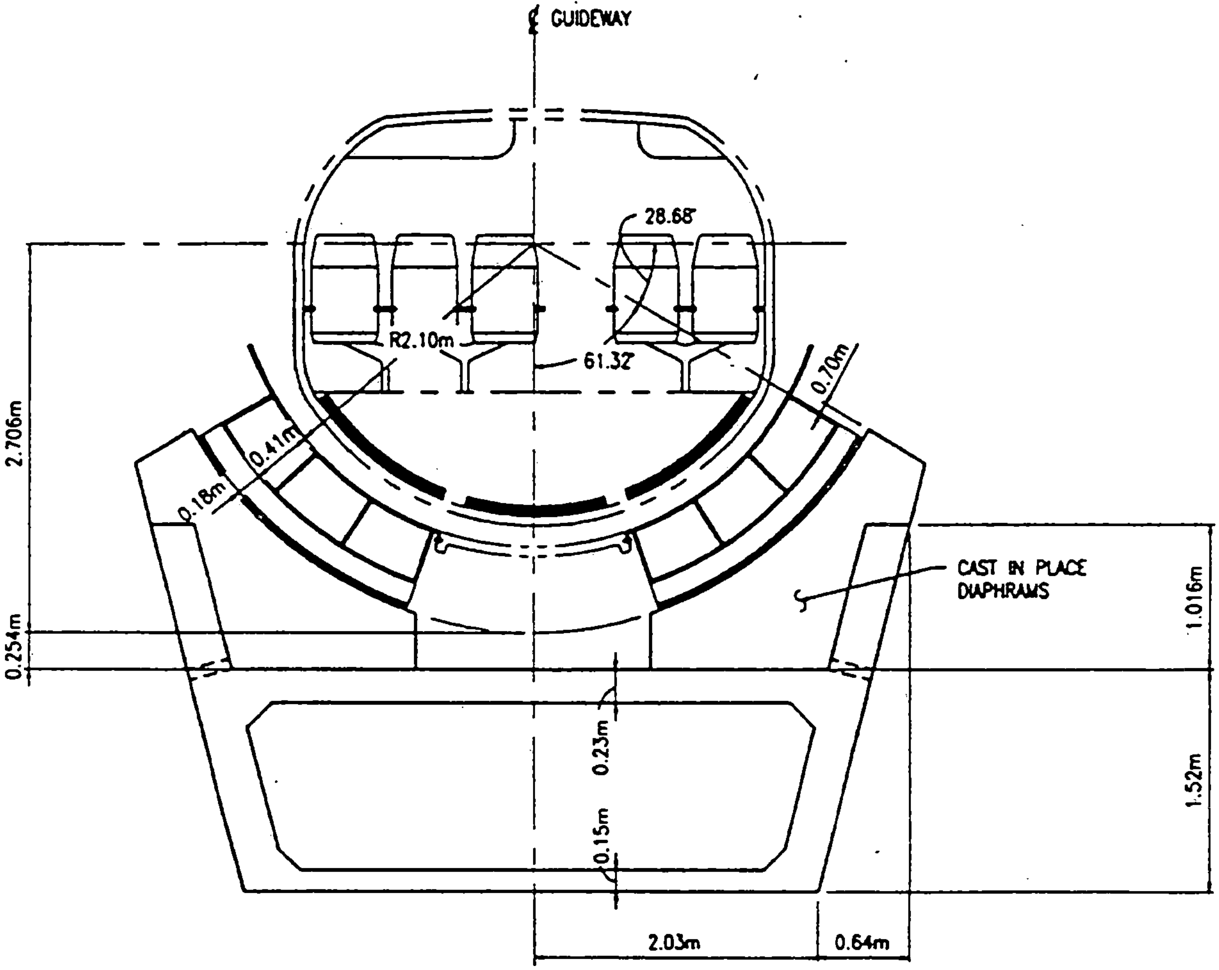


Figure 48 Pre-stressed concrete box-beam, single

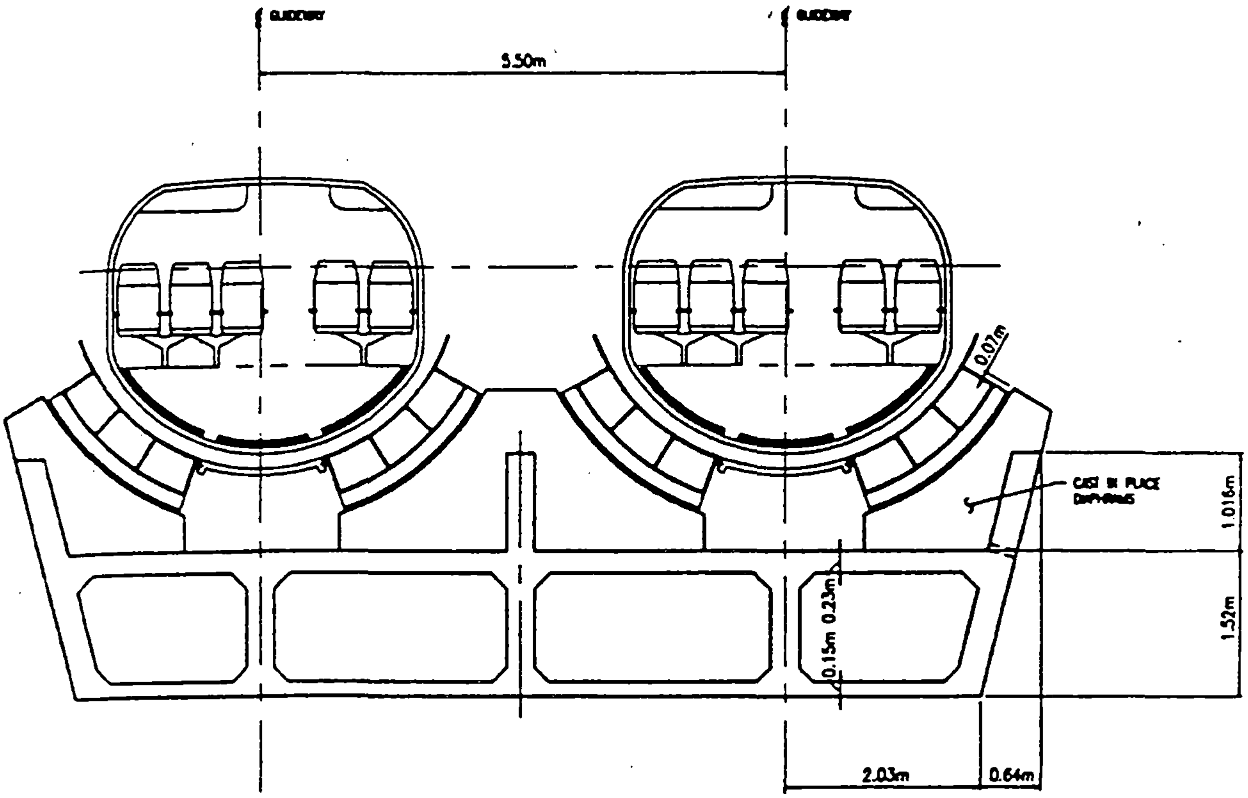


Figure 49 Pre-stressed concrete box-beam, double

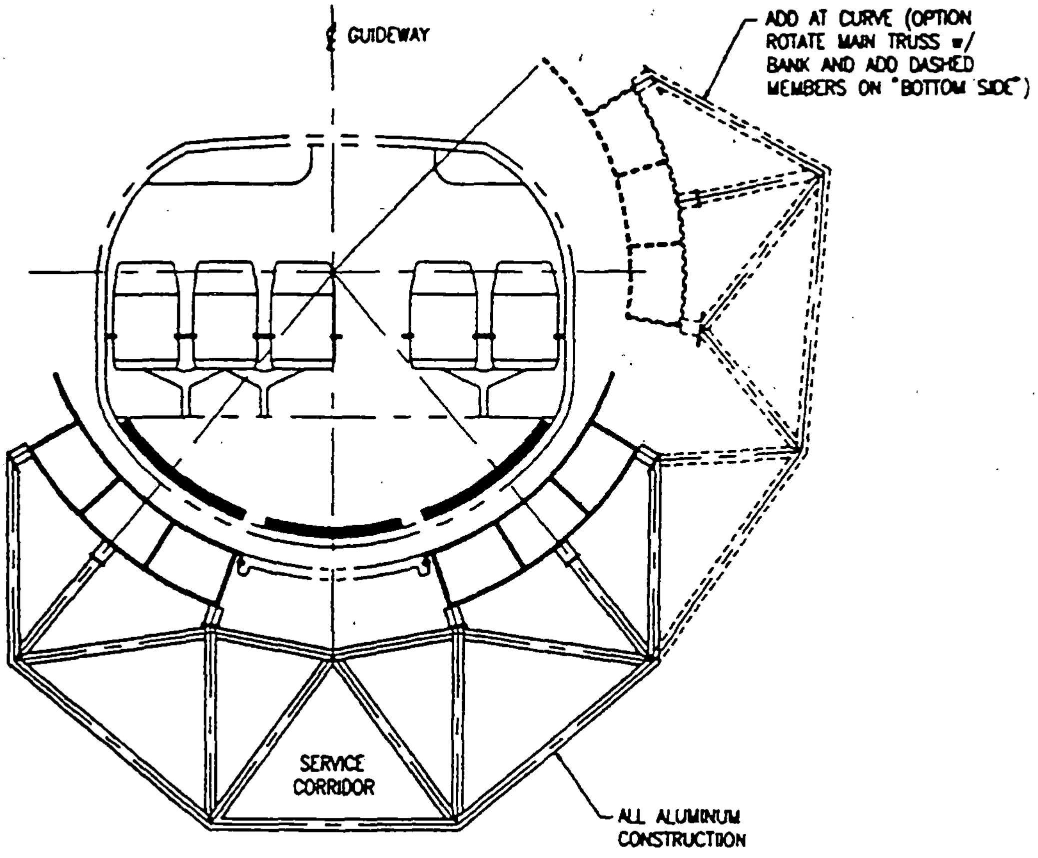


Figure 50 Aluminum truss

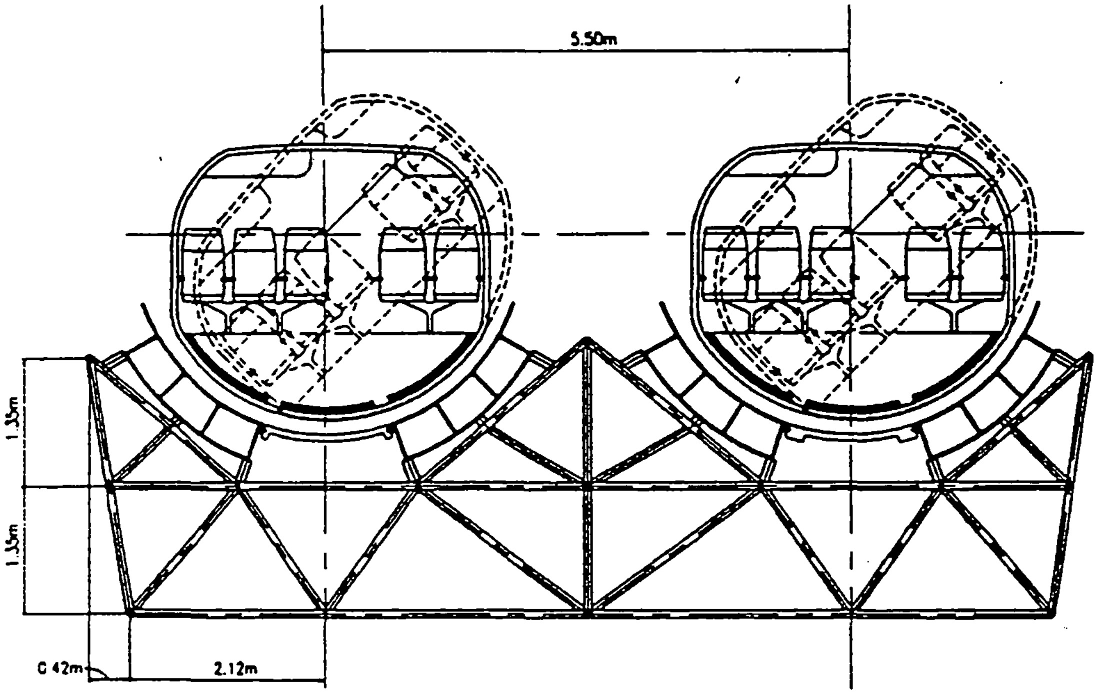


Figure 51 Steel truss under - double

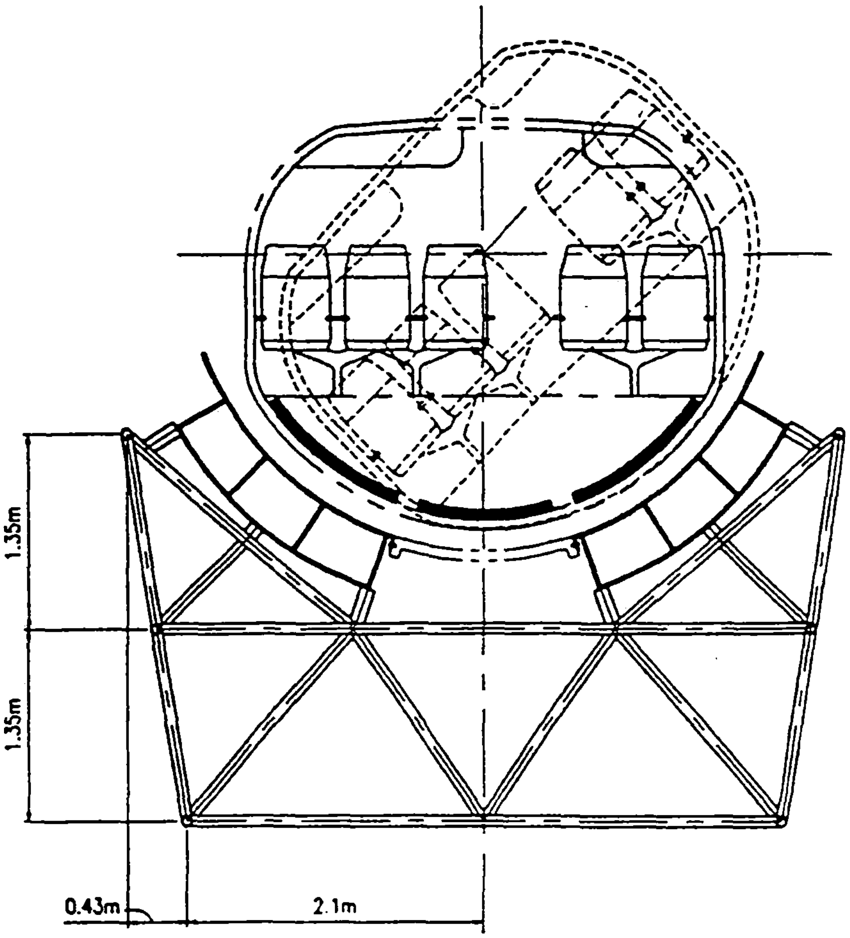


Figure 52 Steel truss under - single

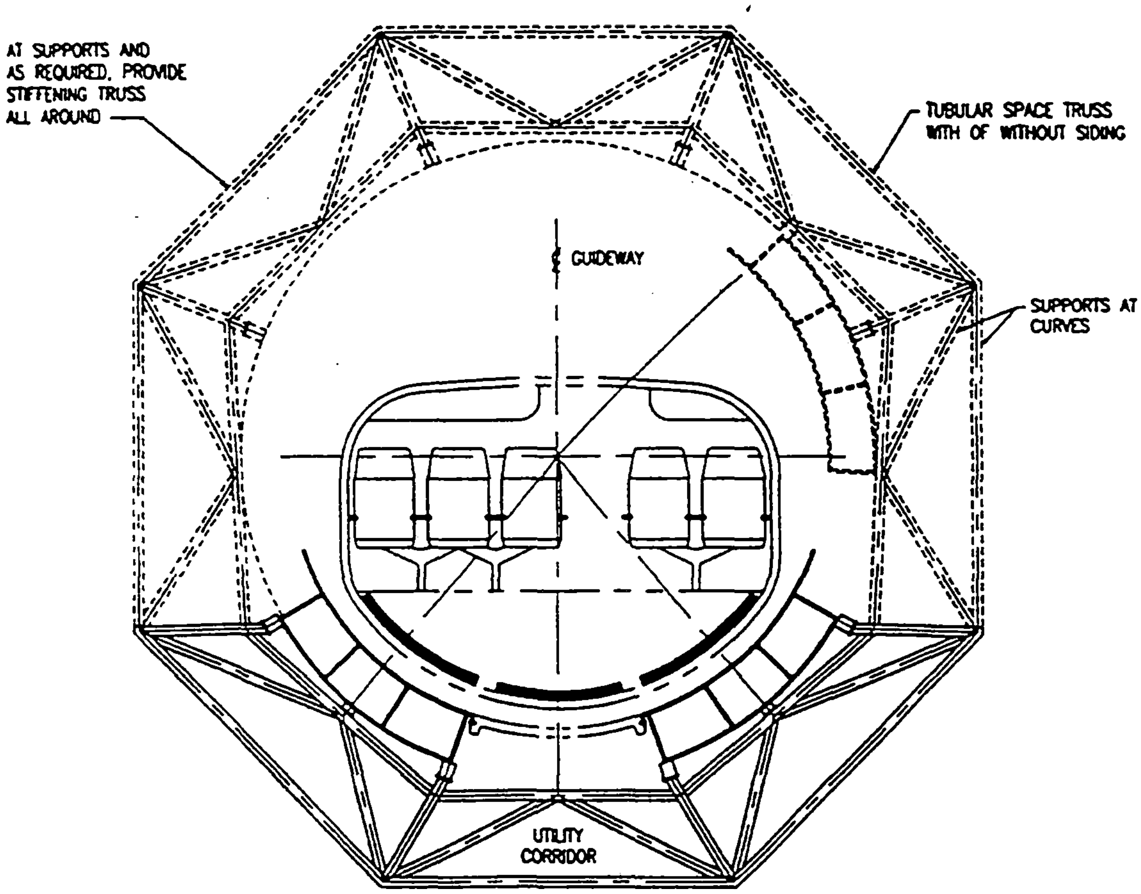


Figure 53 Steel truss - octagonal enclosed

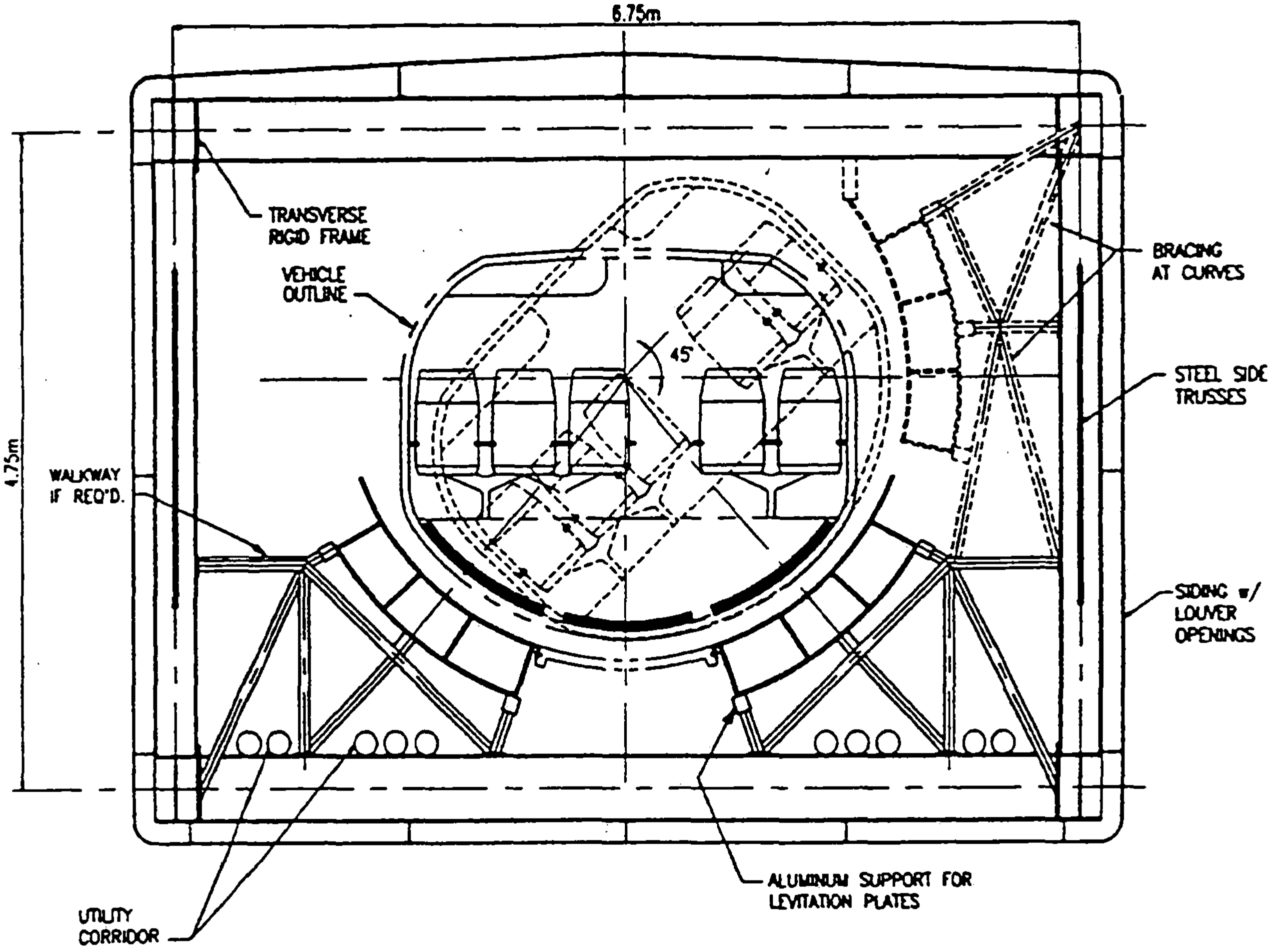


Figure 54 Steel truss - rectangular enclosed

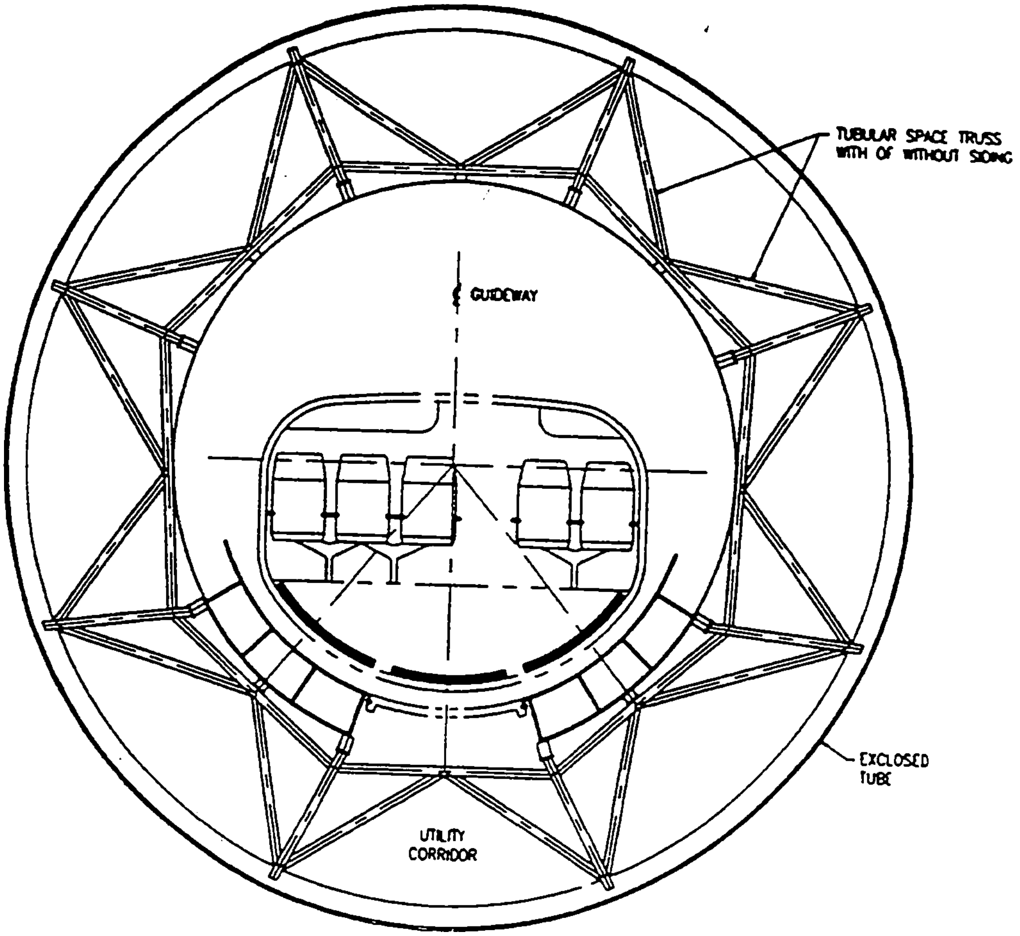


Figure 55 Steel tube

GUIDEWAY HEIGHT FEET	METERS	SPAN-FT - METERS	15 4.57	30 9.14	45 13.72	75 22.86	120 36.58
SINGLE GUIDEWAY				COST PER METER			
2	0.61	ALUM	3,849	4,089	4,872		
		CONC		5,354		5,756	7,805
		STEEL		4,761		4,857	6,102
3	0.91	ALUM	3,906	4,118	4,891		
		CONC		5,397		5,779	7,815
		STEEL		4,809		4,882	6,114
17	5.18	ALUM	4,847	4,617	5,237		
		CONC		6,177		6,224	8,115
		STEEL		5,639		5,217	6,383
25	7.62	ALUM	5,448	4,889	5,432		
		CONC		6,523		6,403	8,361
		STEEL		6,002		5,355	6,499
30	9.14	ALUM	5,694	5,019	5,519		
		CONC		6,725		6,515	8,478
		STEEL		6,206		5,443	6,570
65.61	20.00	ALUM	10,347	7,355	7,086		
		CONC		12,305		9,175	10,974
		STEEL		11,652		7,604	8,226

GUIDEWAY HEIGHT FEET	METERS	SPAN-FT - METERS	15 4.57	30 9.14	45 13.72	75 22.86	120 36.58
DOUBLE GUIDEWAY				COST PER METER			
2	0.61	ALUM	7,699	8,179	9,745		
		CONC		10,708		11,511	15,609
		STEEL		9,522		9,713	12,205
3	0.91	ALUM	7,813	8,236	9,783		
		CONC		10,794		11,559	15,631
		STEEL		9,617		9,764	12,228
17	5.18	ALUM	9,695	9,235	10,473		
		CONC		13,457		13,104	16,687
		STEEL		12,057		11,395	14,058
25	7.62	ALUM	10,896	9,778	10,863		
		CONC		14,704		13,683	16,860
		STEEL		12,717		11,679	14,302
30	9.14	ALUM	11,387	10,039	11,037		
		CONC		15,218		13,958	17,039
		STEEL		13,139		11,840	14,450
65.61	20.00	ALUM	20,694	14,709	14,173		
		CONC		24,775		17,436	20,367
		STEEL		19,219		14,252	16,235

Figure 56 Results of preliminary designs (summary page plus 18 pages of detail)

SPAN	FEET (METERS)		15	(4.57)		15	(4.57)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	25	8800	17,195	25	8800	17,195
CONCRETE	CY	134.73	14	4928	663,949	14	4928	663,949
BACKFILL	CY	8.904	11	3872	34,476	11	3872	34,476
PEDESTAL	CY	309.46	3	1197	370,362	4	1478	457,506
ALUM FAB	TON	8279.46	2	564	4,670,278	2	564	4,670,278
AL DEL&ER	TON	240.55	2	564	135,689	2	564	135,689
ALIGNMT	LF	1.5	15	5280	7,920	15	5280	7,920
MOB&DEMOB		5%			294,993			299,351
TOTAL					6,194,863			6,286,365
				$/METER	3,849		$/METER	3,906

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	25	4400	8,598	25	4400	8,598
CONCRETE	CY	134.73	14	2464	331,975	14	2464	331,975
BACKFILL	CY	8.904	11	1936	17,238	11	1936	17,238
PEDESTAL	CY	309.46	3	598	185,181	4	739	228,753
ALUM FAB	TON	8279.46	4	671	5,555,518	4	671	5,555,518
AL DEL&ER	TON	240.55	4	671	161,409	4	671	161,409
ALIGNMT	LF	1.5	30	5280	7,920	30	5280	7,920
MOB&DEMOB		5%			313,392			315,571
TOTAL					6,581,230			6,626,981
				$/METER	4,089		$/METER	4,118

SPAN	FEET (METERS)		45	(13.72)		45	(13.72)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	25	2933	5,732	25	2933	5,732
CONCRETE	CY	134.73	14	1643	221,316	14	1643	221,316
BACKFILL	CY	8.904	11	1291	11,492	11	1291	11,492
PEDESTAL	CY	309.46	3	399	123,454	4	493	152,502
ALUM FAB	TON	8279.46	7	833	6,897,342	7	833	6,897,342
AL DEL&ER	TON	240.55	7	833	200,394	7	833	200,394
ALIGNMT	LF	1.5	45	5280	7,920	45	5280	7,920
MOB&DEMOB		5%			373,383			374,835
TOTAL					7,841,033			7,871,533
				$/METER	4,872		$/METER	4,891

DP-12 ALUMINUM BOX BEAM AT GRADE - SINGLE

SPAN	FEET (METERS)		15	(4.57)		15	(4.57)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	50	17600	34,390	50	17600	34,390
CONCRETE	CY	134.73	28	9856	1,327,899	28	9856	1,327,899
BACKFILL	CY	8.904	22	7744	68,953	22	7744	68,953
PEDESTAL	CY	309.46	7	2394	740,723	8	2957	915,011
ALUM FAB	TON	8279.46	3	1128	9,340,556	3	1128	9,340,556
AL DEL&ER	TON	240.55	3	1128	271,379	3	1128	271,379
ALIGNMT	LF	1.5	30	10560	15,840	30	10560	15,840
MOB&DEMOB		5%			589,987			598,701
TOTAL					12,389,727			12,572,729
				$/METER	7,699		$/METER	7,813

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	50	8800	17,195	50	8800	17,195
CONCRETE	CY	134.73	28	4928	663,949	28	4928	663,949
BACKFILL	CY	8.904	22	3872	34,476	22	3872	34,476
PEDESTAL	CY	309.46	7	1197	370,362	8	1478	457,506
ALUM FAB	TON	8279.46	8	1342	11,111,035	8	1342	11,111,035
AL DEL&ER	TON	240.55	8	1342	322,818	8	1342	322,818
ALIGNMT	LF	1.5	60	10560	15,840	60	10560	15,840
MOB&DEMOB		5%			626,784			631,141
TOTAL					13,162,460			13,253,961
				$/METER	8,179		$/METER	8,236

SPAN	FEET (METERS)		45	(13.72)		45	(13.72)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	50	5867	11,463	50	5867	11,463
CONCRETE	CY	134.73	28	3285	442,633	28	3285	442,633
BACKFILL	CY	8.904	22	2581	22,984	22	2581	22,984
PEDESTAL	CY	309.46	7	798	246,908	8	986	305,004
ALUM FAB	TON	8279.46	14	1666	13,794,684	14	1666	13,794,684
AL DEL&ER	TON	240.55	14	1666	400,788	14	1666	400,788
ALIGNMT	LF	1.5	90	10560	15,840	90	10560	15,840
MOB&DEMOB		5%			746,765			749,670
TOTAL					15,682,066			15,743,067
				$/METER	9,745		$/METER	9,783

DP-13 ALUMINUM BOX BEAM AT GRADE - DOUBLE

SPAN	FEET (METERS)		15	(4.57)		15	(4.57)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.95	19.00	6688	13,059	21.00	7392	14,434
CONCRETE	CY	134.72	10.50	3696	497,925	12.00	4224	569,057
BACKFILL	CY	8.90	8.50	2992	26,617	9.00	3168	28,183
COLUMN	CY	728.81	3.00	1056	769,623	6.30	2218	1,616,209
CROSSBM	CY	530.96	7.00	2464	1,308,285	7.00	2464	1,308,285
ALUM FAB	TON	8279.46	1.60	564	4,670,278	1.60	564	4,670,278
AL DEL&ER	TON	240.56	1.60	564	135,695	1.60	564	135,695
ALIGNMT	LF	1.50	15.00	5280	7,899	15.00	5280	7,899
MOB&DEMOB		5%			371,469			417,502
TOTAL					7,800,851			8,767,542
				$/METER	4,847		$/METER	5,448

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.95	20.50	3608	7,045	21.00	3696	7,217
CONCRETE	CY	134.72	11.50	2024	272,673	12.00	2112	284,529
BACKFILL	CY	8.90	9.00	1584	14,091	9.00	1584	14,091
COLUMNS	CY	728.81	3.15	554	404,052	6.30	1109	808,105
CROSSBM	CY	530.96	7.00	1232	654,143	7.00	1232	654,143
ALUM FAB	TON	8279.46	3.81	671	5,555,518	3.81	671	5,555,518
AL DEL&ER	TON	240.56	3.81	671	161,416	3.81	671	161,416
ALIGNMT	LF	1.50	30.00	5280	7,899	30.00	5280	7,899
MOB&DEMOB		5%			353,842			374,646
TOTAL					7,430,679			7,867,562
				$/METER	4,617		$/METER	4,889

SPAN	FEET (METERS)		45	(13.72)		45	(13.72)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.95	20.00	2347	4,582	21.00	2464	4,811
CONCRETE	CY	134.72	11.00	1291	173,879	12.00	1408	189,686
BACKFILL	CY	8.90	8.50	997	8,872	9.00	1056	9,394
COLUMNS	CY	728.81	3.00	352	256,541	6.30	739	538,736
CROSSBM	CY	530.96	7.65	898	476,590	7.65	898	476,590
ALUM FAB	TON	8279.46	7.10	833	6,897,342	7.10	833	6,897,342
AL DEL&ER	TON	240.56	7.10	833	200,403	7.10	833	200,403
ALIGNMT	LF	1.50	45.00	5280	7,899	45.00	5280	7,899
MOB&DEMOB		5%			401,305			416,243
TOTAL					8,427,413			8,741,104
				$/METER	5,237		$/METER	5,432

DP-14 ALUMINUM BOX BEAM ELEVATED - SINGLE (5.2 & 7.6)

SPAN	FEET (METERS)		15	(4.57)		15	(4.57)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.95	21.50	7568	14,777	33.50	11792	23,025
CONCRETE	CY	134.72	12.00	4224	569,057	20.00	7040	948,429
BACKFILL	CY	8.90	9.50	3344	29,748	13.50	4752	42,274
COLUMN	CY	728.81	7.76	2732	1,990,759	34.00	11968	8,722,398
CROSSBM	CY	530.96	7.00	2464	1,308,285	7.00	2464	1,308,285
ALUM FAB	TON	8279.46	1.60	564	4,670,278	1.60	564	4,670,278
AL DEL&ER	TON	240.56	1.60	564	135,695	1.60	564	135,695
ALIGNMT	LF	1.50	15.00	5280	7,899	15.00	5280	7,899
MOB&DEMOB		5%			436,325			792,914
TOTAL					9,162,824			16,651,197
				$/METER	5,694		$/METER	10,347

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.95	22.00	3872	7,560	35.00	6160	12,028
CONCRETE	CY	134.72	12.50	2200	296,384	21.00	3696	497,925
BACKFILL	CY	8.90	9.50	1672	14,874	14.00	2464	21,920
COLUMNS	CY	728.81	7.76	1366	995,380	34.00	5984	4,361,199
CROSSBM	CY	530.96	7.00	1232	654,143	7.00	1232	654,143
ALUM FAB	TON	8279.46	3.81	671	5,555,518	3.81	671	5,555,518
AL DEL&ER	TON	240.56	3.81	671	161,416	3.81	671	161,416
ALIGNMT	LF	1.50	30.00	5280	7,899	30.00	5280	7,899
MOB&DEMOB		5%			384,659			563,602
TOTAL					8,077,832			11,835,649
				$/METER	5,019		$/METER	7,355

SPAN	FEET (METERS)		45	(13.72)		45	(13.72)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.95	22.00	2581	5,040	36.50	4283	8,362
CONCRETE	CY	134.72	12.50	1467	197,589	22.00	2581	347,757
BACKFILL	CY	8.90	9.50	1115	9,916	14.50	1701	15,135
COLUMNS	CY	728.81	7.76	911	663,586	34.00	3989	2,907,466
CROSSBM	CY	530.96	7.65	898	476,590	7.65	898	476,590
ALUM FAB	TON	8279.46	7.10	833	6,897,342	7.10	833	6,897,342
AL DEL&ER	TON	240.56	7.10	833	200,403	7.10	833	200,403
ALIGNMT	LF	1.50	45.00	5280	7,899	45.00	5280	7,899
MOB&DEMOB		5%			422,918			543,048
TOTAL					8,881,284			11,404,002
				$/METER	5,519		$/METER	7,086

DP-15 ALUMINUM BOX BEAM ELEVATED - SINGLE (9.1 & 20)

SPAN	FEET (METERS)		15	(4.57)		15	(4.57)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.95	38.00	13376	26,118	42.00	14784	28,867
CONCRETE	CY	134.72	21.00	7392	995,850	24.00	8448	1,138,115
BACKFILL	CY	8.90	17.00	5984	53,234	18.00	6336	56,365
COLUMNS	CY	728.81	6.00	2112	1,539,247	12.60	4435	3,232,418
CROSSBM	CY	530.96	14.00	4928	2,616,571	14.00	4928	2,616,571
ALUM FAB	TON	8279.46	3.21	1128	9,340,556	3.21	1128	9,340,556
AL DEL&ER	TON	240.56	3.21	1128	271,390	3.21	1128	271,390
ALIGNMT	LF	1.50	30.00	10560	15,798	30.00	10560	15,798
MOB&DEMOB		5%			742,938			835,004
TOTAL					15,601,701			17,535,083
				$/METER	9,695		$/METER	10,896

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.95	41.00	7216	14,090	42.00	7392	14,434
CONCRETE	CY	134.72	23.00	4048	545,347	24.00	4224	569,057
BACKFILL	CY	8.90	18.00	3168	28,183	18.00	3168	28,183
COLUMNS	CY	728.81	6.30	1109	808,105	12.60	2218	1,616,209
CROSSBM	CY	530.96	14.00	2464	1,308,285	14.00	2464	1,308,285
ALUM FAB	TON	8279.46	7.63	1342	11,111,035	7.63	1342	11,111,035
AL DEL&ER	TON	240.56	7.63	1342	322,832	7.63	1342	322,832
ALIGNMT	LF	1.50	60.00	10560	15,798	60.00	10560	15,798
MOB&DEMOB		5%			707,684			749,292
TOTAL					14,861,357			15,735,124
				$/METER	9,235		$/METER	9,778

SPAN	FEET (METERS)		45	(13.72)		45	(13.72)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.95	40.00	4693	9,164	42.00	4928	9,622
CONCRETE	CY	134.72	22.00	2581	347,757	24.00	2816	379,372
BACKFILL	CY	8.90	17.00	1995	17,745	18.00	2112	18,788
COLUMNS	CY	728.81	6.00	704	513,082	12.60	1478	1,077,473
CROSSBM	CY	530.96	15.30	1795	953,179	15.30	1795	953,179
ALUM FAB	TON	8279.46	14.20	1666	13,794,684	14.20	1666	13,794,684
AL DEL&ER	TON	240.56	14.20	1666	400,805	14.20	1666	400,805
ALIGNMT	LF	1.50	90.00	10560	15,798	90.00	10560	15,798
MOB&DEMOB		5%			802,611			832,486
TOTAL					16,854,825			17,482,208
				$/METER	10,473		$/METER	10,863

DP-16 ALUMINUM BOX BEAM ELEVATED - DOUBLE (5.2 & 7.6)

SPAN	FEET (METERS)		15	(4.57)		15	(4.57)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.95	43.00	15136	29,555	67.00	23584	46,050
CONCRETE	CY	134.72	24.00	8448	1,138,115	40.00	14080	1,896,858
BACKFILL	CY	8.90	19.00	6688	59,496	27.00	9504	84,548
COLUMNS	CY	728.81	15.52	5463	3,981,518	68.00	23936	17,444,796
CROSSBM	CY	530.96	14.00	4928	2,616,571	14.00	4928	2,616,571
ALUM FAB	TON	8279.46	3.21	1128	9,340,556	3.21	1128	9,340,556
AL DEL&ER	TON	240.56	3.21	1128	271,390	3.21	1128	271,390
ALIGNMT	LF	1.50	30.00	10560	15,798	30.00	10560	15,798
MOB&DEMOB		5%			872,650			1,585,828
TOTAL					18,325,648			33,302,394
				$/METER	11,387		$/METER	20,694

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.95	44.00	7744	15,121	70.00	12320	24,056
CONCRETE	CY	134.72	25.00	4400	592,768	42.00	7392	995,850
BACKFILL	CY	8.90	19.00	3344	29,748	28.00	4928	43,839
COLUMNS	CY	728.81	15.52	2732	1,990,759	68.00	11968	8,722,398
CROSSBM	CY	530.96	14.00	2464	1,308,285	14.00	2464	1,308,285
ALUM FAB	TON	8279.46	7.63	1342	11,111,035	7.63	1342	11,111,035
AL DEL&ER	TON	240.56	7.63	1342	322,832	7.63	1342	322,832
ALIGNMT	LF	1.50	60.00	10560	15,798	60.00	10560	15,798
MOB&DEMOB		5%			769,317			1,127,205
TOTAL					16,155,664			23,671,299
				$/METER	10,039		$/METER	14,709

SPAN	FEET (METERS)		45	(13.72)		45	(13.72)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.95	44.00	5163	10,081	73.00	8565	16,725
CONCRETE	CY	134.72	25.00	2933	395,179	44.00	5163	695,514
BACKFILL	CY	8.90	19.00	2229	19,832	29.00	3403	30,270
COLUMNS	CY	728.81	15.52	1821	1,327,173	68.00	7979	5,814,932
CROSSBM	CY	530.96	15.30	1795	953,179	15.30	1795	953,179
ALUM FAB	TON	8279.46	14.20	1666	13,794,684	14.20	1666	13,794,684
AL DEL&ER	TON	240.56	14.20	1666	400,805	14.20	1666	400,805
ALIGNMT	LF	1.50	90.00	10560	15,798	90.00	10560	15,798
MOB&DEMOB		5%			845,837			1,086,095
TOTAL					17,762,567			22,808,003
				$/METER	11,037		$/METER	14,173

DP-17 ALUMINUM BOX BEAM ELEVATED - DOUBLE (9.1 & 20)

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	11	1936	3,783	12	2112	4,127
CONCRETE	CY	134.73	5	880	118,562	5	880	118,562
BACKFILL	CY	8.904	6	1056	9,403	7	1232	10,970
PEDESTAL	CY	309.46	2.6	458	141,609	4	686	212,413
STEEL FAB	TON	2205	4.86	855	1,886,069	5	855	1,886,069
ST DEL&ER	TON	379.4	4.86	855	324,524	5	855	324,524
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	30	5280	7,920	30	5280	7,920
MOB&DEMOB		5%			364,858			368,494
TOTAL					7,662,013			7,738,364
				$/METER	4,761		$/METER	4,809

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	13	915	1,788	15	1056	2,063
CONCRETE	CY	134.73	6	422	56,910	7	493	66,395
BACKFILL	CY	8.904	7	493	4,388	8	563	5,015
PEDESTAL	CY	309.46	2.6	183	56,644	4	275	84,965
STEEL FAB	TON	2205	13.8	972	2,142,202	14	972	2,142,202
ST DEL&ER	TON	379.4	13.8	972	368,595	14	972	368,595
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	75	5280	7,920	75	5280	7,920
MOB&DEMOB		5%			372,187			374,122
TOTAL					7,815,918			7,856,562
				$/METER	4,857		$/METER	4,882

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	29	1276	2,493	29	1276	2,493
CONCRETE	CY	134.73	15	660	88,922	15	660	88,922
BACKFILL	CY	8.904	14	616	5,485	14	616	5,485
PEDESTAL	CY	309.46	2.6	114	35,402	4	172	53,103
STEEL FAB	TON	2205	38.76	1705	3,760,495	39	1705	3,760,495
ST DEL&ER	TON	379.4	38.76	1705	647,044	39	1705	647,044
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	120	5280	7,920	120	5280	7,920
MOB&DEMOB		5%			467,652			468,537
TOTAL					9,820,699			9,839,285
				$/METER	6,102		$/METER	6,114

DP-18 STEEL TRUSS AT GRADE - SINGLE

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	22	3872	7,566	24	4224	8,254
CONCRETE	CY	134.73	10	1760	237,125	10	1760	237,125
BACKFILL	CY	8.904	12	2112	18,805	14	2464	21,939
PEDESTAL	CY	309.46	5.2	915	283,218	7.8	1373	424,827
STEEL FAB	TON	2205	9.72	1711	3,772,138	9.72	1711	3,772,138
ST DEL&ER	TON	379.4	9.72	1711	649,047	9.72	1711	649,047
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	60	10560	15,840	60	10560	15,840
MOB&DEMOB		5%			729,715			736,987
TOTAL					15,324,025			15,476,728
				$/METER	9,522		$/METER	9,617

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	26	1830.	3,577	30	2112	4,127
CONCRETE	CY	134.73	12	844.8	113,820	14	985.6	132,790
BACKFILL	CY	8.904	14	985.6	8,776	16	1126.	10,029
PEDESTAL	CY	309.46	5.2	366.0	113,287	7.8	549.1	169,931
STEEL FAB	TON	2205	27.6	1943.	4,284,403	27.6	1943.	4,284,403
ST DEL&ER	TON	379.4	27.6	1943.	737,189	27.6	1943.	737,189
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	150	10560	15,840	150	10560	15,840
MOB&DEMOB		5%			744,373			748,244
TOTAL					15,631,836			15,713,125
				$/METER	9,713		$/METER	9,764

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	58	2552	4,987	58	2552	4,987
CONCRETE	CY	134.73	30	1320	177,844	30	1320	177,844
BACKFILL	CY	8.904	28	1232	10,970	28	1232	10,970
PEDESTAL	CY	309.46	5.2	228.8	70,804	7.8	343.2	106,207
STEEL FAB	TON	2205	77.52	3410.	7,520,990	77.52	3410.	7,520,990
ST DEL&ER	TON	379.4	77.52	3410.	1,294,088	77.52	3410.	1,294,088
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	240	10560	15,840	240	10560	15,840
MOB&DEMOB		5%			935,305			937,075
TOTAL					19,641,399			19,678,571
				$/METER	12,205		$/METER	12,228

DP-19 STEEL TRUSS AT GRADE - DOUBLE

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	23	4048	7,910	29	5104	9,973
CONCRETE	CY	134.73	12	2112	284,550	16	2816	379,400
BACKFILL	CY	8.904	11	1936	17,238	13	2288	20,372
COLUMNS	CY	728.8	6.67	1174	855,553	10	1799	1,310,907
CROSSBM	CY	530.94	4.86	855	454,145	5	855	454,145
STEEL FAB	TON	2205	4.86	855	1,886,069	5	855	1,886,069
ST DEL&ER	TON	379.4	4.86	855	324,524	5	855	324,524
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	30	5280	7,920	30	5280	7,920
MOB&DEMOB		5%			432,160			459,930
TOTAL					9,075,353			9,658,525
				$/METER	5,639		$/METER	6,002

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	27	1901	3,714	32	2253	4,402
CONCRETE	CY	134.73	14	986	132,790	17	1197	161,245
BACKFILL	CY	8.904	13	915	8,149	14	986	8,776
COLUMNS	CY	728.8	6.22	438	319,133	10	689	501,788
CROSSBM	CY	530.94	5.56	391	207,823	6	391	207,823
STEEL FAB	TON	2205	13.8	972	2,142,202	14	972	2,142,202
ST DEL&ER	TON	379.4	13.8	972	368,595	14	972	368,595
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	75	5280	7,920	75	5280	7,920
MOB&DEMOB		5%			399,781			410,402
TOTAL					8,395,391			8,618,436
				$/METER	5,217		$/METER	5,355

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	42	1848	3,611	49	2156	4,213
CONCRETE	CY	134.73	23	1012	136,347	27	1188	160,059
BACKFILL	CY	8.904	19	836	7,444	21	924	8,227
COLUMNS	CY	728.8	7.7	339	246,917	12	547	398,916
CROSSBM	CY	530.94	7.22	318	168,669	7	318	168,669
STEEL FAB	TON	2205	38.76	1705	3,760,495	39	1705	3,760,495
ST DEL&ER	TON	379.4	38.76	1705	647,044	39	1705	647,044
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	120	5280	7,920	120	5280	7,920
MOB&DEMOB		5%			489,187			498,041
TOTAL					10,272,919			10,458,871
				$/METER	6,383		$/METER	6,499

DP-20 STEEL TRUSS ELEVATED - SINGLE (5.2 & 7.6)

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	32	5632	11,005	48	8448	16,507
CONCRETE	CY	134.73	17	2992	403,112	28	4928	663,949
BACKFILL	CY	8.904	15	2640	23,507	20	3520	31,342
COLUMNS	CY	728.8	12	2189	1,595,664	75	13267	9,668,902
CROSSBM	CY	530.94	5	855	454,145	5	855	454,145
STEEL FAB	TON	2205	5	855	1,886,069	5	855	1,886,069
ST DEL&ER	TON	379.4	5	855	324,524	5	855	324,524
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	30	5280	7,920	30	5280	7,920
MOB&DEMOB		5%			475,562			892,932
TOTAL					9,986,792			18,751,576
				$/METER	6,206		$/METER	11,652

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	35	2464	4,815	54	3802	7,428
CONCRETE	CY	134.73	19	1338	180,215	31	2182	294,035
BACKFILL	CY	8.904	16	1126	10,029	23	1619	14,417
COLUMNS	CY	728.8	12	845	615,690	74	5223	3,806,505
CROSSBM	CY	530.94	6	391	207,823	6	391	207,823
STEEL FAB	TON	2205	14	972	2,142,202	14	972	2,142,202
ST DEL&ER	TON	379.4	14	972	368,595	14	972	368,595
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	75	5280	7,920	75	5280	7,920
MOB&DEMOB		5%			417,129			582,710
TOTAL					8,759,702			12,236,920
				$/METER	5,443		$/METER	7,604

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	52	2288	4,471	78	3432	6,706
CONCRETE	CY	134.73	29	1276	171,915	46	2024	272,694
BACKFILL	CY	8.904	23	1012	9,011	32	1408	12,537
COLUMNS	CY	728.8	15	678	494,156	91	4015	2,926,453
CROSSBM	CY	530.94	7	318	168,669	7	318	168,669
STEEL FAB	TON	2205	39	1705	3,760,495	39	1705	3,760,495
ST DEL&ER	TON	379.4	39	1705	647,044	39	1705	647,044
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	120	5280	7,920	120	5280	7,920
MOB&DEMOB		5%			503,448			630,390
TOTAL					10,572,415			13,238,193
				$/METER	6,570		$/METER	8,226

DP-21 STEEL TRUSS ELEVATED – SINGLE (9.1 & 20)

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	37	6512	12,724	44	7744	15,132
CONCRETE	CY	134.73	21	3696	497,962	25	4400	592,812
BACKFILL	CY	8.904	17	2992	26,641	19	3344	29,775
COLUMNS	CY	728.8	13.33	2346	1,709,823	20	3597	2,621,814
CROSSBM	CY	530.94	14.22	2503	1,328,794	14	2503	1,328,794
STEEL FAB	TON	2205	11.6	2042	4,501,728	12	2042	4,501,728
ST DEL&ER	TON	379.4	11.6	2042	774,583	12	2042	774,583
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	60	10560	15,840	60	10560	15,840
MOB&DEMOB		5%			923,933			974,552
TOTAL					19,402,600			20,465,602
				$/METER	12,057		$/METER	12,717

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	61	4294	8,391	72	5069	9,904
CONCRETE	CY	134.73	36	2534	341,460	43	3027	407,855
BACKFILL	CY	8.904	25	1760	15,671	29	2042	18,178
COLUMNS	CY	728.8	11.56	814	593,115	19	1314	957,911
CROSSBM	CY	530.94	23.7	1668	885,863	24	1668	885,863
STEEL FAB	TON	2205	32.94	2319	5,113,342	33	2319	5,113,342
ST DEL&ER	TON	379.4	32.94	2319	879,819	33	2319	879,819
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	150	10560	15,840	150	10560	15,840
MOB&DEMOB		5%			873,204			894,964
TOTAL					18,337,276			18,794,249
				$/METER	11,395		$/METER	11,679

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	82	3608	7,050	100	4400	8,598
CONCRETE	CY	134.73	50	2200	296,406	61	2684	361,615
BACKFILL	CY	8.904	32	1408	12,537	38	1672	14,887
COLUMNS	CY	728.8	13.04	574	418,156	23	991	722,153
CROSSBM	CY	530.94	28.44	1251	664,397	28	1251	664,397
STEEL FAB	TON	2205	92.53	4071	8,977,261	93	4071	8,977,261
ST DEL&ER	TON	379.4	92.53	4071	1,544,659	93	4071	1,544,659
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	240	10560	15,840	240	10560	15,840
MOB&DEMOB		5%			1,077,344			1,095,999
TOTAL					22,624,221			23,015,981
				$/METER	14,058		$/METER	14,302

DP-22 STEEL TRUSS ELEVATED - DOUBLE (5.2 & 7.6)

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	49	8624	16,851	75	13200	25,793
CONCRETE	CY	134.73	28	4928	663,949	45	7920	1,067,062
BACKFILL	CY	8.904	21	3696	32,909	30	5280	47,013
COLUMNS	CY	728.8	25	4381	3,192,610	94	16583	12,085,486
CROSSBM	CY	530.94	14	2503	1,328,794	14	2503	1,328,794
STEEL FAB	TON	2205	12	2042	4,501,728	12	2042	4,501,728
ST DEL&ER	TON	379.4	12	2042	774,583	12	2042	774,583
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	60	10560	15,840	60	10560	15,840
MOB&DEMOB		5%			1,006,892			1,472,844
TOTAL					21,144,729			30,929,714
				$/METER	13,139		$/METER	19,219

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	74	5210	10,180	105	7392	14,444
CONCRETE	CY	134.73	45	3168	426,825	65	4576	616,524
BACKFILL	CY	8.904	30	2112	18,805	40	2816	25,074
COLUMNS	CY	728.8	23	1627	1,185,717	91	6425	4,682,324
CROSSBM	CY	530.94	24	1668	885,863	24	1668	885,863
STEEL FAB	TON	2205	33	2319	5,113,342	33	2319	5,113,342
ST DEL&ER	TON	379.4	33	2319	879,819	33	2319	879,819
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	150	10560	15,840	150	10560	15,840
MOB&DEMOB		5%			907,348			1,092,190
TOTAL					19,054,310			22,935,992
				$/METER	11,840		$/METER	14,252

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	109	4796	9,371	168	7392	14,444
CONCRETE	CY	134.73	67	2948	397,184	107	4708	634,309
BACKFILL	CY	8.904	41	1804	16,063	61	2684	23,898
COLUMNS	CY	728.8	28	1251	911,991	106	4662	3,397,841
CROSSBM	CY	530.94	28	1251	664,397	28	1251	664,397
STEEL FAB	TON	2205	93	4071	8,977,261	93	4071	8,977,261
ST DEL&ER	TON	379.4	93	4071	1,544,659	93	4071	1,544,659
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	240	10560	15,840	240	10560	15,840
MOB&DEMOB		5%			1,107,367			1,244,161
TOTAL					23,254,704			26,127,380
				$/METER	14,450		$/METER	16,235

DP-23 STEEL TRUSS ELEVATED – DOUBLE (9.1 & 20)

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	19	3344	6,534	18	3168	6,190
CONCRETE	CY	134.73	9	1584	213,412	9	1584	213,412
BACKFILL	CY	8.904	9	1584	14,104	9	1584	14,104
PEDESTAL	CY	309.46	4.81	847	261,976	6	1060	327,879
CONBM FAB	CY	401.21	31	5456	2,189,002	31	5456	2,189,002
BM DEL&ER	CY	129.76	31	5456	707,971	31	5456	707,971
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	30	5280	7,920	30	5280	7,920
MOB&DEMOB		5%			410,310			413,588
TOTAL					8,616,515			8,685,352
				$/METER	5,354		$/METER	5,397

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	31	2182	4,264	32	2253	4,402
CONCRETE	CY	134.73	17	1197	161,245	18	1267	170,730
BACKFILL	CY	8.904	14	986	8,776	15	1056	9,403
PEDESTAL	CY	309.46	4.81	339	104,791	6	424	131,152
CONBM FAB	CY	401.21	99.76	7023	2,817,740	100	7023	2,817,740
BM DEL&ER	CY	129.76	99.76	7023	911,318	100	7023	911,318
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	75	5280	7,920	75	5280	7,920
MOB&DEMOB		5%			441,067			442,897
TOTAL					9,262,406			9,300,847
				$/METER	5,756		$/METER	5,779

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	94	4136	8,082	94	4136	8,082
CONCRETE	CY	134.73	58	2552	343,831	58	2552	343,831
BACKFILL	CY	8.904	37	1628	14,496	37	1628	14,496
PEDESTAL	CY	309.46	4.81	212	65,494	6	265	81,970
CONBM FAB	CY	401.21	287.5	12650	5,075,307	288	12650	5,075,307
BM DEL&ER	CY	129.76	287.5	12650	1,641,464	288	12650	1,641,464
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	120	5280	7,920	120	5280	7,920
MOB&DEMOB		5%			598,094			598,918
TOTAL					12,559,973			12,577,272
				$/METER	7,805		$/METER	7,815

DP-24 CONCRETE BEAM AT GRADE - SINGLE

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	38	6688	13,068	36	6336	12,381
CONCRETE	CY	134.73	18	3168	426,825	18	3168	426,825
BACKFILL	CY	8.904	18	3168	28,208	18	3168	28,208
PEDESTAL	CY	309.46	9.62	1693	523,953	12.04	2119	655,758
CONBM FAB	CY	401.21	62	10912	4,378,004	62	10912	4,378,004
BM DEL&ER	CY	129.76	62	10912	1,415,941	62	10912	1,415,941
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	60	10560	15,840	60	10560	15,840
MOB&DEMOB		5%			820,620			827,176
TOTAL					17,233,030			17,370,703
				$/METER	10,708		$/METER	10,794

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	62	4364.	8,529	64	4505.	8,804
CONCRETE	CY	134.73	34	2393.	322,490	36	2534.	341,460
BACKFILL	CY	8.904	28	1971.	17,552	30	2112	18,805
PEDESTAL	CY	309.46	9.62	677.2	209,581	12.04	847.6	262,303
CONBM FAB	CY	401.21	199.5	14046	5,635,479	199.5	14046	5,635,479
BM DEL&ER	CY	129.76	199.5	14046	1,822,636	199.5	14046	1,822,636
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	150	10560	15,840	150	10560	15,840
MOB&DEMOB		5%			882,134			885,795
TOTAL					18,524,812			18,601,693
				$/METER	11,511		$/METER	11,559

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		2	(0.61)		3	(0.91)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	188	8272	16,163	188	8272	16,163
CONCRETE	CY	134.73	116	5104	687,662	116	5104	687,662
BACKFILL	CY	8.904	74	3256	28,991	74	3256	28,991
PEDESTAL	CY	309.46	9.62	423.2	130,988	12.04	529.7	163,940
CONBM FAB	CY	401.21	575	25300	10,150,613	575	25300	10,150,613
BM DEL&ER	CY	129.76	575	25300	3,282,928	575	25300	3,282,928
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	240	10560	15,840	240	10560	15,840
MOB&DEMOB		5%			1,196,188			1,197,835
TOTAL					25,119,945			25,154,544
				$/METER	15,609		$/METER	15,631

DP-25 CONCRETE BEAM AT GRADE - DOUBLE

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	27	4752	9,285	31	5456	10,661
CONCRETE	CY	134.73	14	2464	331,975	17	2992	403,112
BACKFILL	CY	8.904	13	2288	20,372	14	2464	21,939
COLUMNS	CY	728.8	6.67	1174	855,553	10	1799	1,310,907
CROSSBM	CY	530.94	5.78	1017	540,115	6	1017	540,115
CONBM FAB	CY	401.21	31	5456	2,189,002	31	5456	2,189,002
BM DEL&ER	CY	129.76	31	5456	707,971	31	5456	707,971
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	30	5280	7,920	30	5280	7,920
MOB&DEMOB		5%			473,374			499,846
TOTAL					9,940,852			10,496,758
				$/METER	6,177		$/METER	6,523

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	44	3098	6,053	49	3450	6,741
CONCRETE	CY	134.73	25	1760	237,125	28	1971	265,580
BACKFILL	CY	8.904	19	1338	11,910	21	1478	13,164
COLUMNS	CY	728.8	7.11	501	364,796	12	834	607,994
CROSSBM	CY	530.94	10.11	712	377,893	10	712	377,893
CONBM FAB	CY	401.21	99.76	7023	2,817,740	100	7023	2,817,740
BM DEL&ER	CY	129.76	99.76	7023	911,318	100	7023	911,318
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	75	5280	7,920	75	5280	7,920
MOB&DEMOB		5%			477,002			490,682
TOTAL					10,017,043			10,304,316
				$/METER	6,224		$/METER	6,403

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	109	4796	9,371	121	5324	10,403
CONCRETE	CY	134.73	68	2992	403,112	75	3300	444,609
BACKFILL	CY	8.904	42	1848	16,455	45	1980	17,630
COLUMNS	CY	728.8	6.51	286	208,757	17	743	541,615
CROSSBM	CY	530.94	11.56	509	270,057	12	509	270,057
CONBM FAB	CY	401.21	287.5	12650	5,075,307	288	12650	5,075,307
BM DEL&ER	CY	129.76	287.5	12650	1,641,464	288	12650	1,641,464
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	120	5280	7,920	120	5280	7,920
MOB&DEMOB		5%			621,886			640,715
TOTAL					13,059,616			13,455,005
				$/METER	8,115		$/METER	8,361

DP-26 CONCRETE BEAM ELEVATED – SINGLE (5.2 & 7.6)

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	33	5808	11,349	63	11088	21,666
CONCRETE	CY	134.73	18	3168	426,825	37	6512	877,362
BACKFILL	CY	8.904	15	2640	23,507	26	4576	40,745
COLUMNS	CY	728.8	12	2189	1,595,664	75	13267	9,668,902
CROSSBM	CY	530.94	6	1017	540,115	6	1017	540,115
CONBM FAB	CY	401.21	31	5456	2,189,002	31	5456	2,189,002
BM DEL&ER	CY	129.76	31	5456	707,971	31	5456	707,971
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	30	5280	7,920	30	5280	7,920
MOB&DEMOB		5%			515,382			942,948
TOTAL					10,823,018			19,801,916
				$/METER	6,725		$/METER	12,305

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	52	3661	7,153	88	6195	12,105
CONCRETE	CY	134.73	30	2112	284,550	53	3731	502,705
BACKFILL	CY	8.904	22	1549	13,791	34	2394	21,313
COLUMNS	CY	728.8	15	1043	759,864	90	6321	4,606,389
CROSSBM	CY	530.94	10	712	377,893	10	712	377,893
CONBM FAB	CY	401.21	100	7023	2,817,740	100	7023	2,817,740
BM DEL&ER	CY	129.76	100	7023	911,318	100	7023	911,318
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	75	5280	7,920	75	5280	7,920
MOB&DEMOB		5%			499,276			703,133
TOTAL					10,484,790			14,765,802
				$/METER	6,515		$/METER	9,175

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		30	(9.14)		65	(20.00)	
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	129	5676	11,091	192	8448	16,507
CONCRETE	CY	134.73	81	3564	480,178	123	5412	729,159
BACKFILL	CY	8.904	48	2112	18,805	69	3036	27,033
COLUMNS	CY	728.8	21	939	683,993	132	5827	4,246,980
CROSSBM	CY	530.94	12	509	270,057	12	509	270,057
CONBM FAB	CY	401.21	288	12650	5,075,307	288	12650	5,075,307
BM DEL&ER	CY	129.76	288	12650	1,641,464	288	12650	1,641,464
ALUM FAB	TON	8279.46		564	4,669,615		564	4,669,615
AL DEL&ER	TON	240.55		564	135,670		564	135,670
ALIGNMT	LF	1.5	120	5280	7,920	120	5280	7,920
MOB&DEMOB		5%			649,705			840,986
TOTAL					13,643,806			17,660,698
				$/METER	8,478		$/METER	10,974

DP–27 CONCRETE BEAM ELEVATED – SINGLE (9.1 & 20)

SPAN	FEET (METERS)		30	(9.14)		30	(9.14)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.954	44	7744	15,132	51	8976	17,539
CONCRETE	CY	134.73	25	4400	592,812	30	5280	711,374
BACKFILL	CY	8.904	19	3344	29,775	22	3872	34,476
COLUMNS	CY	728.8	13.33	2346	1,709,823	27	4798	3,496,607
CROSSBM	CY	530.94	18.96	3337	1,771,726	19	3337	1,771,726
CONBM FAB	CY	401.21	73.61	12955	5,197,820	74	12955	5,197,820
BM DEL&ER	CY	129.76	73.61	12955	1,681,088	74	12955	1,681,088
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	60	10560	15,840	60	10560	15,840
MOB&DEMOB		5%			1,031,229			1,126,852
TOTAL					21,655,815			23,663,894
				$/METER	13,457		$/METER	14,704

SPAN	FEET (METERS)		75	(22.86)		75	(22.86)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.954	81	5702	11,142	91	6406	12,518
CONCRETE	CY	134.73	49	3450	464,765	56	3942	531,160
BACKFILL	CY	8.904	32	2253	20,059	35	2464	21,939
COLUMNS	CY	728.8	12.22	860	626,978	28	1982	1,444,307
CROSSBM	CY	530.94	37.93	2670	1,417,754	38	2670	1,417,754
CONBM FAB	CY	401.21	211.8	14911	5,982,330	212	14911	5,982,330
BM DEL&ER	CY	129.76	211.8	14911	1,934,815	212	14911	1,934,815
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	150	10560	15,840	150	10560	15,840
MOB&DEMOB		5%			1,004,213			1,048,562
TOTAL					21,088,467			22,019,796
				$/METER	13,104		$/METER	13,683

SPAN	FEET (METERS)		120	(36.58)		120	(36.58)	
HEIGHT	FEET (METERS)		17	(5.18)		25	(7.62)	
		UNIT	QTY/	QTY/	COST/	QTY/	QTY/	COST/
ITEM	UNITS	PRICE	SPAN	MILE	MILE	SPAN	MILE	MILE
EXCAV	CY	1.954	194	8536	16,679	212	9328	18,227
CONCRETE	CY	134.73	125	5500	741,015	137	6028	812,152
BACKFILL	CY	8.904	70	3080	27,424	75	3300	29,383
COLUMNS	CY	728.8	19.26	847	617,614	25	1108	807,773
CROSSBM	CY	530.94	47.41	2086	1,107,562	47	2086	1,107,562
CONBM FAB	CY	401.21	575.24	25311	10,154,850	575	25311	10,154,850
BM DEL&ER	CY	129.76	575.24	25311	3,284,298	575	25311	3,284,298
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	240	10560	15,840	240	10560	15,840
MOB&DEMOB		5%			1,278,793			1,292,033
TOTAL					26,854,647			27,132,690
				$/METER	16,687		$/METER	16,860

DP-28 CONCRETE BEAM ELEVATED - DOUBLE (5.2 & 7.6)

SPAN	FEET (METERS)		30	(9.14)		30		
HEIGHT	FEET (METERS)		30	(9.14)		65		
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	54	9504	18,571	101	17776	34,734
CONCRETE	CY	134.73	31	5456	735,087	62	10912	1,470,174
BACKFILL	CY	8.904	23	4048	36,043	39	6864	61,117
COLUMNS	CY	728.8	33	5841	4,257,241	141	24874	18,128,230
CROSSBM	CY	530.94	19	3337	1,771,726	19	3337	1,771,726
CONBM FAB	CY	401.21	74	12955	5,197,820	74	12955	5,197,820
BM DEL&ER	CY	129.76	74	12955	1,681,088	74	12955	1,681,088
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	60	10560	15,840	60	10560	15,840
MOB&DEMOB		5%			1,166,199			1,898,565
TOTAL					24,490,186			39,869,864
				$/METER	15,218		$/METER	24,775

SPAN	FEET (METERS)		75	(22.86)		75		
HEIGHT	FEET (METERS)		30	(9.14)		65		
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	98	6899	13,481	152	10701	20,909
CONCRETE	CY	134.73	60	4224	569,100	96	6758	910,559
BACKFILL	CY	8.904	38	2675	23,820	56	3942	35,103
COLUMNS	CY	728.8	36	2503	1,824,495	132	9324	6,795,168
CROSSBM	CY	530.94	38	2670	1,417,754	38	2670	1,417,754
CONBM FAB	CY	401.21	212	14911	5,982,330	212	14911	5,982,330
BM DEL&ER	CY	129.76	212	14911	1,934,815	212	14911	1,934,815
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	150	10560	15,840	150	10560	15,840
MOB&DEMOB		5%			1,069,610			1,336,153
TOTAL					22,461,817			28,059,203
				$/METER	13,958		$/METER	17,436

SPAN	FEET (METERS)		120	(36.58)		120		
HEIGHT	FEET (METERS)		30	(9.14)		65		
ITEM	UNITS	UNIT PRICE	QTY/ SPAN	QTY/ MILE	COST/ MILE	QTY/ SPAN	QTY/ MILE	COST/ MILE
EXCAV	CY	1.954	221	9724	19,001	314	13816	26,996
CONCRETE	CY	134.73	143	6292	847,721	207	9108	1,227,121
BACKFILL	CY	8.904	78	3432	30,559	108	4752	42,312
COLUMNS	CY	728.8	33	1434	1,045,070	179	7885	5,746,442
CROSSBM	CY	530.94	47	2086	1,107,562	47	2086	1,107,562
CONBM FAB	CY	401.21	575	25311	10,154,850	575	25311	10,154,850
BM DEL&ER	CY	129.76	575	25311	3,284,298	575	25311	3,284,298
ALUM FAB	TON	8279.46		1128	9,339,231		1128	9,339,231
AL DEL&ER	TON	240.55		1128	271,340		1128	271,340
ALIGNMT	LF	1.5	240	10560	15,840	240	10560	15,840
MOB&DEMOB		5%			1,305,774			1,560,800
TOTAL					27,421,245			32,776,792
				$/METER	17,039		$/METER	20,367

DP-29 CONCRETE BEAM ELEVATED - DOUBLE (9.1 & 20)

5.3.2.24. SINGLE/DUAL MAGWAY

5.3.2.24.1. MOTIVATION

It is desired to determine the cost difference, if any, between two single magways that are structurally independent (eastbound and westbound, for example) and one dual, or double, magway, that holds the east and westbound troughs on the same structure.

5.3.2.24.2. CONCLUSIONS

- For magways at grade two single magways are essentially the same cost as one dual magway. This is true for all three structural systems (aluminum, concrete or steel).
- For elevated aluminum magways, two single magways cost essentially the same as one dual magway.
- For elevated steel and concrete magways at normal heights and the nominal 23 m (75') span, the costs of two single magways show to be slightly less than one dual magway. This is primarily due to the fact that the dual steel truss or concrete beam is more expensive than two single trusses or beams.
- For elevated steel and concrete magways at the 20 m (66') height, the costs of two single magways is slightly more than one dual magway. At this height, the column costs become more significant and columns for dual magways can be made for less material than two individual columns.

The fact that the costs of two single or one dual magways are essentially equivalent provides flexibility to the system. That is, for magways of nominal height and span, dual magways may be single structures separated by any required distance, or may be on a dual structure supported on single piers or columns.

5.3.2.22.3. CALCULATIONS

The preliminary designs and cost estimates presented in Section 5.3.2.23. were used to perform this analysis.

Dual magways at grade are seen to cost twice as much as single magways.

Height	Steel	Concrete
5.18m (17')	0.92	0.95
7.62m (25')	0.92	0.94
9.14m (30')	0.92	0.93
20.0m (66')	1.06	1.05

Figure 57 Ratio of twice the single magway cost to the dual magway cost

The costs for elevated magways were compared for the nominal 23 m (75') span. The values shown in Figure 57 were obtained by multiplying the single magway cost by two and dividing by the dual magway cost.

5.3.2.25. MAGWAY HEIGHT

5.3.2.25.1. MOTIVATION

This tradeoff analysis provides cost estimates for a double magway as a function of height. The magway height for purposes of this report and specifically for this study is the clearance from grade to the underside of the magway structure. In the case of the aluminum box beams spanning between concrete bents, it would be to the underside of the lowest point of the spanning box beams. In the case of steal truss or concrete beam supporting structure, it would be to the underside of the truss or beam.

In an actual Magneplane route, it will be necessary for the magway to have varying heights above grade. Some sections may be placed essentially at grade; i.e., 0.61 m (2 ft.) The nominal height for a typical elevated section is 5.18 (17 ft.) which provides standard clearance for highway traffic. A height of 7 m (23 ft.) is required to provide required clearance for railroads. Other situations such as topography and clearance above an existing overpass will require increased heights.

5.3.2.25.2. CONCLUSIONS

Figure 58 summarizes the results of this analysis. The cost of a double magway in thousands of dollars per meter is plotted as a function of magway height for the three types of magway construction; i.e., aluminum box beam, steel supporting truss, or concrete supporting beam. The following may be noted from the graph:

- Costs increase with increasing height. For the aluminum box beam, the costs of a magway at a height of 20 m are 181% of the costs for a magway at grade.
- The aluminum box beam is the least expensive and the concrete supporting beam the most expensive of the systems studied.
- The steel truss becomes more competitive with the aluminum box beam at increased heights.

It should be noted that the costs carry no contingency and are used here for relative comparisons only. The costs are minimum cost for the height based on using the optimum span for the height for each type of construction. The lengths of these optimum spans are shown in section 5.3.2.26. If a span length different from the optimum span for the desired height must be used due to topography, roadway width clearance, etc., the magway costs will increase above those shown.

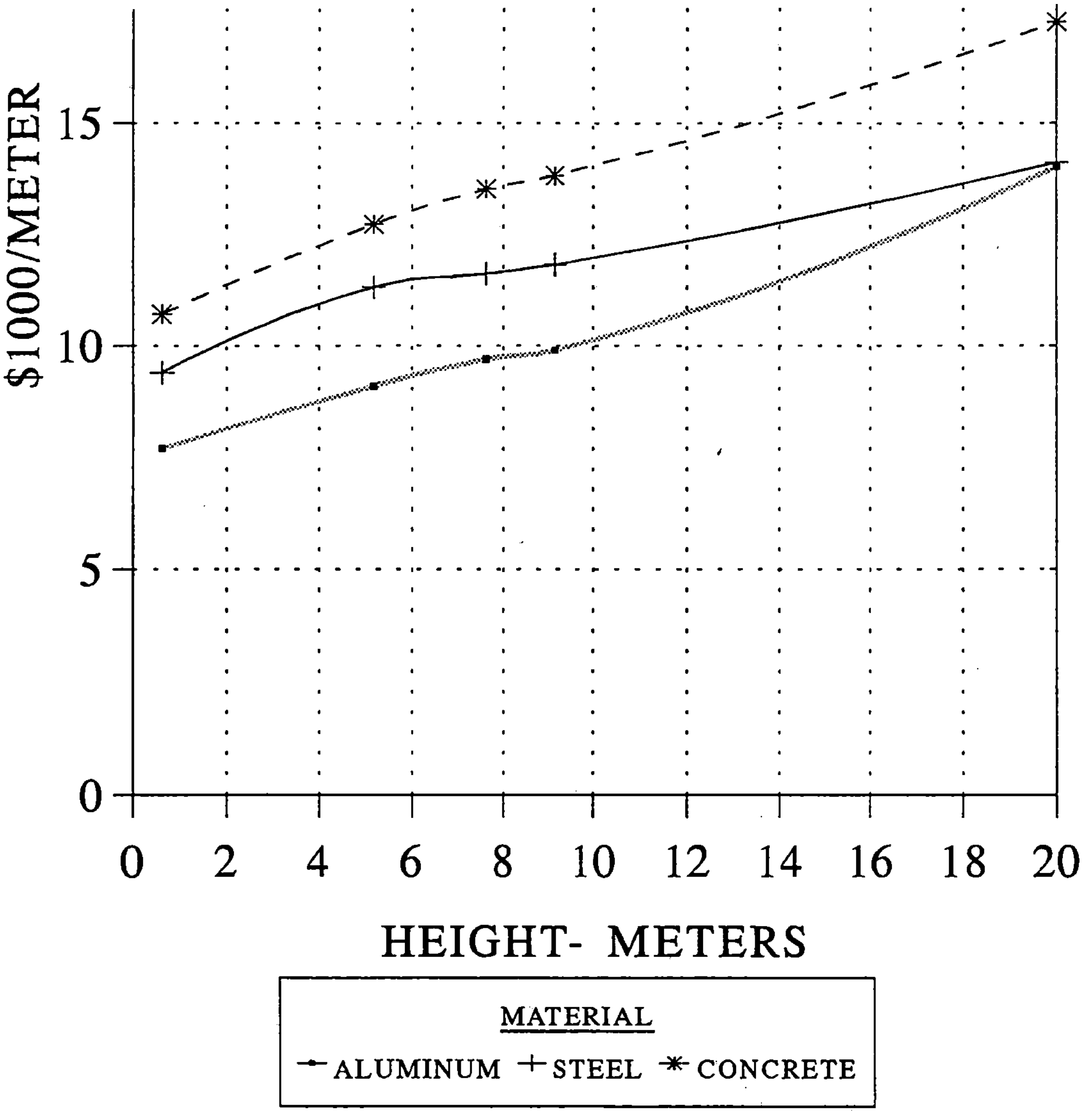


Figure 58 Cost of double magway as a function of height

5.3.2.25.3. CALCULATIONS

The graphs are based upon cost estimates that were made for a variety of spans and heights for each of the three support systems. These estimates are further discussed in Section 5.3.2.23. The assumptions used for the estimating are given in Section 5.3.11. Preliminary designs and engineering material takeoffs provide the basis for the material quantities used.

5.3.2.26. SPAN LENGTH

5.3.2.26.1. MOTIVATION

The magway costs vary considerably as a function of the length of the spans between vertical supporting members. It is important to quantify this relationship so that the cost of a magway of a particular span can be determined. Additionally, it is important to establish the optimum span; that is the most economical span length for each structural system. This analysis will present both results in graphical form for the aluminum box beam and steel truss structural systems for various heights above grade.

5.3.2.26.2. CONCLUSIONS

Figure 59 plots the optimum span length for each of the three structural systems as a function of magway height and shows the following:

- For all systems, the optimum span increases with increasing height.
- The aluminum box beam has the shortest optimum span length varying from 5 m (16 ft) for the at grade magway to 12 m (39 ft) for a magway height of 20 m (66 ft).
- The steel truss system has the longest optimum span length varying from 15 m (49 ft) for the at grade magway to 25 m (82 ft) for a magway height of 20 m (66 ft).
- At the nominal height of 5.2 m (17 ft) the optimum span for the aluminum, steel and concrete systems is 8.25 m (27 ft), 19.5 m (64 ft), and 18 m (59 ft) respectively.

Figure 60 plots minimum cost for a double magway as a function of span length. Three curves are provided in order to present costs for three magway heights: 0.61 m (2 ft), 5.18 m (17 ft), and 20 m (66 ft). The following can be noted from the figure:

- For spans of 5 m (16 ft) to approximately 15 m (49 ft), the aluminum box beam magway is the most cost effective.
- At spans above 15 m (49 ft) the steel truss magway is the most cost effective.
- For either system, the optimum span length increases with increasing magway height above grade.

5.3.2.26.3. CALCULATIONS

The cost of the magway is the sum of the cost of various components most of which vary with the length of the span. For example, as spans increase, the cost per mile of the crossbeams columns and footings generally decrease since although they may get slightly larger, there will be fewer of them per mile. Conversely, the cost of the spanning member (aluminum box beam, steel truss, or concrete beam) will increase since increased depth is required to provide adequate stiffness for a longer span.

The estimated costs for the structural systems for a variety of heights and span lengths as described in Section 5.3.2.23. were used to develop the information presented this analysis. Preliminary designs of all the structural components and the associated material tradeoffs provided the basis for the material quantities used. The assumptions used for cost estimating are given in Section 5.3.11.

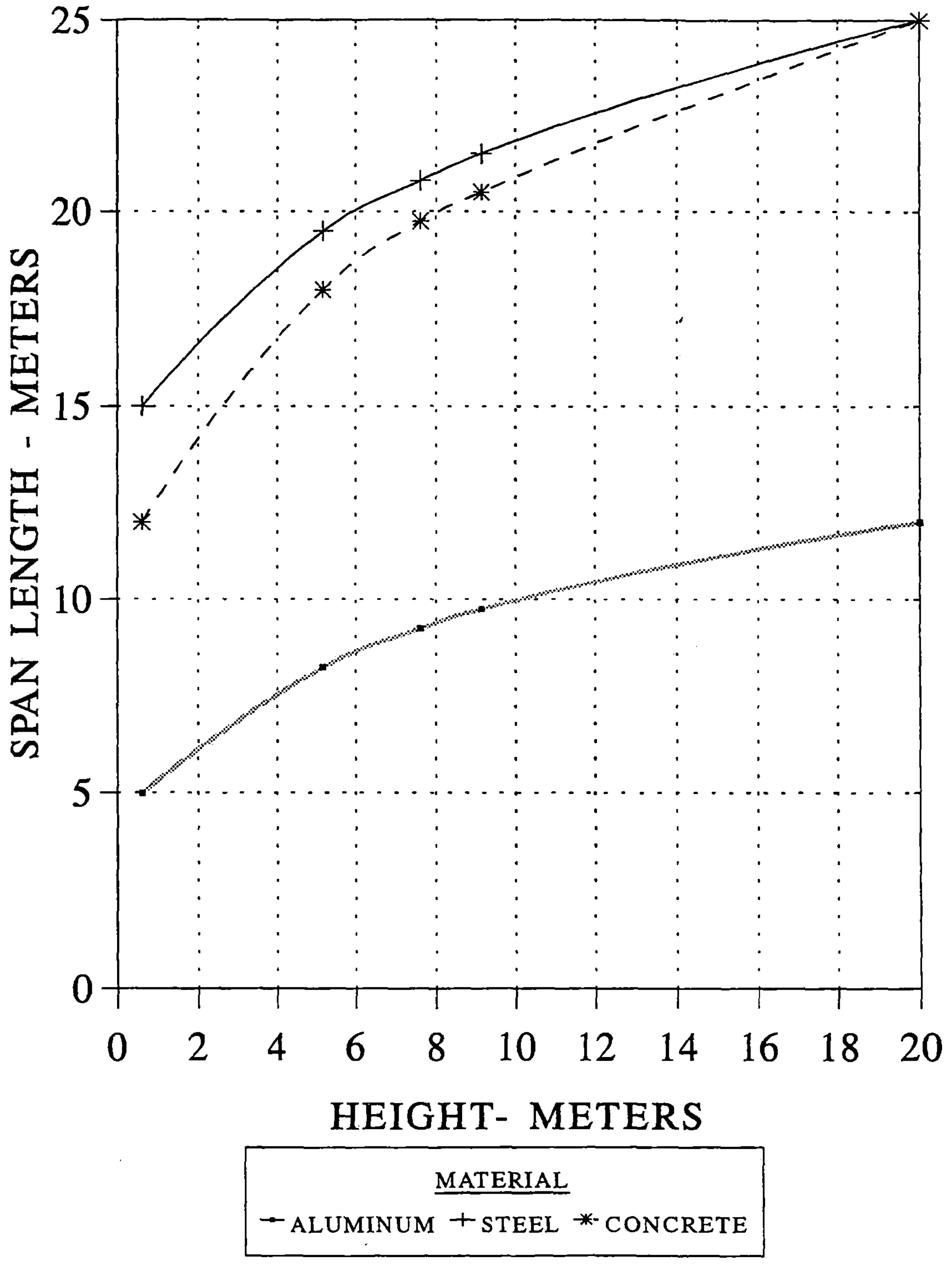


Figure 59 Optimum span as a function of height

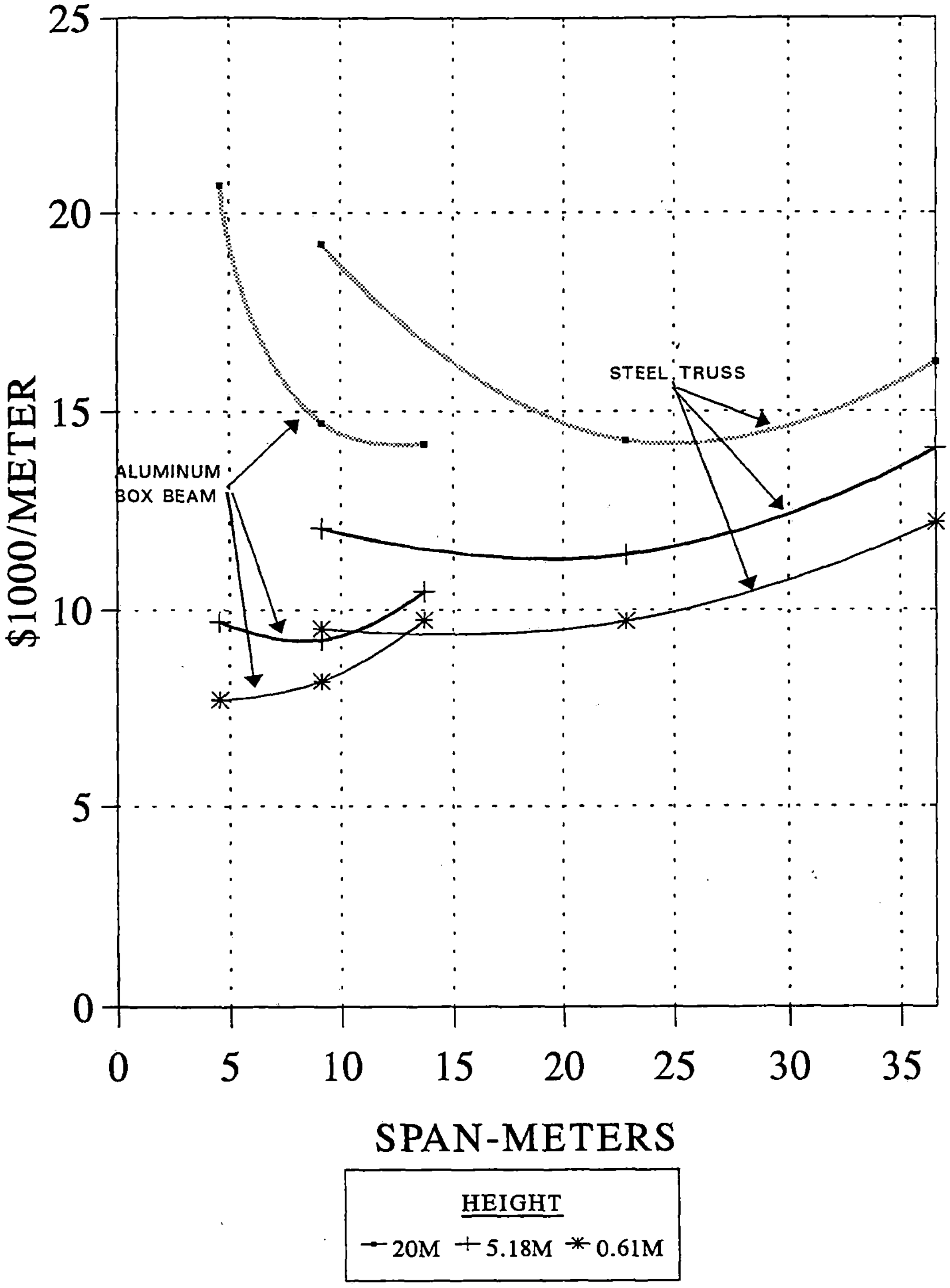


Figure 60 Costs of various span lengths

5.3.2.27. MAGWAY BANK ANGLE

5.3.2.27.1. MOTIVATION

The selection of a maximum design magway bank angle depends largely on the following factors:

(a) Required speed in a coordinated turn
(b) Minimum speed at which turn can be negotiated
(c) Lateral passenger ride quality limits
(d) Construction cost

A large bank angle is required to allow a high turn speed and to maintain a high average trip speed. However, the magway construction cost increases rapidly with design bank angle, and a large bank angle makes it more difficult to negotiate the turn at abnormal or emergency low speed conditions.

Design bank angle can be reduced by trading-off with passenger lateral acceleration up to the ride comfort limits. The side forces which produce the lateral acceleration are generated by the magnetic keel effect described in Section 3.2.2.g. By increasing the gap between the levitation plates, the onset of the keel effect can be delayed. In analyzing the banked turn performance, it is assumed that the gap is increased to 1.8 m from the nominal value of 1.4 m.

The trade-off parameters V_D, V_M and V_C are defined as follows:

V_D	is the design speed for the curve with a passenger lateral acceleration of 0.16g outward.
V_M	is the minimum magnetically levitated speed in the turn with an emergency level, of 0.3g inward for the passenger lateral acceleration.
V_C	is the equivalent coordinated turn speed at 45° bank and the same turn radius.

5.3.2.27.2. CONCLUSIONS

The effect of track bank angle on these parameters is presented in Figure 61, together with the cost factor. The cost factor is defined as the percentage increase in cost per unit length of turn over that of the straight & level track.

The table shows that an increase in bank angle above 35° will result in a high construction cost. The V_D/V_C ratio shows that a bank angle of 35° allows the same speed performance as a 45° coordinated turn

Bank Angle (deg)	25	30	35
V_M/V_D	0	0.27	0.39
V_D/V_C	0.72	0.85	1.00
Cost Factor (%)	40	51	63

Figure 61 Magway bank angle comparison

to be achieved. Also at 35° bank, the speed ratio V_M/V_D is low enough that the pads can be deployed and the keel effect further reduced, allowing further speed reduction. Propulsive forces can be obtained from interaction between the LSM and the levitation coils. A bank angle of 35° is therefore felt to be optimum as a design value.

5.3.2.28. MAGWAY ALIGNMENT AND DEFLECTION

5.3.2.28.1. MOTIVATION

The most important single parameter determining ride quality is the track deviation from its straight form. To assess the trade-off in ride quality, the track mis-alignment and deflection characteristics are combined into a single requirement for the maximum deflection of the magway between support columns. As a worst case forcing input for the vehicle heave response, the magway shape is modelled as a sinusoid with wavelength equal to the column spacing and amplitude equal to half the maximum deflection.

5.3.2.28.2. CONCLUSIONS

The trade-off between ride quality and magway deflection as a function of vehicle speed is presented in Figure 62 for the design column spacing of 9.1 m. The critical behavior is at the low speed end, and the results show~~s~~ that an acceptable acceleration level of 0.04 to 0.05 g rms can be achieved at 50 m/s provided the deflection does not exceed 0.02 m.

5.3.2.28.3. CALCULATIONS

The aerodynamic surface and LSM heave phase controls are assumed to be operating without bandwidth limitation. The aerodynamic control surface effectiveness increases with the square of the vehicle speed while the LSM damping force amplitude is given approximately by the product of the propulsive force and the maximum phase angle. The quantities used in the analysis are summarized as follows:

LSM Force = 30,000 N
LSM Phase angle = 20°

Aerodynamic surface area = 2.8 m^2
Lift coefficient slope with surface deflection = 4.5 per rad
Control surface maximum deflection = 15°

Vehicle heave natural frequency = 1.5 Hz
Vehicle weight = 450,000 N.

The root mean square of the vertical acceleration of the vehicle is used as the measure of passenger ride comfort. With the above characteristics, it is found that the ride quality is insensitive to support column spacing when less than 15 m and for speeds above 50 m/s.

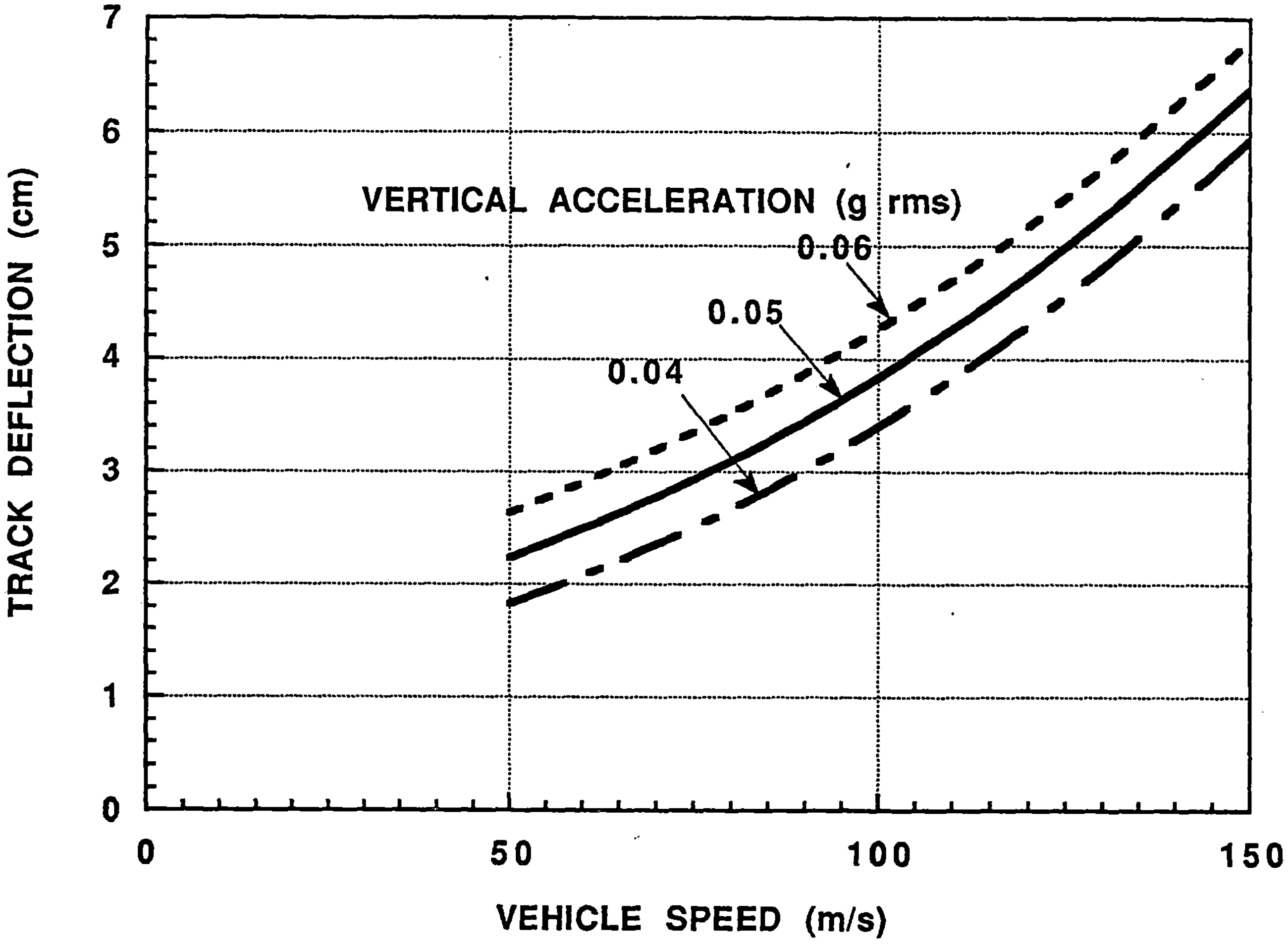


Figure 62 Magway deflection tradeoff

5.3.2.29. MAGWAY SEPARATION

5.3.2.29.1. MOTIVATION

The magway separation (distance between dual magways) is a tradeoff between ride quality and construction costs.

5.3.2.29.2. CONCLUSIONS

To minimize construction costs the magway separation should be kept as small as possible, provided perturbations during vehicle passing do not exceed ride quality limits. This separation is 5.3 m.

5.3.2.29.3. CALCULATIONS

The aerodynamic effects during vehicle passing were discussed in Section 3.2.3.c, and the resultant maximum lateral accelerations are presented there. for 140 passenger vehicles when each is travelling at 140 m/s. The data in Figure 63 shows both the peak acceleration and the associated jolt as functions of the magway separation. At the design separation of 5.3 m, the peak acceleration meets the design level values for ride comfort, and the jolt meets the minimum requirements. Reduction of separation below this level is not desirable because accelerations can be enhanced when cross-winds are present.

Guideway Separation (m)	4	5	6	7
Peak acceleration (g)	0.068	0.043	0.030	0.022
Jolts (Peak-to-peak g/sec)	0.44	0.28	0.19	0.14

Figure 63 Magway separation tradeoff

5.3.2.30. TUNNEL SIZE AND CONFIGURATION

5.3.2.30.1. MOTIVATION

There will be instances along a Magneplane route where tunnels will be required. As tunnels are a relatively costly item, it will be important to minimize their life cycle costs. Two tunnel configurations have been considered for the magway. One configuration consists of a single magway bored in rock. The second configuration is a cut and fill type tunnel that would be used in an urban or suburban setting where it is desired to place the magway below grade.

5.3.2.30.2. CONCLUSIONS

The life cycle cost analysis indicates that the most efficient tunnel for each configuration is the one with the lowest capital cost; ie., the one with the smallest cross-sectional area.

5.3.2.30.3. CALCULATIONS

It can be readily seen from the parametric study found in section 5.3.3.2.h. that the tunnel with the lowest capital cost will also have the least life cycle cost as the difference in energy requirements between the different size tunnels is almost insignificant.

For this analysis, cost estimates were made for three tunnel sizes for each configuration. The sizes matched the cross-sectional areas given in section 3.2.2.k. The assumptions used in the estimates are also given there.

Figure 64, Figure 65, and Figure 66 depict the three bored tunnel configurations. These figures show single magways. A dual magway would consist of two single bores and would be twice the cost of a single magway. Figure 67 indicates the capital costs for the three sizes of double mined/bored tunnels.

Figure 68, Figure 69, and Figure 70 depict the three cut and fill tunnel configurations. These tunnels provide for double magways. The capital costs for the three cut and fill tunnel sizes are given in Figure 71.

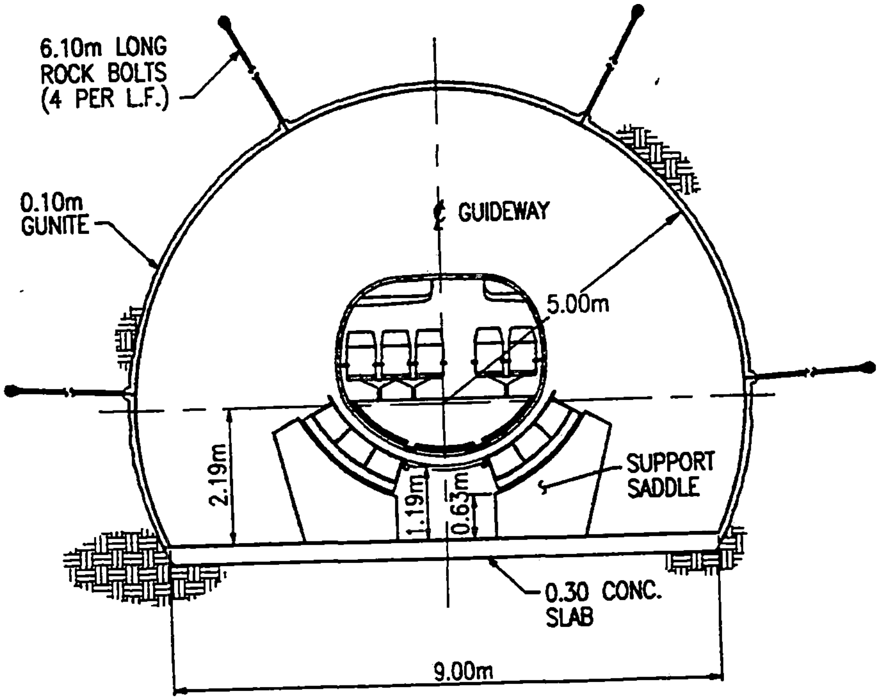


Figure 64 Bored tunnel - 10 m diameter

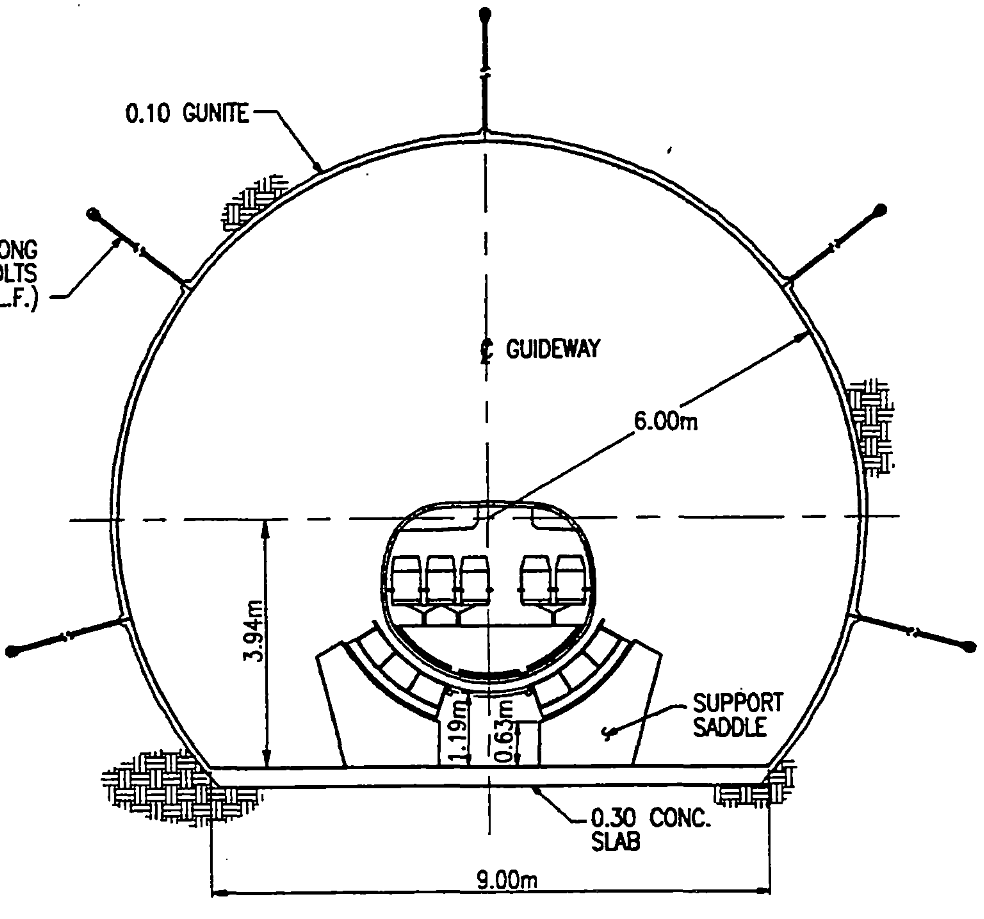


Figure 65 Bored tunnel - 12 m diameter

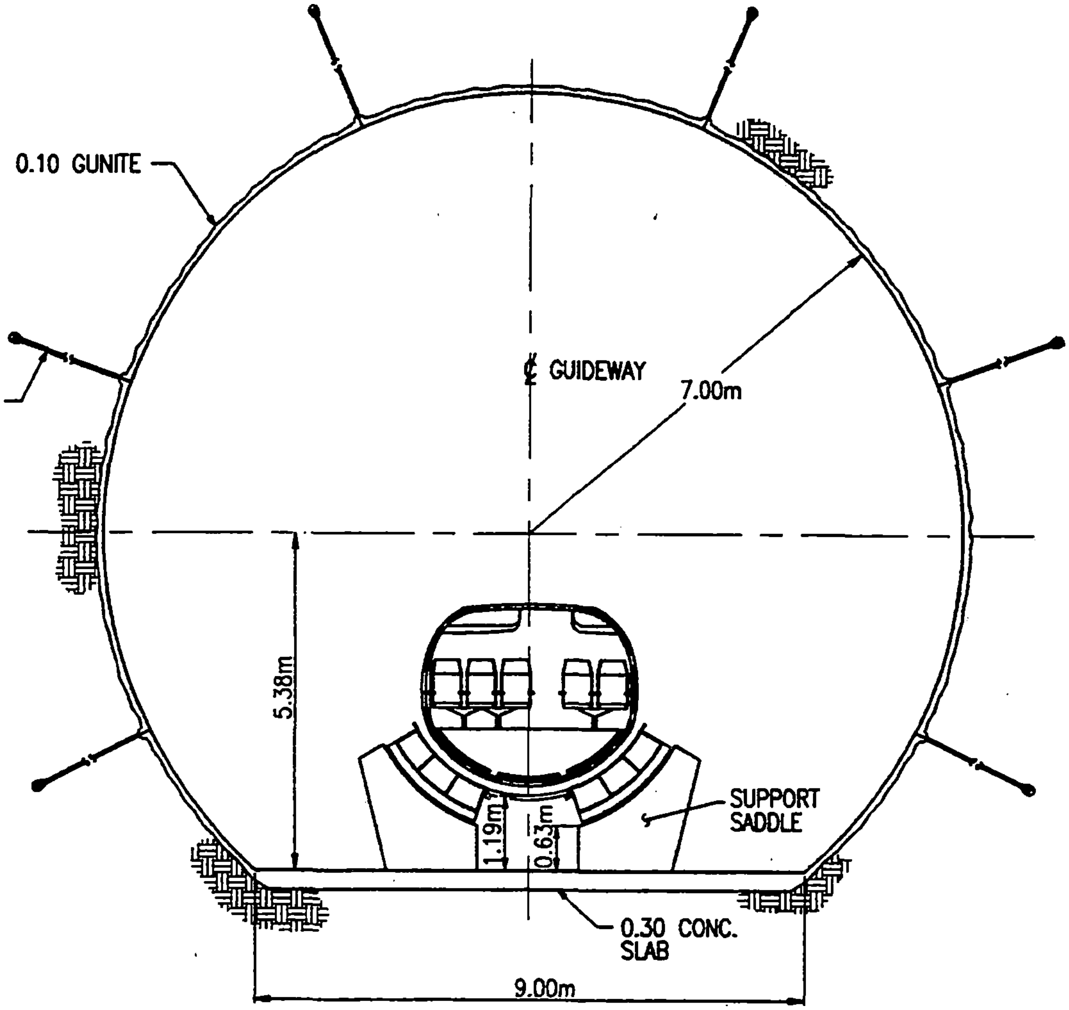


Figure 66 Bored tunnel - 14 m diameter

DOUBLE MINED/BORED			DIAMETER = 10 M		DIAMETER = 12 M		DIAMETER = 14 M	
COST ELEMENT	UNITS	UNIT COST	QTY/ MILE	COST/ MILE	QTY/ MILE	COST/ MILE	QTY/ MILE	COST/ MILE
EXCAVATION	CY	$66.02	288,000	19,014,912	454,080	29,980,178	633,600	41,832,806
LINER	SF	$8.40	718,080	6,030,468	960,960	8,070,185	1,193,280	10,021,219
ROCK BOLTS	EA	$178.76	42,240	7,550,928	52,800	9,438,660	63,360	11,326,392
HAUL ROCK	CY	$8.95	288,000	2,576,448	454,080	4,062,200	633,600	5,668,186
WATERPROOFING	LOT	---	---	1,387,512	---	1,617,848	---	1,887,481
DRAINAGE	LF	$22.68	10,560	239,501	10,560	239,501	10,560	239,501
SURVEY	LOT	---	---	47,880	---	50,401	---	52,921
FOOTING	CY	$118.23	11,616	1,373,311	11,616	1,373,311	11,616	1,373,311
CATWALK	LF	$52.32	10,560	552,515	10,560	552,515	10,560	552,515
LIGHTING	LOT	---	---	496,565	---	526,904	---	557,239
VENTILATION	LOT	---	---	1,487,566	---	1,574,725	---	1,661,869
STEEL CRADLE	TON	$2,104.65	704	1,481,673	704	1,481,673	704	1,481,673
ALUM FAB	TON	$8,279.46	1,128	9,339,231	1,128	9,339,231	1,128	9,339,231
ALUM DEL/ERCT	TON	$240.55	1,128	271,346	1,128	271,346	1,128	271,346
ALIGNMENT	LF	$1.50	10,560	15,800	10,560	15,800	10,560	15,800
MOB/DEMOB	LS	5%		2,593,283		3,429,724		4,314,074
TOTAL				54,458,939		72,024,202		90,595,564
			$/METER	33,839	$/METER	44,754	$/METER	56,293

Figure 67 Relative costs of bored tunnels - double magway

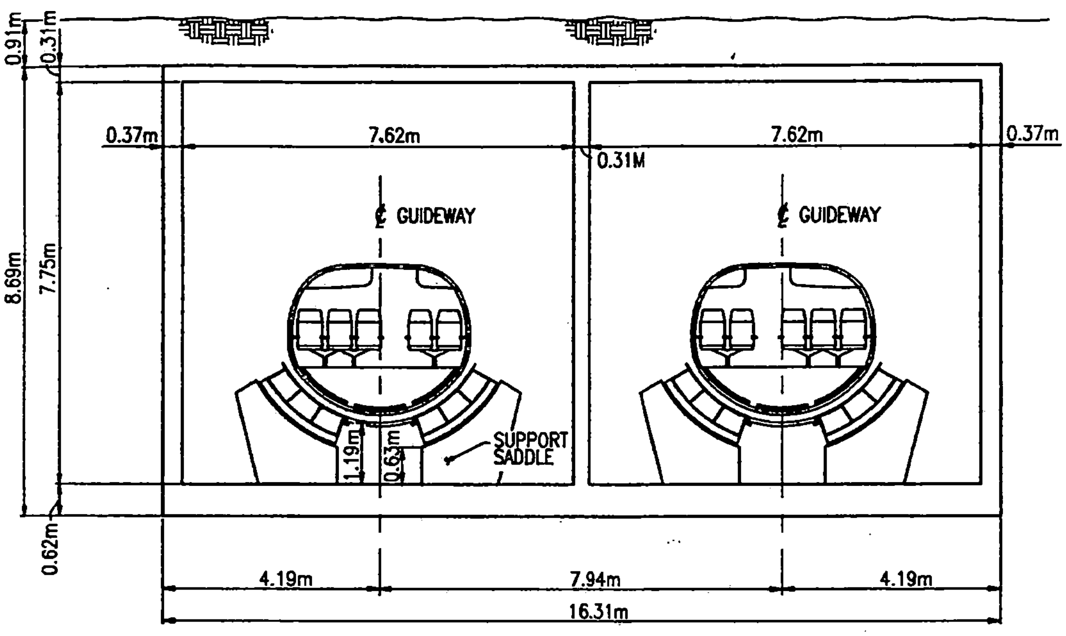


Figure 68 Cut and fill tunnel - 7.8 x 7.6 m

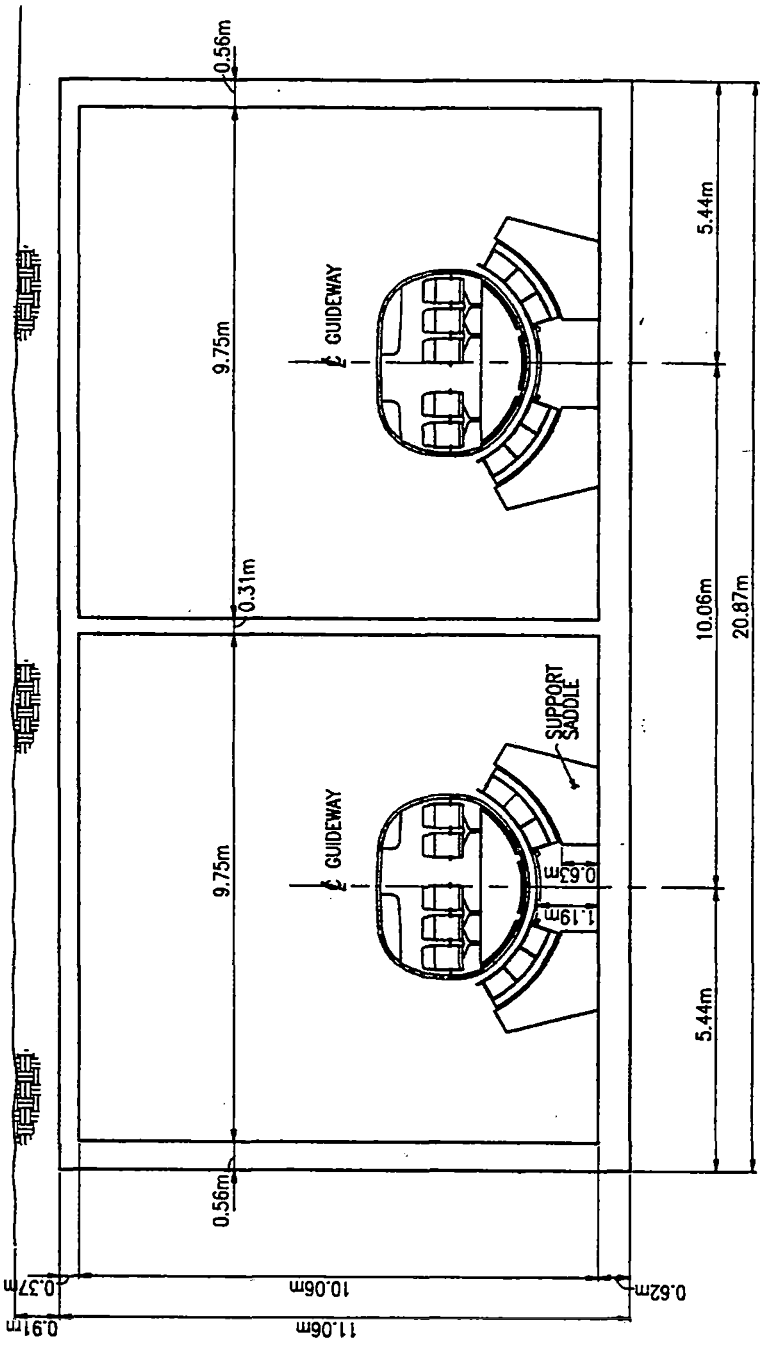


Figure 69 Cut and fill tunnel - 10 x 9.8 m

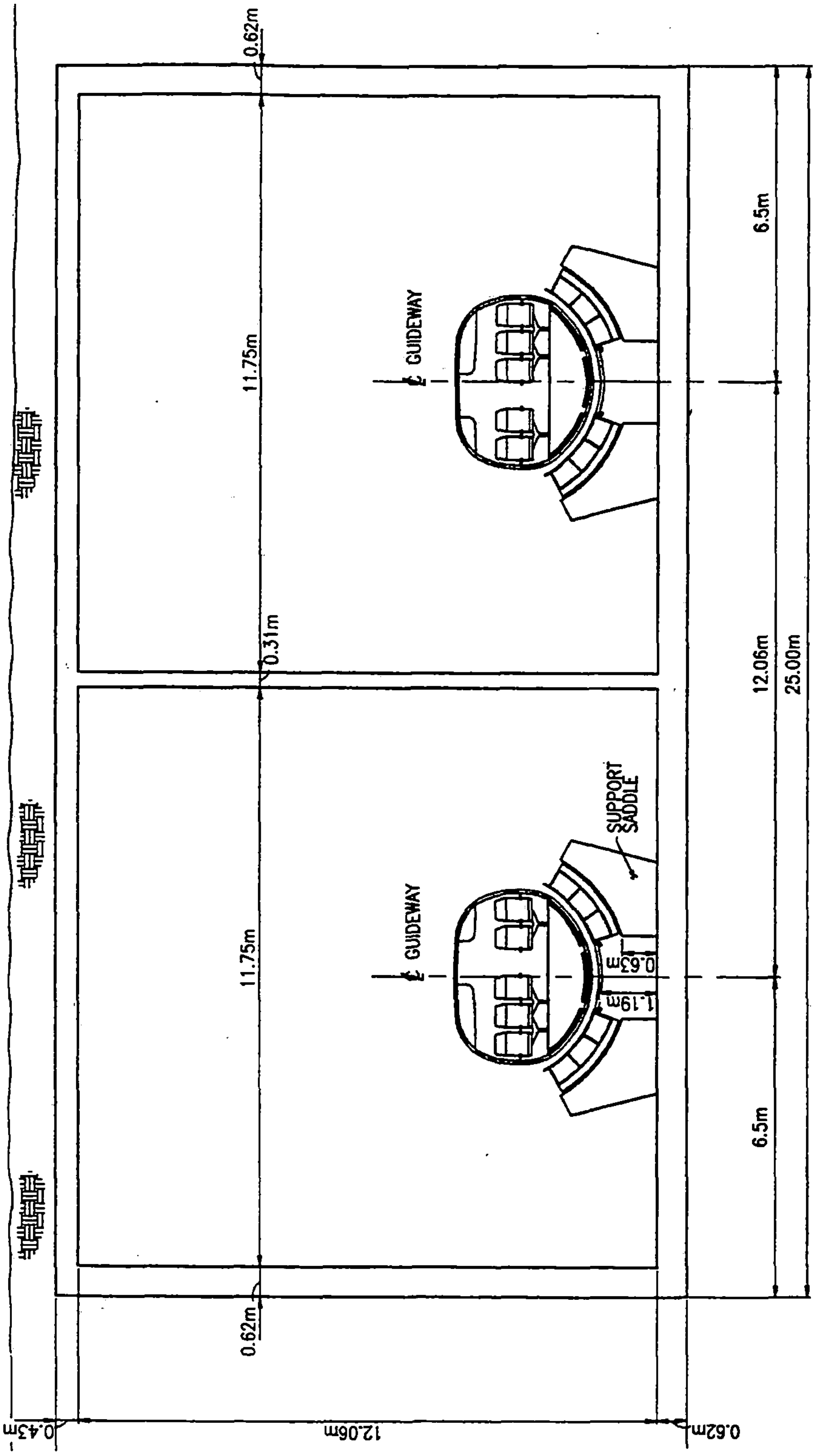


Figure 70 Cut and fill tunnel - 12 x 11.8 m

DOUBLE CUT/FILL								
EQUIVALENT DIAMETER			DIAMETER = 10 M		DIAMETER = 12 M		DIAMETER = 14 M	
SIZE-METERS			(2) 7.8x7.8		(2) 10x10		(2) 12x12	
CROSS AREA-SF			(2) 650		(2) 1083		(2) 1550	
COST ELEMENT	UNITS	UNIT COST	QTY/ MILE	COST/ MILE	QTY/ MILE	COST/ MILE	QTY/ MILE	COST/ MILE
EXCAVATION	CY	$4.06	343,200	1,392,243	549,100	2,227,508	776,200	3,148,773
HAUL	CY	$5.61	310,900	1,745,408	508,100	2,852,499	726,900	4,080,853
BACKFILL	CY	$6.94	32,300	224,244	41,000	284,644	49,300	342,267
SHEETPILING	SF	$7.56	343,200	2,594,592	425,000	3,213,000	500,000	3,780,000
WATERPROOFING	LOT	---	---	561,632	---	780,730	---	933,671
SURVEY	LOT	---	---	28,980	---	31,500	---	34,020
BOTTOM SLAB	CY	$195.46	20,900	4,085,062	27,200	5,316,444	32,500	6,352,369
WALLS	CY	$316.17	17,500	5,532,951	29,000	9,168,890	38,600	12,204,109
TOP SLAB	CY	$324.83	10,700	3,475,727	17,000	5,522,183	24,400	7,925,957
CATWALK	LF	$52.32	10,560	552,515	10,560	552,515	10,560	552,515
LIGHTING	LOT	---	---	797,159	---	981,176	---	1,138,316
VENTILATION	LOT	---	---	2,757,997	---	3,397,252	---	3,956,419
STEEL CRADLE	TON	$2,104.65	704	1,481,673	704	1,481,673	704	1,481,673
ALUM FAB	TON	$8,279.46	1,128	9,339,231	1,128	9,339,231	1,128	9,339,231
ALUM DEL/ERCT	TON	$240.55	1,128	271,346	1,128	271,346	1,128	271,346
ALIGNMENT	LF	$1.50	10,560	15,800	10,560	15,800	10,560	15,800
MOB/DEMOB	LS	5%		1,742,828		2,271,819		2,777,866
TOTAL				36,599,388		47,708,209		58,335,186
			$/METER	22,742	$/METER	29,645	$/METER	36,248

Figure 71 Relative costs of cut and fill tunnels - double magway

5.3.2.31. POWER CONVERTER SELECTION

5.3.2.31.1. MOTIVATION

The purpose of the selection is to identify the most effective technology to use for wayside power conversion. Considerations include: output frequency range, power range, regeneration capability, maturity of the technology and cost.

5.3.2.31.2. CONCLUSION

Converters using Gate turn-off (GTO) pulse width modulated (PWM) technology are the best choice for the application. They are the only established technology which can supply power in the frequency range needed which extends to 100 Hz. They have been used commercially up to 10 MW.

5.3.2.31.3. CALCULATIONS

Some of the primary specifications for the power converter are:

1. Power ratings of 5 - 25 MW
2. Frequency range up to 100 Hz
3. Low harmonic distortion
4. Solid state: no rotating converter equipment
5. Established product in existing applications

	Cycloconverter	GTO PWM Inverter
Power Range	Up to 10 MW	Up to 10 MW Parallel
Power Device	SCR	GTO
Max Frequency	48 Hz on 60 Hz	166 Hz on 60 Hz
Regeneration	Inherent	Needs Added Equipment
Control Response	Slow	Fast
Output Harmonics	High	Low

Figure 72 Power converter tradeoff

Two potential technologies were identified for the application. These are the circulating current cycloconverter and the GTO PWM inverter. A brief comparison is presented in Figure 72.

5.3.2.32. METHOD OF REFRIGERATION

5.3.2.32.1. MOTIVATION

The type of cooling for the superconducting magnets must be identified.

5.3.2.32.2. CONCLUSIONS

Cooling will be provided by a closed-cycle helium refrigerator using a modified Claude cycle. It is a relatively simple cycle, employing two expanders and J-T expansion to provide the refrigeration, and is similar to the cycle used in many commercial helium refrigerator/liquefiers.

5.3.2.32.3. CALCULATIONS

The alternative of using open-cycle cooling from on-board stored liquid helium, though appealing in its simplicity, does not seem practical. The estimated liquid helium consumption rate of approximately 50 liters/hour, when projected for use with 100-200 Magneplanes, would severely tax the total world production of helium, which is a finite resource. The amount of helium produced annually in the USA is equivalent to about 90 million liquid liters (e.g. 1990), and thus each Magneplane operating on open-cycle helium could represent up to 1/2 % of this capacity. Although there exists a tremendous inventory of stockpiled helium, it is not reasonable to expect a fleet of 200 Magneplanes to consume the full annual production of helium in this country. At a market price of $4-5 per liter, the daily expenditure towards replenishing the helium would be between $5,000 and $6,000 per vehicle per day. Moreover, a large (500 to 1,000 liter) on-board liquid helium dewar would be required, along with supply facilities located at stations along the route. Filling a Magneplane with liquid helium twice a day would be disruptive to vehicle scheduling, and requires skilled technical personnel at each fill station. The consideration of cost leads us to conclude that a closed-cycle CRS can achieve payback in very short period of time. However it is possible to employ an open-cycle system in the early stages of Magneplane testing, while simultaneously developing a closed cycle refrigeration system.

5.3.2.33. WORK EXTRACTION DEVICES (PISTON OR TURBOEXPANDER)

Commercial helium refrigerator/liquefier systems manufactured by PSI for the 50-100 W capacity range (of interest for Magneplane) use reciprocating, piston-cylinder expansion engines with cam actuated intake and exhaust valves. These engines are rugged and durable and provide good service for many years in the government and university laboratories where they are principally utilized. However, the engine units are heavy and bulky; the drive mechanism incorporates a large, heavy flywheel which mounts atop the cold box. Basically, this equipment was not intended for mobile service. The reliability/maintainability of the engines may also not be acceptable for the type of service envisioned for Magneplane.

We believe that a better alternative will be to employ turboexpanders in the CRS for the Magneplane. These units are compact and relatively lightweight and, when properly integrated with the CRS, are very reliable and require virtually no maintenance. They have been used in all larger capacity helium refrigerators for many years and, more recently, are being employed in smaller capacity systems.

5.3.2.34. SHIELDING FLUID

The use of LN2 for shielding reduces the 6-8 K heat leak by a factor of 5 over non-shielded vacuum jacked lines, valves, and supports. Other shielding fluids such as liquid natural gas (LNG) would reduce that heat leak some what less, i.e. by a factor of 3. LNG shielding would occur at a temperature of approximately 130 K. If the Magneplane's on-board power were generated by LNG, the use of a portion of the LNG fuel as a coolant for both shielding and precooling would impose no additional cryogenic storage requirements since the fuel flow would be much higher than the coolant flow. The major drawback to the use of LNG is safety. The requirement of having to carry a large LNG container on-board a high speed Magneplane imposes questionable safety consideration for the passengers in the event of an accident. Consequently we have not recommend the use of LNG.

5.3.2.35. SHIELDING TEMPERATURE STAGES

LN2 shielding at approximately 90 K has the benefit of greatly reducing the 6-8 K load and therefore the refrigerator size and power requirements. Additional shielding at a lower temperature of for example 20 K would further reduce that heat leak but it would also add complexity and cost to the overall system. Since 20 K refrigeration would have to be provided by the refrigerator, the additional 20 K piping, valves, and other hardware imposes a potentially high heat load associated with the long distances. It is not clear if 20 K shielding would bring any significant benefit to reducing the refrigerator size. Also space limitation on the bottom of the magnets limit the number of shield levels that can be used.

5.3.2.36. COOLANT (LIQUID OR SUPERCRITICAL HELIUM)

Providing cooling either as liquid or supercritical helium has certain advantages and disadvantages. Providing liquid helium to the magnet will result in heat transfer by boiling; i.e. change of phase. Although this is a desirable method of cooling, one must consider the problem of maintaining the liquid level in the magnet. During Magneplane "flight", it may be difficult to assure that the magnets are always covered by liquid helium. Furthermore it is desirable to maintain the highest possible magnet operating temperature, since it will greatly reduce the refrigerator size. At the desired magnet operating temperature of 6 K, helium does not exist in the liquid phase.

Supercritical helium can readily provide cooling over a wide temperature range. The temperature level at which refrigeration is provided has a strong influence on the CRS input power requirements. The relationship is shown in Figure 73 where the ratio of input power to the heat load is shown for the temperature range 4.2-20 K. The curves are a plot of the equation:

$$\frac{P_{in}}{qL}=\frac{Tw-Tc}{Tc}\cdot\frac{1}{\gamma}$$

where

Pin = Input power
qL = Heat load
Tw = Heat rejection temperature
Tc = Load temperature
γ = Cycle efficiency relative to Carnot efficiency

For a refrigeration load of 50-100 W, which is appropriate to the Magneplane, the cycle efficiency relative to Carnot will be in the range 5 to 8%. Hence, the power inputs are shown for that range of efficiencies. The essentially inverse relationship of the power and the load temperature means that as the load temperature is reduced to low levels, the power input increases dramatically, as Figure 73 shows. Since the size and weight of refrigeration equipment generally tracks with the input power, it is obviously advantageous to have the refrigerated load operate at the highest temperature level consistent with its functioning; i.e. the need to maintain superconductive behavior of the magnets.

The use of small volumes of super critical helium flowing thru the magnet conduits offers advantage during a magnet quench compared to a magnet immersed in a container of liquid helium.

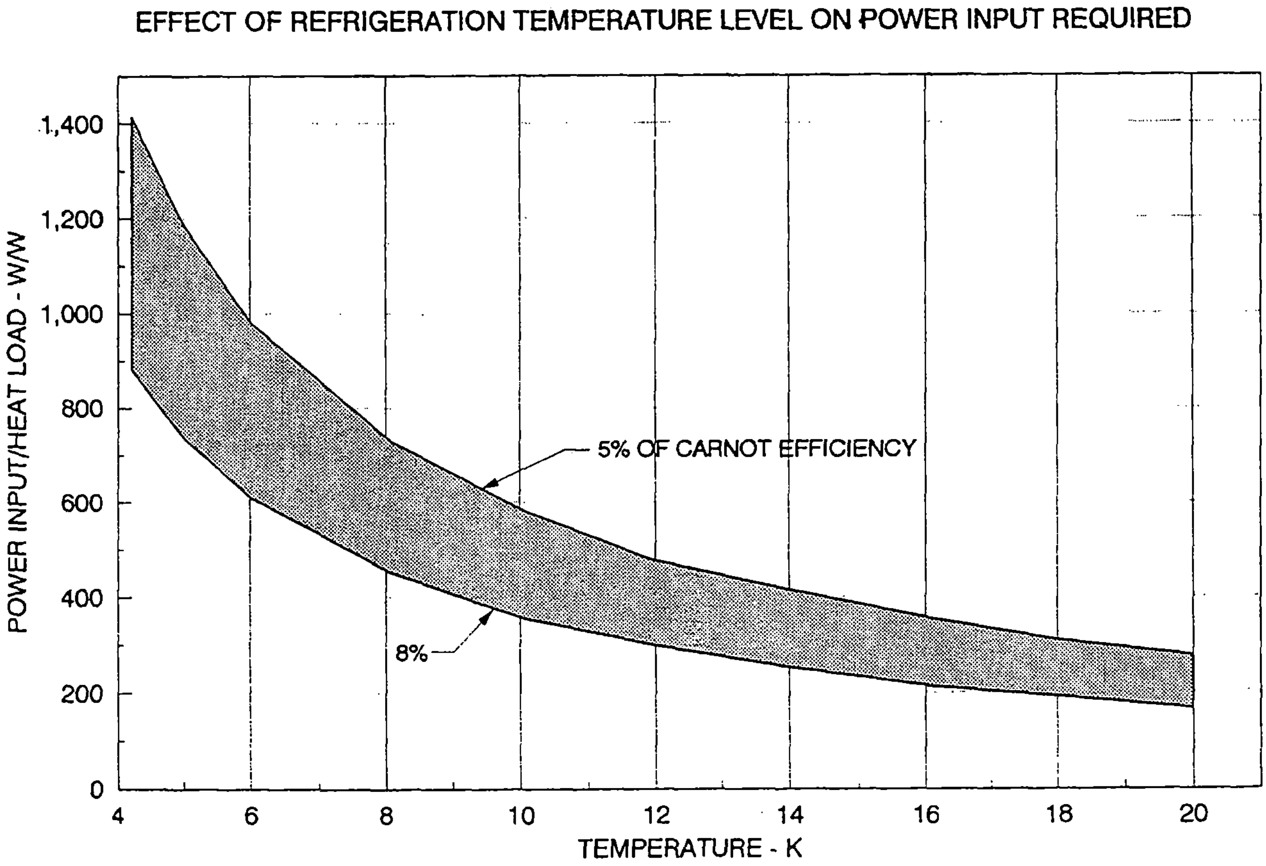


Figure 73 Effect of refrigeration temperature on power input required

5.3.2.37. COMPRESSOR TYPES

5.3.2.37.1. MOTIVATION

The type of compressor for the cooling system must be identified.

5.3.2.37.2. CONCLUSIONS

An oil-flooded twin-screw compressor is used.

5.3.2.37.3. CALCULATIONS

The oil-flooded compressor is the most commonly used compressor type in helium refrigerator/liquefier systems. It is a positive displacement machine which can develop a high pressure ratio in one stage by virtue of the oil injected into the compression space. The oil is injected in sufficient quantity to both cool the gas during compression and seal clearances in the machine to minimize gas back leakage. Thus, a relatively large oil flow is required, i.e. the order of 1-2% of the gas volume flow. Helium exiting the compressor flows through one or two stages of bulk oil removal, then several subsequent stages of oil mist removal by coalescing elements and a final stage of oil vapor removal by an adsorbent such as charcoal.

Separation of oil from helium in the bulk separator and draining of oil from the coalescing elements for return to the compressor relies on gravity. The Magneplane systems will have to accommodate limited changes in direction of the gravity vector associated with acceleration, braking and roll. An oil removal system design to meet this requirement will have to be demonstrated.

The alternative of using an oil-free compressor to eliminate the necessity of oil removal naturally comes to mind. Centrifugal and regenerative compressors are in the oil-free category and we have investigated both types.

Centrifugal compressors are notable for their high reliability and compact size. For these reasons, they are widely used for compressing the Freon refrigerant in large air conditioning systems. However, with a light gas such as helium (as opposed to the much higher molecular weight Freon refrigerants), a large number of compressor stages with intercooling are required to achieve a pressure ratio that is practical for the helium refrigeration cycle. About eight compressor stages would be required to achieve an overall pressure ratio of about 6:1. The wheel diameters would be small, and the rotational speed would be very high such that gas bearings would have to be utilized. Because of the large number of stages, this does not appear to be a feasible approach for the present application.

Like the centrifugal, the regenerative compressor is in the class of dynamic machines, i.e. compressors which impart kinetic energy to the gas, then decelerate it to achieve the pressure rise. However, its operation and performance characteristics are very different than those for a centrifugal compressor. The design of a single-stage machine for helium is shown in Figure 74. The helium flows with swirl around the periphery of a rotating wheel, alternately moving into and out of the blades on the wheel; in effect, one wheel acts as a multi-stage dynamic compressor. Hence, one stage (wheel) can achieve a much higher pressure ratio than a centrifugal stage and at a much lower flow rate. These characteristics better match the helium refrigerator/liquefier requirements. The machine in the figure could achieve a pressure ratio of 1.8:1. Thus, an overall pressure ratio near 6:1 could be accomplished in three stages with intercooling. Because of the tortuous flow path through the machine, fluid viscous losses tend to be high and the achievable efficiency is limited. Nevertheless, improvements in design incorporated in the machine shown in the figure led to an isothermal efficiency of about 0.37 at the pressure ratio of 1.8:1 and a flow of about 11 Nm3/min of helium at a rotational speed of 3,000 RPM. This is a higher flow rate than required for the present application, but the design could be readily scaled down. The isothermal efficiency of 0.37 is comparable to that for the oil-flooded twin screw machine.

The bearings would be oil-lubricated tilt pads for robustness. The oil would be fed from a small pump integrally built with each compressor. The shaft seal would use a small amount of helium to buffer the gas from the lubricant. The small quantity of buffer gas would be fed through a purifier before returning to the circuit. The process fluid would not come in contact with oil, so we consider this an oil-free machine. The use of gas bearings may be a feasible alternative that would completely eliminate the presence of oil in the compressor. The challenge in designing and building this machine to achieve good performance would be in manufacturing the small flow passages with adequate precision. Special tooling would most likely be required to produce the required shapes, using electric discharge machining for example.

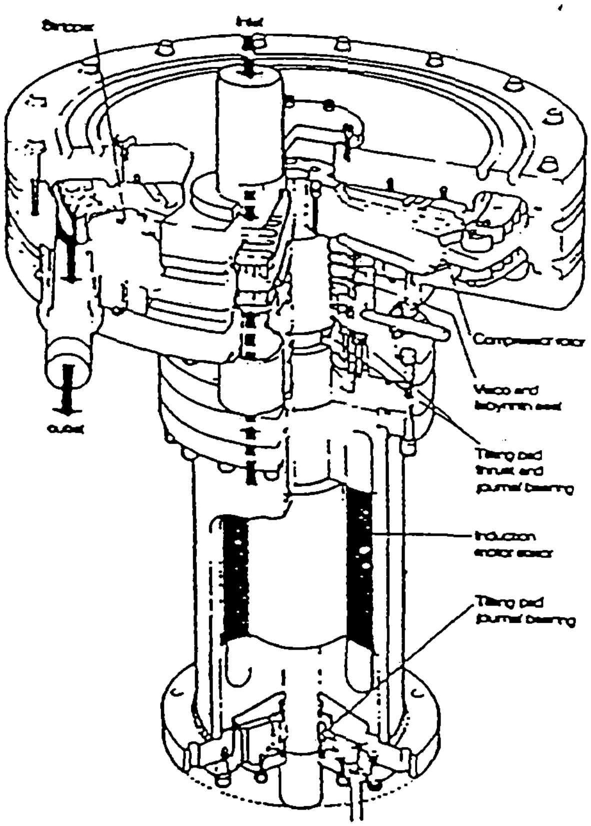


Figure 74 Regenerative compressor for helium

5.3.2.38. NUMBER OF COLD BOXES

5.3.2.38.1. MOTIVATION

The number of cold boxes is a tradeoff between the cost of transfer lines and the cost of an extra cold box. With one cold box, transfer lines are required to carry helium along the length of the vehicle. With two cold boxes, no lines are required.

5.3.2.38.2. CONCLUSIONS

The baseline CRS design has one cold box (and one compressor) supplying helium to all the magnets, as the PFD's indicate.

5.3.2.38.3. CALCULATIONS

The alternative arrangement to the baseline, using two identical cold boxes, each with one-half of full capacity, would allow placement of a cold box adjacent to each bogie and would eliminate transfer lines running the length of the Magneplane. Note, however, that one compressor would still be preferred since there is little penalty in having to convey warm helium the length of the Magneplane. A comparison of one vs. two cold boxes is shown in Figure 75, which lists major parameters. The 6 K heat loads for two cold boxes are reduced by an appropriate amount to reflect the shorter cryogenic helium transfer lines. However, the refrigerator efficiency for each one-half capacity unit would be reduced because of the smaller size expanders by an estimated 10%. The table shows the resulting compressor power inputs.

The power input reductions that could be achieved with two cold boxes have to be weighed against several negatives, as follows:

1. Two cold boxes, both of which have to be operational for the CRS to be considered operational, will reduce overall system reliability (MTBF).
2. The size, weight and cost of each one-half capacity cold box would be only slightly lower than for one full capacity cold box. Hence, the size, weight and cost of this element of the CRS would nearly double with two cold boxes.
3. Cold box maintenance efforts would be doubled.

140 Passengers		
Number of Cold Boxes	1	2
Magnets/Lines Shield Cooling	LN2	LN2
Refrigerator Precooling	No	No
6 K Heat Load, W	53	42
Compressor Power Input, kW	55	48
45 Passengers		
Number of Cold Boxes	1	2
Magnets/Lines Shield Cooling	LN2	LN2
Refrigerator Precooling	No	No
6 K Heat Load, W	48	42
Compressor Power Input, kW	50	48

Figure 75 Comparison of one versus two cold boxes

We conclude that the one cold box configuration is preferable, and our baseline CRS incorporates one cold box.

5.3.2.39. LEAPFROG CONNECTION OF POWER CONVERTERS

5.3.2.39.1. MOTIVATION

Consider the use of the "leapfrog" connection scheme for connecting power converters to the magway blocks. The scheme can be used to reduce system cost.

5.3.2.39.2. CONCLUSION

The 2:1 leapfrog interconnection scheme can be used effectively to reduce the cost of the Magneplane system.

5.3.2.39.3. CALCULATIONS

A simplified diagram of leapfrogging is shown in Figure 76. Each converter is provided with a block selector switch connecting its output to one of two blocks. Converter 1 can be connected to blocks 1A or 1B which are separated by block 2A. When a vehicle is in block 1A converter 1 supplies power to the LSM. When the vehicle proceeds into block 2A the selector switch connects converter 1 to block 1B and begins synchronizing to match the new vehicle speed.

The diagram shows how 2:1 leapfrogging works. This scheme can be used as long as the vehicles are separated by at least 3 block lengths.

The cost as compared to conventional (operation involves the reduction in converter stations and the associated control circuits. On the other hand additional switches and cabling are required at each substation to interconnect the converter to the distant blocks. 8 km of connecting cables are required for 2:1 leapfrogging if the blocks are 2 km long. A summary of the cost changes is presented below:

Cost changes from 1:1 to 2:1 leapfrogging:

Deletions		
1.	station (building, converters, etc)	-5,545,800
2.	wayside controller	- 527,900
		-6,073,700

Additions		
1.	winding switch	+ 63,200
2.	cables	+ 840,000
3.	cable tray	+ 237,000
		+1,140,200
		-4,933,500

The savings is about $5 M for every 2 converter stations in the original (1:1) system.

The costs above suggest that 3:1 leapfrogging could be used to reduce cost further. However, this requires 24 km of cable per converter station and the size of the cable must be increased to reduce resistive losses. In addition, vehicles must separated by at least 5 block lengths, which restricts the use of the scheme as upgrades are made to the system. Therefore 3:1 leapfrogging was not used in the baseline system.

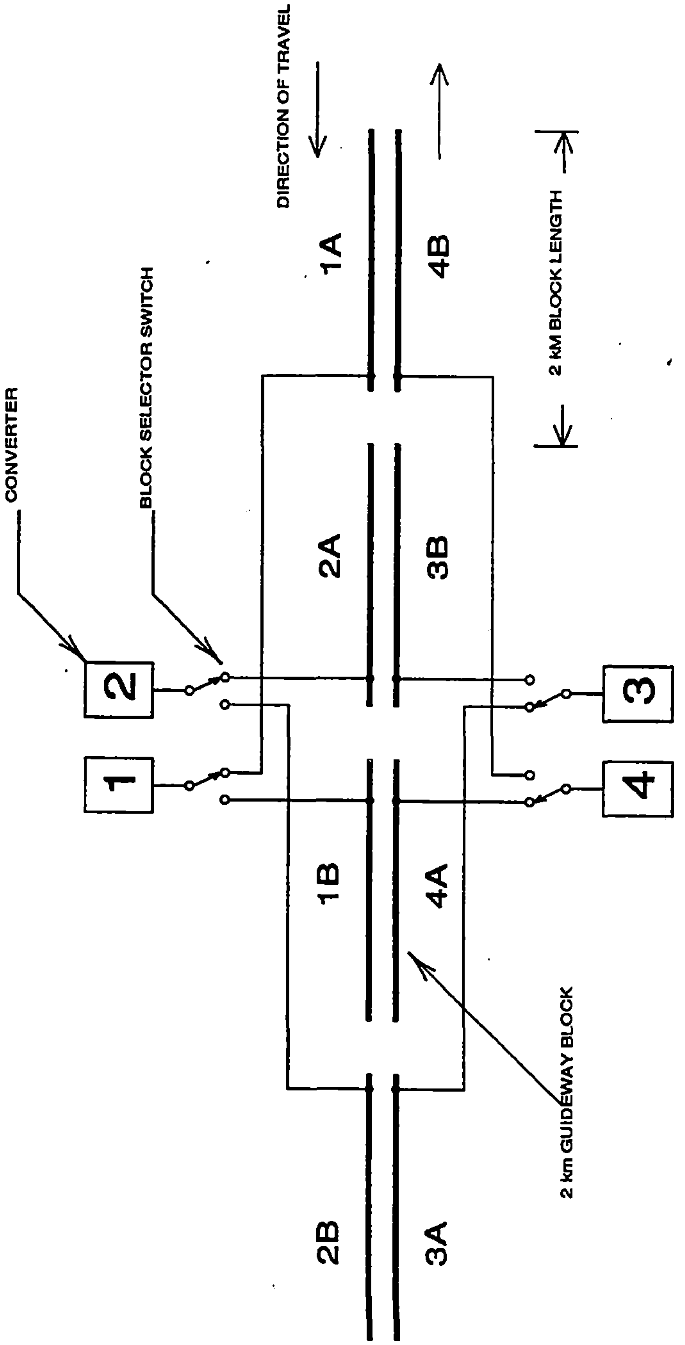


Figure 76 Schematic of 2:1 leapfrog connection

5.3.2.40. MAGPORT DWELL TIME

5.3.2.40.1. MOTIVATION

System capacity can be considered for a local area, and also in a global manner. Local area considerations include the velocity of the traversing vehicles, and the frequency of those vehicles. The global aspect introduces the vehicle size and stock requirements to maintain the capacity, as well as the number of irregular vehicle maneuvers requiring increased spacing.

The capacity issue is heavily dependant on the time a vehicle is held at a magport before it starts a journey. In the model used for cost evaluation, a vehicle travelling the 160 km route at 134 m/s is at its destination in 20 minutes. If a vehicle takes 10 minutes to maneuver and unload, 10 minutes for systems check, cleaning and re-stocking, and then 10 minutes to maneuver and load, it will dwell at the magport for 30 minutes between flights. To provide a continuous service between two magports at a certain capacity can impose more vehicle stock dwelling at magports than there is active on the magway at any one time. This presents a significant burden on stock cost. Figure 77 summarizes the extent of the potential burden. It depicts the quantity of vehicle stock required to service a 160 km route terminated with a magport at each end, and the vehicle capacity required of each of those magports. The cost model does not have any magports, hence the stock implications are not part of the equation for establishing the cost.

5.3.2.40.2. CONCLUSIONS

The burden of dwell time on the vehicle stock requirement to continuously satisfy a system capacity is very dominant. The obvious way to reduce the impact is to minimize the dwell at magports, and strategies to achieve this must be developed when designing the magport.

It is more reasonable to design a system capable of sustaining a peak capacity, for a defined period, with a lower system capacity as the vehicles are re-grouped. This is consistent with anticipated loading of such a system, where traffic burden early morning will peak for a short period in one direction, and an opposing traffic flow will peak mid-afternoon. Traffic stock management schemes can be employed to reduce the number of total active vehicles required to satisfy a local peak demand on the system, however the magport design must accommodate the peak capacity requirements for this to work.

Dwell Time	Cost Model		10 minutes		30 minutes	
	Total	Magport	Total	Magport	Total	Magport
4,000 seats/hour	20		30	6	50	16
8,000 seats/hour	40		60	11	98	30
12,000 seats/hour	60		90	16	146	44
22,900 seats/hour	110		166	29	274	83

Figure 77 Magport dwell times according to capacity

5.3.2.40.3. CALCULATIONS

A. Number of vehicles required to satisfy a system capacity.

$$\begin{aligned} &\textit{Route Length} = R_L = 160{,}000\,\textit{meters} \\ &\textit{Route Velocity} = R_V = 134\,m/s \\ &\textit{Vehicle Capacity} = V_C = 140\,\textit{Passengers} \\ &\textit{System Capacity} = S_C \textit{ in Seats/Hour} \end{aligned}$$

$$\textit{Number Of Vehicles} = \frac{S_C.R_L}{R_V.V_C.3{,}600}$$

Total number of vehicles in 2*magways*:

$$T_M = 2.(N_V \rightarrow \textit{rounded to next integer})$$

B. Number of Additional Vehicles Required to Dwell at Magports

$$Dwell\ Time = D_T = 30\,minutes$$

$$Dwelling\ Vehicles = D_V = \frac{S_C.D_T}{V_C.60}$$

Total vehicles dwelling at 2 Magports:

$$T_P = 2.(D_V \rightarrow rounded\ to\ next\ integer)$$

C. Total Vehicles required for a System Capacity.

$$Total\ Vehicle\ Requirement = T_M + T_P$$

5.3.2.41. CONTROL UNIT FOR VEHICLE SPACING

5.3.2.41. MOTIVATION

The following discussions outline the different descriptions of how vehicles are spaced, and the implications of that spacing.

The prime Magneplane vehicle control strategy is based on vehicle slots. A vehicle slot separates it from its neighbors by a pre-determined time period. There are two descriptive elements of a slot, the headway distance, and the headway time. Figure 80 depicts the two elements. The headway distance is defined between two consecutive vehicles. Vehicle 1 maintains a minimum headway distance with respect to vehicle 2 such that if vehicle 2 instantaneously stops, then vehicle one has sufficient distance in which to stop, with a 0.5g (4.9 m/s^2) deceleration. In normal operation, at system capacities less than 25,000 seats/hour, this headway distance is (substantially) longer than the minimum required.

There are three basic laws of linear motion that apply to this problem:

if:

Time = t *seconds*
Distance = s *meters*
Final Velocity = v *meters/second*
Initial Velocity = u *meters/second*
and
Acceleration = a *meters/second*^{2}

then:

$$v^2 = u^2 + 2as$$

$$s = ut + \frac{1}{2}at^2$$

$$t = \frac{v-u}{a}$$

Maximum system capacity is based on spacing the vehicles at the minimum required to stop safely, including the reaction time of the system.

At an initial velocity of 134 m/s, a final velocity of 0, and a deceleration of 4.9 m/s^2, the first equation yields a distance of 1830 meters for the vehicle to stop. This is the distance the vehicle will travel once it has deployed its brakes to provide the deceleration.

Current Velocity	Deployment Distance	Clearance Distance	Stopping Distance	Minimum Headway Distance	Minimum Headway Time
50	200	300	255	755	15.1
75	300	300	573	1173	15.6
100	400	300	1019	1719	17.2
125	500	300	1567	2367	18.9
134	536	300	1830	2666	19.9

Figure 78 Minimum instantaneous safe headway distances and times for various instantaneous velocities

If it takes 4 seconds for the vehicle to determine that the emergency brakes are required, and deploy them, it will have travelled an additional 4 x 134 = 536 meters. In addition it is desirable for the vehicle to come to a stop some distance away from the incident. This distance is chosen to be 300 m. This defines that a vehicles minimum headway distance is (536+300) meters plus the stopping distance, a total of 2666 meters at 134 m/s.

The second descriptive element is the headway time, and is primarily defined by the relative distance between the vehicles. Headway time is calculated as starting at the moment a vehicle passes a fixed point, to the time that the second vehicle passes that same point, as depicted in the lower half of the figure. The minimum condition for headway time is derived from the minimum condition for the headway distance, in accordance with Figure 78.

The deployment distance is derived from the current velocity and the 4 second deployment time. The clearance distance is fixed. The stopping distance is derived from the first equation defined above, with v=current velocity, $u=0$ and $a=4.9$ m/s^2. The minimum headway distance is the sum of the previous columns, and the headway time is calculated in seconds, based on the current velocity.

A third time element is significant, and should not be confused with headway time. This is the stopping time of the vehicle. The stopping time is the total time it takes the vehicle to deploy the brakes and traverse the stopping distance. The stopping time is typically longer than the headway time, as shown in Figure 79.

The deployment time is fixed at 4 seconds. The stopping distance and minimum headway time are extracted from the previous table. The stopping time is calculated using the third equation from above, assuming a deceleration (a) of 4.9 m/s^2, and a final velocity (u) of 0. The second equation can be used

Velocity	Deployment Time	Stopping Distance	Minimum Headway Time	Stopping Time
50	4	255	15.1	14.2
75	4	573	15.6	19.3
100	4	1019	17.2	24.4
125	4	1567	18.9	29.5
134	4	1830	19.9	31.3

Figure 79 Stopping time for various instantaneous velocities, showing the comparison to stopping distance and minimum safe headway time

to confirm the results. Note that at low velocities (50 m/s) the stopping time is shorter than the headway time because of the fixed deployment time and desire to stop the vehicle with 300 m clearance.

Headway time has two elements, as depicted in the figure. It has a minimum headway time and a maneuver time. The minimum headway time is as defined above. The sum of the maneuver time and minimum headway time is fixed, based on the required throughput of vehicles. (The required throughput of vehicles is defined by the size of the vehicles and the required system capacity). The maneuver time can be used dynamically by a vehicle to preform some temporary change in velocity relative to the next vehicle. This feature is used at low system capacities for vehicles to slow down to take-turn-offs. When a vehicle slows down it reduces the headway time of the vehicle **immediately preceding.** The feature is also required to permit vehicles to slow down to negotiate curved sections at less than the maximum velocity. As long as a vehicle never violates the minimum headway time, the system safety is never compromised. A system capacity of 12,000 seats/hour, utilizing 140 seat vehicles, requires a total headway time of 42 seconds, permitting 22 seconds of maneuver time at 134 m/s.

5.3.2.41.3. CONCLUSIONS

It is convenient to refer to vehicle spacing in terms of headway time, as it associates the system capacity, vehicle velocity and headway distance. As the headway time essentially consists of two elements, one fixed, and one adjustable, strategies to control the vehicles are dependant on this term. The headway time is dynamically changing as vehicles traverse a section of magway, especially where curves and turn-offs impose accelerations on the vehicles.

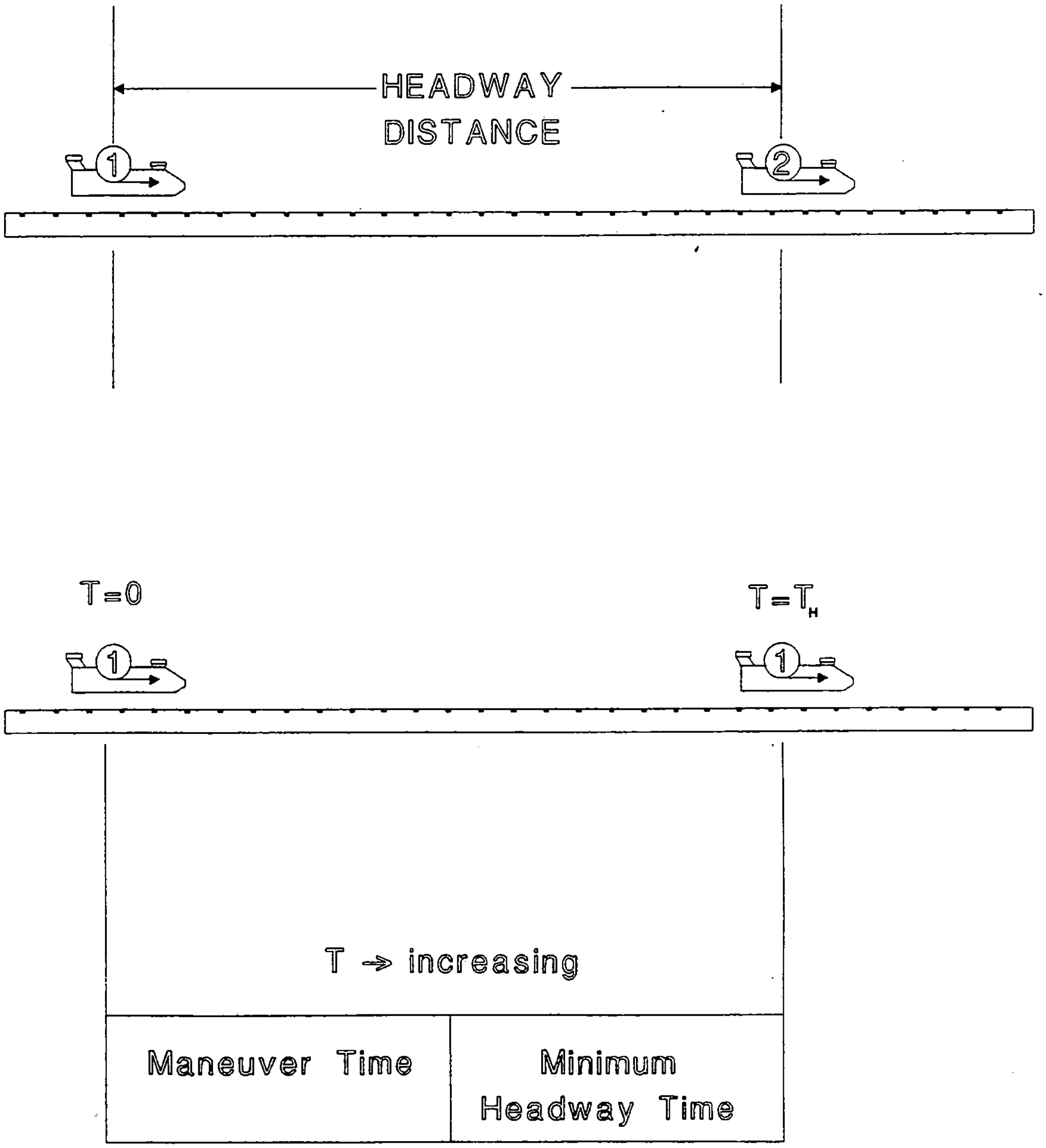


Figure 80 Diagram of headway distance and time

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