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HIGH SPEED SWITCHES FOR MAGLEV VEHICLES

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

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October 1993
Final Report

FINAL REPORT

HIGH SPEED SWITCHES FOR MAGLEV VEHICLES

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Submitted to:

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Research and Special Programs Administration
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FINAL PROJECT SUMMARY REPORT

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High Speed Switches for Maglev Vehicles

SUMMARY OF COMPLETED PROJECT

The data in this final report shall not be released outside the government without permission of the contractor for a period of two years from the completion date (Oct. 1993) of this project from which the data were generated.

Analysis of guideway switching systems for high speed Maglev vehicles demonstrates:

- Ride quality dynamic limits require switch lengths of 300 m or more.
- High speed mechanical switches of this length are impractical. Reliability analysis indicates that electrical switches are much more reliable than mechanical switches.
- Foster-Miller's concept incorporates a suitable high speed electrical switch.
- The MIT/Bechtel, Magneplane, Grumman, and Transrapid system concepts do not include a suitable high speed switch configuration. Because electrical high speed switches are critical to the successful implementation of a national high speed Maglev system, a major portion of this report is dedicated to high speed switch concepts for these four system configurations. The best switch concepts for these systems requires modification of the vehicle.

Major conclusions of this work are:

- High speed switches are required for a successful and expandable Maglev system in order to maintain scheduling flexibility and passenger throughput during peak travel times. Passenger satisfaction depends on these features.
- Vertical switch configurations provide a substantial advantage in right of way requirements and system flexibility relative to lateral switches.
- Wrap-around vehicle configurations are much more difficult to switch than vehicle configurations that do not encompass the guideway.

APPROVAL SIGNATURES

1. PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR *(Typed)*	2. PRINCIPAL INVESTIGATOR/ PROJECT DIRECTOR *(Signature)*	3. DATE
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16. Abstract

High speed switches are required to maintain throughput capacity and schedule and route flexibility in a successful Maglev system. Ride quality constraints at full speed require switch lengths of 300m or more. Moving mechanical guideways of this length safely and reliably is impractical. Electromagnetic switches that utilize the same basic principles as Maglev for levitation and guidance provide a means of switching vehicles safely, reliably, quickly, and cost-effectively at full speed. Most of the major System Concept Definition (SCD) configurations do not include a high speed switch. Several conceptual designs for high speed switches based on electromagnetic levitation and guidance with no moving guideway components were developed in this program and are described in this report.

Preliminary high speed switch concepts for the M.I.T./Bechtel, Magneplane, Transrapid, and Grumman configurations are developed and analyzed. The Foster-Miller concept, which already incorporates a high speed switch, is described in this report. The best switch configurations for each concept were selected based on their respective impacts on system performance and safety. Most of the best switch configurations require some modification of the vehicle yet maintain the key attributes of each configuration. It is critical to make the changes required to achieve safe high speed switches while the SCD configurations are still flexible concepts in early development.

The tradeoff analysis reveals that vertical switches provide the best overall switch configuration. Vertical switches minimize switch length, cost, and right of way requirements. They also provide safe backup systems and simplify route layout and upgrades. The EDS systems can be modified to provide high speed vertical switches. The EMS systems of Transrapid and Grumman encompass the guideway as presently configured and are not suited to vertical switching. A variety of lateral switch configurations are developed for these configurations. A roof mounted switch based on the EMS principles provides a means of switching any of the proposed configurations but requires modification of the vehicles. Because high speed switching capability is a requirement for a successful long-term expandable Maglev system, it is recommended that further analysis of switches developed in this program and their system impact be performed.

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HIGH SPEED SWITCHES FOR MAGLEV VEHICLES

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HIGH SPEED SWITCHES FOR MAGLEV VEHICLES

EXECUTIVE SUMMARY

High speed switches are required to maintain guideway throughput and scheduling flexibility for a successful Maglev system. If vehicles must reduce speed to switch, the Maglev system will be subject to the same type of peak demand traffic jams that currently plague our highway system. Ride quality requirements dictate that high speed switches of any type must be on the order of 300 meters long. Reliability analysis shows that moving mechanical guideway components of this length is impractical. There are too many high maintenance and failure prone parts that must all work at the same time for typical mechanical switches to provide a safe, fast, and reliable mechanical switch. Electromagnetic switches provide a safe, fast, and reliable means of switching Maglev vehicles at high speeds (134 m/s) because they utilize the same basic principles as normal Maglev operation. Safe, fast, and reliable electromagnetic high speed switches are required to achieve a successful and expandable Maglev system.

Not all System Concepts developed for the United States National Maglev Initiative are compatible with electromagnetic high speed switches. Except for the Foster-Miller system configuration, which implements a high speed vertical switch with no change in operating characteristics, the system concepts put forth by M.I.T./Bechtel, Magneplane, Grumman, and the German Transrapid do not include an electromagnetic high speed switch concept.

Under this program high speed electromagnetic switch concepts are developed for each of the above configurations and are described in this report. The switch concepts developed in this program are evaluated and compared. Often the best of these switch concepts require some modifications to the vehicle and/or guideway. The system concept configurations developed under the DOT System Concept Definition program are in the early conceptual stage of development as are the perceived objectives and requirements of the national Maglev system. These concepts can and must evolve substantially to meet the evolving requirements. The vertical switch configuration provides significant benefits to system performance, safety, and cost. Vertical switch configurations were developed for all of the EDS systems. EMS systems are more suited to lateral switching and are generally more difficult to switch. This report includes a summary of the key unique characteristics of each system and the primary advantages and disadvantages that characterize each system. The best switch configurations which maintain the key unique characteristics and advantages of each system concept are summarized along with the modifications required to achieve a high speed electromagnetic switch for each system.

Because high speed switching is a critical requirement for a successful and expandable Maglev system, further development, analysis, and evaluation of the system-wide impact of the best high speed switch configurations for each system concept is required. Evaluation of the safety, cost, and other parameters required to ensure success of the Maglev system must include and, indeed, depends heavily upon the characteristics of the high speed switch.

1. INTRODUCTION

1.1. Section Synopsis

The motivation for high speed electromagnetic switch design is described in this section. High speed switches must be used to maintain guideway capacity of a successful system and are required to maintain performance during peak demand as the system expands. A high speed switch must be very long (over 300 meters) to meet ride quality requirements. This makes systems which require mechanical motion of the guideway impractical and dangerous because of the quantity and/or size of the components required. Electromagnetic switches are the safest means of switching Maglev vehicles because the switching operation is based on the same basic principle as the normal operation of Maglev vehicles. In the long term, a successful Maglev system requires high speed electromagnetic switches.

1.2. Status of Maglev Switch Designs by Original Concept Developers

Most major MAGLEV system concepts were not designed with switching as a major configuration driver. The switch design is generally performed in an ad hoc manner. It is a mistake to continue this method of system design because the effects of switch characteristics on system growth, capacity, and reliability are substantial. Fortunately, the U.S. system configurations are at the conceptual stage and can be modified substantially to accommodate safe and reliable high speed switch designs.

1.3. Objective of This Program

The objective of this program is to create viable high speed switch concepts for the major system configurations.

The Phase I work consisted of two major tasks:
- Create high speed switch configurations and determine feasibility through first order analysis.
- Select the most promising configurations for each system.

1.4. Motivation for High Speed Switches

1.4.1. Synopsis of Motivation for High Speed Electromagnetic Switches for MAGLEV systems.

High speed switches are a key requirement for growth of a successful long term MAGLEV system. High speed switches improve reliability and safety, reduce system cost, and, ultimately, are required to achieve a successful expandable Maglev system. These issues are summarized below and described in more detail in other sections of the report.

RELIABILITY- Electromagnetic high speed switches are more reliable than mechanical, pneumatic, or hydraulic switches. Moving guideway components require maintenance and are subject to degradation and catastrophic failure. This also has a direct impact on the safety of the system.

SAFETY- High speed electromagnetic switches do not require speed reduction for safe passage and are therefore more tolerant of system or operator failures or glitches. There are no mechanical guideway parts to wear, jam, or corrode in a manner that compromises safety. All load bearing guideway components are stationary; the switch section is as strong or can be stronger than the rest of the guideway structure.

COST- High speed electromagnetic switches maintain maximum capacity of the guideway structure. A successful Maglev system will grow to the point that some sections of guideway are fully utilized. The time required to slow, switch, and accelerate vehicles must be added to the safe time spacing between vehicles. This means that the guideway capacity and throughput during passage of a group of vehicles is directly affected. For example, if the time required between vehicles is doubled, then the guideway capacity during that time is reduced by a factor of two. This effectively doubles the cost per passenger mile for frequently traveled routes. Net guideway capacity can be salvaged to some extent for a lightly loaded system by special scheduling: however, this reduces scheduling flexibility and severely complicates rerouting due to any schedule changes or station delays. As required system capacity increases, this approach losses effectiveness just when the extra capacity is required. Mechanical and/or reduced speed switches greatly reduce the usable throughput capacity of the guideway structure relative to the design capacity. Additional guideway must be built to carry the required traffic even though it is well below the actual design capacity of the existing guideway. High speed electromagnetic switches allow the existing guideway to be utilized at maximum design capacity. The cost of right of way and guideway structure for additional lanes completely dwarfs the costs of switches.

Additional factors that are not considered in depth in this report are:

Passenger comfort - Repetitive longitudinal acceleration and deceleration associated with slowing for a switch and reaccelerating afterwards reduces passenger comfort and may restrict mobility within the cabin.

Trip time - Trip time is directly affected by slow passage through switches. Although the impact for long trips is relatively small, passenger perception of the slowing for a switch and reaccelerating afterwards may not be.

Peak power requirements - Peak power requirements (not net energy used) will drive the energy costs of the system. The deceleration and acceleration required for a slow speed switch increases the peak power requirements. Several switches within one power zone can further complicate scheduling constraints.

Single guideway operation for service and low usage routes - Guideway repair and maintenance will occasionally require closing one side of a dual guideway. Efficient usage of the remaining guideway structure is directly affected by the time required to switch vehicles and the spacing required between vehicles in a group. Low usage areas or those with a short distance between stops may be served by a single guideway utilizing high speed switches. The relative impact of switch delays increases for short trips such as spur lines and branch interconnects.

Motivation Summary: Without high speed switches the MAGLEV system capacity is reduced and the system becomes prone to traffic jams due to slowdowns at switch points. Capacity is significantly reduced at the least desirable times. High speed switches allow maximum utilization of guideway capacity as the system grows to any length and number of branches.

1.4.1.1. Effect of Vehicle Speed and Switch Speed on System Throughput

An example can be used to illustrate the effect of switch speed on guideway capacity. For simplicity, consider a single switch in a high speed system. Parameters that affect throughput are: allowable vehicle speeds in the switch, emergency braking g levels, safe headway, and switch configuration change time.
For a 0.2g emergency braking capacity, the stopping time from full speed (134 m/s) is 69 sec. Braking of 0.2g is a reasonable level for a skidding vehicle in an emergency situation. This stopping time is often considered the safe headway between vehicles. Requiring vehicles to slow on the main guideway in order to exit on a switch increases the headway requirement since following vehicles must allow enough additional time for a leading exiting vehicle to slow before entering the switch to exit the main guideway.

Consider the headway requirement between a vehicle exiting the main guideway and the following vehicle. For a switch designed for 50 m/sec exit speed with a mechanical switch time of 15 sec, the additional time gap required to allow for the leading vehicle to decelerate is 54 sec. After the lead vehicle exits, the switch must return to the through direction position which takes 15 sec. Thus, the increased headway requirement is 54 + 15 = 69 sec in addition to the 69 sec safe headway. ***The effect of the situation just described is a 50 percent reduction in guideway capacity***. Although scheduling can reduce the effect of the increased headway requirements in a lightly loaded system, as the system approaches full capacity the scheduling flexibility is reduced. Low switching speeds greatly reduce guideway capacity just when the guideway capacity requirements increase.

While the simple example for a single switch designed for an exit speed of 50 m/sec reduced the throughput by a factor of two, even a mechanical switch designed for full speed vehicle operation has a substantial guideway capacity impact due to the time required for motion of the mechanical parts. If the system has a 15 sec actuation time, the capacity is reduced by 25 percent. As Maglev systems grow together to become a network, the additional cost of the long switch lengths required for ride comfort in a high-speed switch will be very small compared to the cost of the additional parallel guideway structure in both directions required to meet the same throughput with slow switches.

Throughput for a crowded system is most strongly affected by lack of high speed switches. The higher the demand, number of switches, and route options, the lower the available capacity of the guideway becomes. An initially successful Maglev system becomes self-limited - hobbled by the long headway required by slow switching systems.

The ability to perform high-speed switching is key to maintaining system capacity as the Maglev system expands. Cost of additional guideways to make up for reduced capacity dwarfs the cost of switches designed for full-speed operation. Thus, high-speed switching capability is a critical requirement for a successful Maglev system.

1.4.2. Dynamic Limitations on High Speed Switch Length

High speed switches for Maglev vehicles require long switch lengths. This is because ride comfort considerations combined with high speeds severely constrain the curvature and curvature variations of the guideway. The switch length requirements described in this section are a function of ride quality limitations and vehicle speed and hold for any switch whether mechanical or electromagnetic.

Switching simplified to its basic features is moving a vehicle from one straight guideway to an intersecting guideway. Switching is required to eliminate on-line stations which would greatly reduce convenience and capacity of a high speed system. A high speed switch allows a vehicle to take either of two or more guideway paths at high speed or allows merging from two or more guideways onto one at high speed. The switch can be used to merge or split two parallel guideways, start or merge branches, or connect with crossing routes. For the immediately following examples the case of exiting from a straight section of guideway onto another section in a y type configuration is considered. The case of switching on parallel guideways is considered later.

Two key aspects of Maglev systems affect switch design: guideway/vehicle interface configuration and ride quality. The most fundamental for any system is the trajectory requirement imposed by ride quality considerations. Allowable accelerations, jerk (acceleration rate), roll rate, and roll angle impose fundamental limits on the vehicle trajectory. Many methods have been utilized in formulating suitable trajectories, but the simplest for development purposes is based on using the maximum allowable jerk or roll initiation rate until the maximum allowable acceleration or roll rate is obtained. This results in the minimum switch length at a given speed. Variations in allowable g loading in vertical and lateral directions combined with allowing combined vertical and lateral displacements can lead to Chandel like maneuvers that tighten turn radii; however, for simplicity and practicality the switch designs presented are based on pure horizontal or vertical motion.

A few simple relationships can be used to quantify the length requirements of a switch. The basic parameter that quantifies a switch is the lateral (or vertical) distance that must be traversed to cross from one guideway to another. Given a constant vehicle speed V and the small lateral distances required to switch, the analysis of limiting trajectories is relatively straightforward (see Appendix A). Two types of horizontal motion switch acceleration profiles will be used for illustrative purposes. The first is simple lateral acceleration without roll. The second utilizes the increased allowable "vertical" acceleration by rolling into a coordinated turn similar to that of an aircraft.

For the first case of simple lateral acceleration for small displacements, the lateral displacement y can be initially approximated as a function of time t by:

$$y = \frac{J \cdot t^3}{6} \qquad (1)$$

where J is the maximum allowable jerk (rate of change of acceleration) from the start of the lateral motion until maximum lateral acceleration is reached at time (a/J). After this time, the maximum allowable acceleration has been achieved and the lateral position can be approximated by the following expression:

$$y = \frac{a}{2} \cdot \left[t - \frac{a}{J}\right]^2 + \frac{J}{2} \cdot \left[\frac{a}{J}\right]^2 \cdot \left[t - \frac{a}{J}\right] + \frac{J}{6} \cdot \left[\frac{a}{J}\right]^3 \qquad (2)$$

For the small lateral distances considered and constant vehicle speed, the distance traveled in time t is x = V·t. Note that the allowable lateral displacement time history equation for small displacements is independent of forward speed; it is strictly a function of time. If you were on a lateral elevator, the time based accelerations that could be comfortably experienced would be described by the above equations. The length of the switch is determined by the forward distance traveled in the time required for the lateral motions to occur.

The relations can be converted to a distance variable x along the guideway by substituting x/V = t. Given the limiting values for ride quality parameters shown in Table 1 for unbelted passengers, the time for which equation 1 holds is 1.43 sec. This corresponds to a lateral motion of 0.33m which is adequate lateral displacement for switching only for a very narrow guideway. After that point the displacement is limited by maximum acceleration as described in equation 2. In this case the limiting g level is also a key factor in switch length since the g limit is reached quickly.

Table 1. Design Ride Quality Limits

Lateral limits	Lateral acceleration = 0.1 g max.
	Lateral jerk = 0.07 g/sec max.
Roll limits	Roll rate = 5 degrees/sec max.
	Roll acceleration = 15 degrees/sec max.
Vertical limits	Vertical acceleration rising = 0.3 g max.
	Vertical acceleration falling = 0.2 g max.
	Vertical jerk = 0.1 g/s max.

For the second case of a fully coordinated turn, the limiting parameters are the maximum roll angle, roll rate, and rate of change in roll rate (roll acceleration). For the values given in Table 1 the maximum roll acceleration is 15 degrees/sec^2. Ramping up to the maximum roll rate of 5 degrees/sec means that acceleration up to maximum roll rate requires 1/3 sec which amounts to 0.83 degrees of roll.

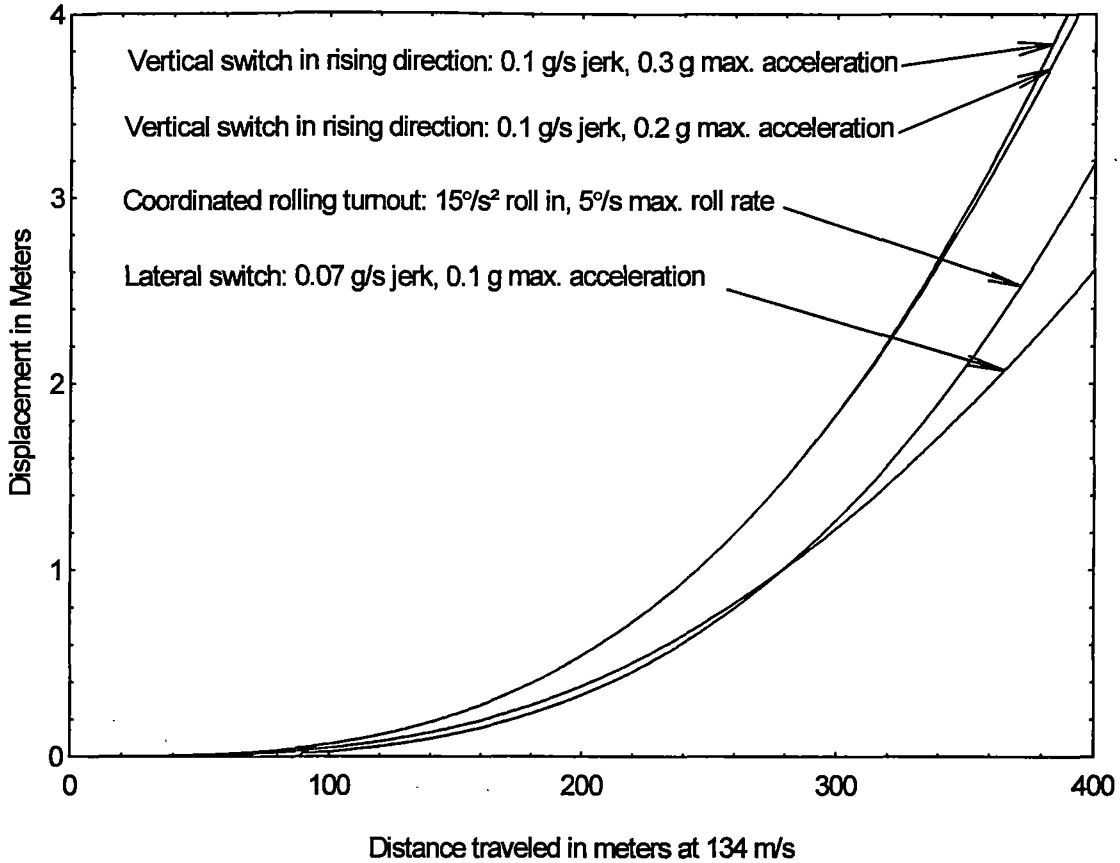


Figure 1. Effect of Ride Quality on Switch Length (Updated Vertical Limits)

The equations governing the motion were derived and used to generate the curves shown in Figure 1. The distance traveled verses lateral displacement for the pure lateral motion and the coordinated turn are shown for full speed operation at 134 m/sec in Figure 1. Again, the actual constraining variable is time, but for guideway considerations it is more important to consider the switch length. The switch length is directly proportional to the travel speed, so the distance x traveled for a given lateral displacement for other speeds can be obtained from Figure 1 by dividing the given value for x by 134 m/sec and multiplying by the speed of interest. Examination of Figure 1 shows that the difference in length for the coordinated roll and pure lateral motion cases for the small lateral displacements required for switching is small; therefore, *implementing roll in the switch does not provide a substantial reduction in switch length*. Both lateral and roll motions could be combined to provide a slightly shorter switch, but the reduction in switch length is relatively small and does not change the fact that long switch lengths are required for high speed switches. Moving spans of this length quickly is impractical, and the speed of the switch itself also directly impacts the headway and throughput capacity of the guideway. Electromagnetic means of switching the path of the vehicle are most attractive for high speed switches. Although the cost of such long high speed switches may appear high, the cost of the switch must be compared with the cost of additional guideway capacity. For many situations high speed switches will be cost-effective. This is particularly true as the system approaches full capacity and expands into a network. *The* *ability to implement a high speed switch may actually be a driving parameter in the selection of the Maglev system guideway/vehicle configuration.*

1.4.2.1. Switching to an adjacent parallel guideway

Switching to parallel guideways may be required for servicing one side of a dual guideway. Certain route requirements which utilize a single guideway for two way traffic can utilize such switches to allow vehicles to pass in opposite directions over a single guideway utilizing short parallel passing sections. Ride quality constraints limit the allowable jerk, or transition in acceleration. This constraint requires a long switch since the transition from curving off of one guideway and onto a parallel one requires reversing the direction of acceleration. For example, moving from a right side guideway to a parallel left guideway requires accelerating to the left and then to the right with the rate of change of acceleration being restricted by the allowable jerk. The allowable jerk constraint means that this transition is a substantial part of the length required for such a switch.

A calculation of the switch length for a lateral switch to parallel guideways based on the design ride quality limits is shown in Figure 2. This figure illustrates the path of a vehicle in a switch between parallel guideways along with the lateral velocity and lateral acceleration as a function of distance for full speed operation (134 m/s). Note that the switch must be one kilometer long to provide adequate ride comfort. The time required to traverse this switch is slightly less than eight seconds. It is possible to insert a section of normal guideway for part of the central region of the switch when the guideways are widely spaced: however, this section is considered part of the switch since it is not useful for anything other than the switching operation.

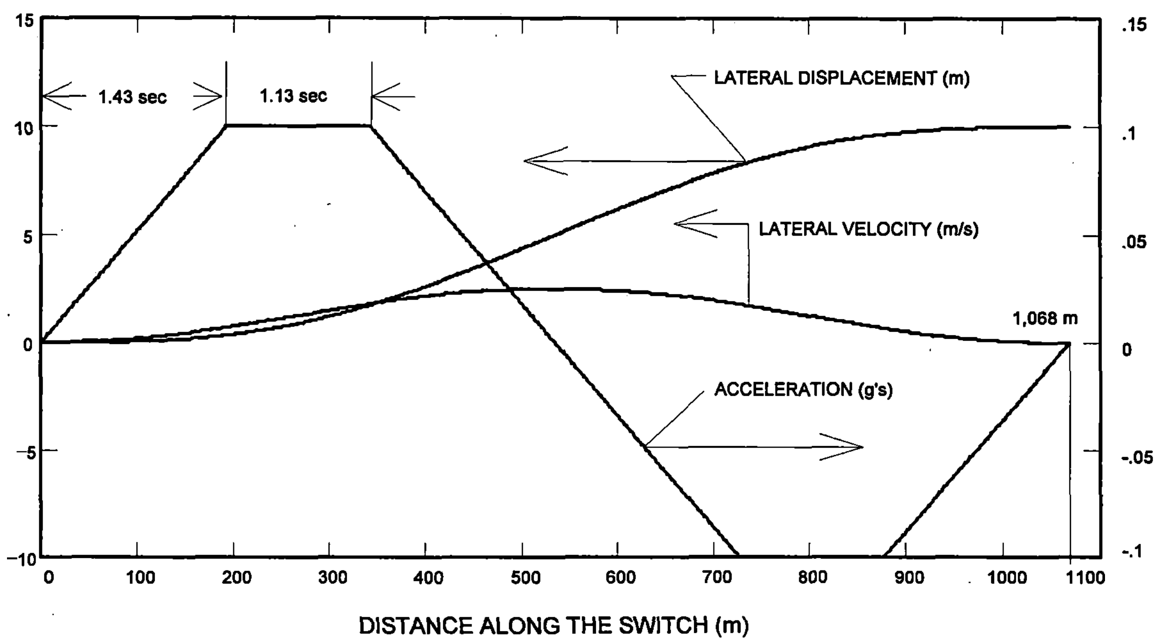


Figure 2. Path constraints for lateral switch to a parallel guideway 10 meters away using 0.07 g/s maximum allowable jerk and 0.1 g maximum lateral acceleration

Switch length requirements for parallel guideways for both the lateral switch and vertical switch are shown as a function of the spacing between guideways in Figure 3. For this case the vertical switch is designed to not exceed 0.2 g maximum acceleration either up or down. It is possible to use 0.3 g maximum acceleration in the concave up direction which allows for a slightly shorter switch when the guideway spacing is large than that shown in the figure. Note that this asymmetrical design is still fine for full speed travel in both directions since the points of rising and falling sensation along the guideway do not depend on the direction of travel.

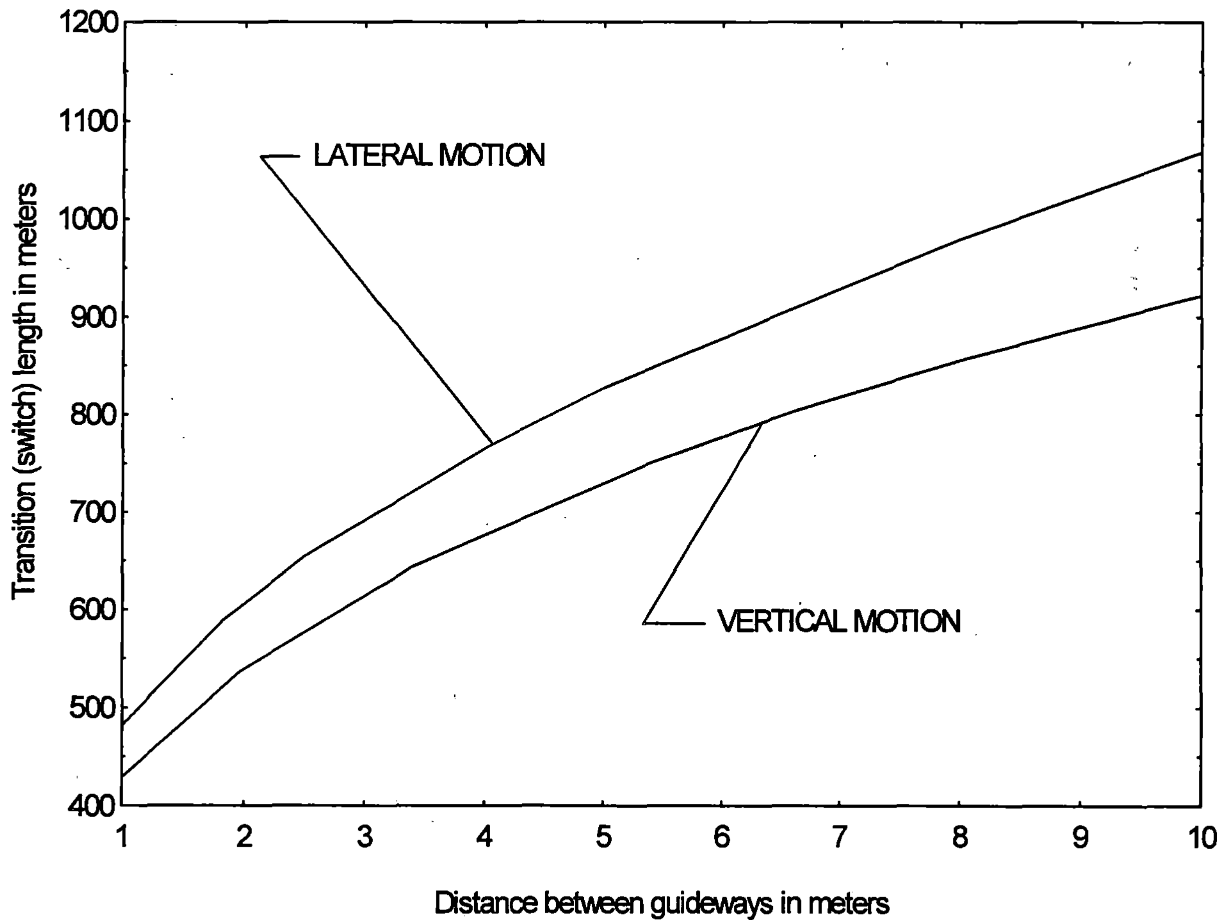


Figure 3. Switch length required for vertical and lateral switches for a range of guideway spacings set by ride quality limits of 0.07 g/s jerk and 0.1g max. acceleration in the lateral direction and 0.1 g/s jerk and 0.2 g max. acceleration in the vertical direction

The vertical switch requires approximately 10% less length than the lateral switch since the allowable jerk and acceleration are higher. The advantages of the vertical switch are particularly apparent in the case where the guideways are stacked for passing zones since less structure and real estate is required for this configuration. An additional benefit of the vertical switch configuration is that some lateral curvature to follow the route is possible in the switch section without substantial effect on the switch design and performance.

1.4.3. Mechanical Vs Electromagnetic Switches: Comparison of Electrical and Mechanical Switch Reliability

Electrical based switching systems are inherently more reliable than mechanical systems. For example, consider a comparison of an electromagnetic switch system where the switch direction selection is made by semiconductor based electrical components versus a hydraulic based mechanical system which moves sections of guideway. Table 2 shows the key components for each design which are relevant to a first-order comparison. At this point most attention is given to the components which characterize the two approaches - the heavy-duty electrical switch for the electronic option and the hydraulic system for the mechanical option. (The part counts are also based on first-order estimates at this point.)

Table 2. Switch Comparison: Key Components and Failure Rates*

Component	Count	Failure Rate (per million hr)	Totals
Electronic switch:			
On/off switch	1,440 (4 per meter)	1.80	2,563.2
Mechanical switch:			
Hydraulic cylinder	28 (2 per span)	125.60	3,517.2
Hydraulic connector	112 (2 per hose)	0.20	22.4
Hydraulic hose	56 (2 per cylinder)	0.23	12.9
Pump and motor	28 (1 per cylinder)	3.48	97.4
			3.649.9
*Source: Nonelectronic Parts Reliability Data 3 RADC 1985 - those rates include all failure rates.			

The major failure contributors are seen to be the switch and the hydraulic cylinder. Each of these components is a "special" rather than an off-the-shelf part, so part-specific failure data does not exist. The numbers used here are based on analogy with similar parts in identical environmental applications ("Ground-Fixed" Environment). The part counts are based on a switch 360m long.

At this point the systems appear comparable in terms of failure rate. However, these numbers refer to all failures, and so can only be used as a rough prediction of required maintenance frequency.

But, from a safety point of view, these failures are not equal. The hydraulic components are in series reliability, all components must operate correctly and simultaneously, a failure which halts any subsystem brings the system down until it is fixed. Failure of a hydraulic component can cause the guideway to be deflected in a way that leads to catastrophic damage to the vehicle. Failure of a single electrical switch will cause a momentary localized reduction in lift or guidance, possibly a jar at low speed, but will generally not endanger the train.

Further analysis of the hydraulic system leads to a catastrophic condition existing 692 times every million hours of operation for this design (MTBF = 1,445 hr). For the electrical switch or power relay, failures in the "open" mode are 78.2 percent of all failures, so (without inspection and maintenance) a potential failure condition of three open failures would exist every 499 hours. *But* the great majority (99.99981 percent) of these conditions would *not* lead to vehicle damage because the failed switches would not be adjacent to each other. If three consecutive failed coils are required for vehicle damage, the MTBF for this catastrophic condition would be

$$\frac{499 \cdot 1440^2}{4} = 258,682,000 \text{ hr}$$

Note that this is the failure rate that would exist *without* inspection, maintenance, or built-in test.

If the failure rate for the switch were 100 times as great, the relative safety of the two systems would still be overwhelmingly in favor of the electronic switch. *The safety lies in the design as much as, or more than, the components.*

Another advantage of the electronic system would be the simplicity of provision for built-in test. Operation of individual switches (with no trains passing) would alert the system to the presence of failed components. This inspection procedure compares quite favorably to visually inspecting a mechanical switch for mechanical problems and vandalism. Even the case for a mechanical system as a backup to the electrical system is weak given the relative failure rates and the huge differential in maintenance costs for the mechanical system. The potential advantages of an electromagnetic switch in terms of safety, reliability, and life-cycle costs are large.

1.4.4. Summary of High Speed Switch Requirements

Increased headway requirements of low speed mechanical switching systems greatly reduce the revenue capacity, throughput, and average trip speed of Maglev main guideway structures. Guideway cost for Maglev systems is too high to limit capacity with low speed switching systems. High speed switches are required for a successful Maglev system; they allow guideway capacity to be fully utilized while maintaining flexible, convenient scheduling.

Some of the Maglev vehicle/guideway topologies make implementation of high speed switches very difficult. Inability to switch at high speeds will ultimately prevent the system from growing into a fully utilized network. The purpose of this project is to develop switch systems for these difficult topologies, that are capable of switching vehicles operating at full speed quickly, reliably, and safely.

High speed switches must be 200 to 400m long to provide full speed operation while meeting ride quality requirements. It is not practical or economical to mechanically bend or move guideway sections of this length reliably, quickly and safely. The need exists for high speed switches for Maglev systems that are reliable, economical, and safe. The concepts developed in the Phase I research and described in this report provide a means of switching Maglev vehicles at full speed (134 m/sec) electromagnetically, without moving sections of guideway. The high speed electromagnetic switches developed in this project will be capable of safely switching vehicles operating at full speed. They will provide nearly instantaneous reconfiguration of guideway route selection, as well as increased safety and reliability, reduced susceptibility to interference, and lower life-cycle costs than low speed mechanical switches. Switch characteristics such as relative safety, reliability, capacity, cost, and other critical characteristics are determined. The best switch concepts for each topology are determined. This allows the critical issues of high speed switching to be accurately considered when determining the best topology for the nation's Maglev system.

High speed switches are required for a successful Maglev system. Such switches are constrained to be long by ride quality requirements. Mechanical switches of such length based on guideway motion are unreliable and slow compared to electromagnetic systems. Such systems pose a substantial safety hazard as well. The U.S. Maglev system must incorporate high speed electromagnetic switches for long term success.

2. TECHNICAL DISCUSSION

2.1. Introduction to technical discussion

As stated in the introduction, the objective of this program is to create viable high speed switch concepts for the major system configurations.

The Phase I work consisted of two major tasks:
- Create high speed switch configurations and determine feasibility through first order analysis.
- Select the most promising configurations for each system.

This technical discussion is divided into several sections. The first summarizes some of the basic constraints of high speed switch design. Then some of the switch concepts are described in some detail so that the concepts, requirements, and characteristics of the designs are understood. A concept compatibility matrix shows which concepts for switching are most compatible with which major system configurations. The tradeoff criteria and tradeoff technique are described, and a summary of the best switch configurations for each system configuration based on this tradeoff analysis are presented.

2.2. Basic constraints

There are several issues related to all switch types that are summarized below:

- Levitation and guidance must be adequate.

- Propulsion must be supplied to achieve a smooth ride, but coasting through the switch is possible within the ride quality limits for many of the designs. Drag to mass ratios indicate a .05 to .15 g deceleration while coasting through a switch for most configurations.

- Single sided propulsion generates torque on the vehicle. The torque depends on the details of the switch and vehicle. Initial analysis indicates that the torques are not insignificant but are within the guidance capability for most system configurations.

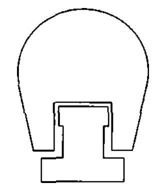
- A roof switch is compatible with all system configurations but requires an increase in vehicle weight of 3 to 5% due to the weight of the steel used to lift the vehicle. Electromagnetic levitation systems generally require something similar this ratio of steel return path to vehicle weight for pole configurations which provide reasonable air gaps.

- Powered ground coil switches use transient rated high field normally conducting ground coils in the guideway and passive coils or sheets mounted to the bottom surface of the vehicle in what is essentially an inverted version of the Magneplane-type levitation. They have a high power draw of 4 to 6 MW per side levitated due to resistive losses alone.

2.3. System Configurations

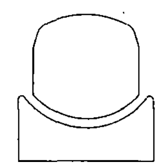
Phase I concepts were generated for the following topologies (from Reference 1&2):

- A beam guideway configuration in which the vehicle overlaps the sides of the guideway to some extent, similar to the M.I.T./Bechtel system (Figure 4).



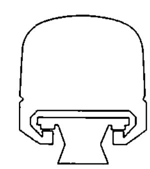
Estimated Specifications:	Vehicle width -	3.7 m
	Guideway width -	1.5 m
	Bogie magnet loading -	1.8 Ton/m

- A trough guideway configuration where the vehicle floats in a trough similar to the Magneplane system (Figure 5).



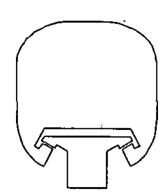
Estimated Specifications:	Vehicle width -	3.2 m
	Guideway width -	3.65 m
	Bogie magnet loading -	1.6 Ton/m

- A T-shaped guideway configuration in which the vehicle wraps partially underneath the guideway and utilizes attractive magnetic forces similar to Transrapid (Figure 6).



Estimated Specifications:	Vehicle width -	3.7 m
	Guideway width -	2.8 m
	Bogie magnet loading -	2 Ton/m

- A Y-shaped guideway combining levitation, guidance, and roll with a superconducting ferromagnetic attractive levitation and guidance system as proposed by Grumman (Figure 7).



Estimated Specifications:	Vehicle width -	3.8 m
	Guideway width -	2 m
	Bogie magnet loading -	1.7 Ton/m

There are many configurations for Maglev systems. The ones listed above have received significant development efforts and are difficult to switch at high speeds. Basic information on dimensions are obtained from the System Concept Definition (SCD) Executive Summary Report (1). Approximate values are adequate since all systems are still at the concept level except for Transrapid which has an operating prototype. The Phase I technical objectives were met. High speed switch concepts were developed for each of these topologies. The Foster-Miller open bottom guideway with sidewall levitation topology, Figure 8, is well suited to high speed switching, so the Foster-Miller switch concept will also be included as a basis of comparison.

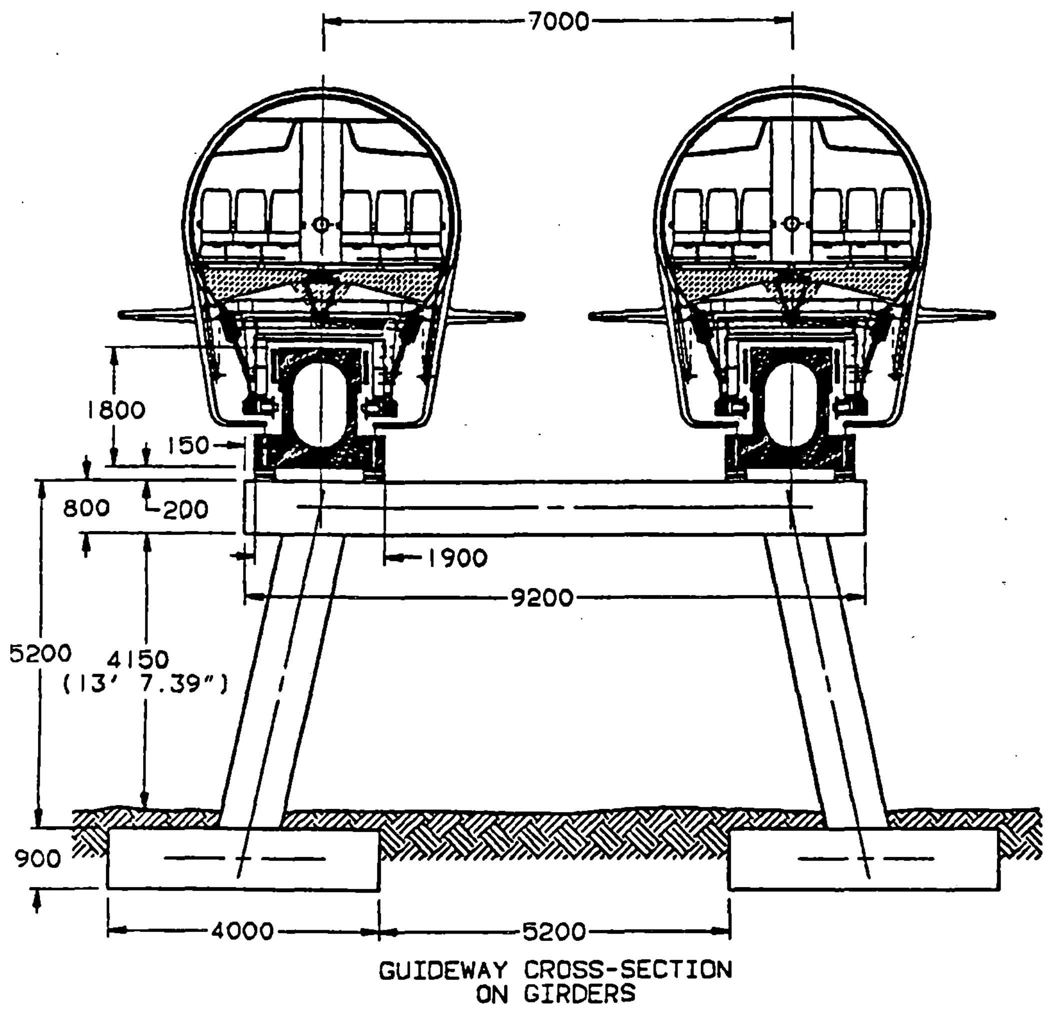
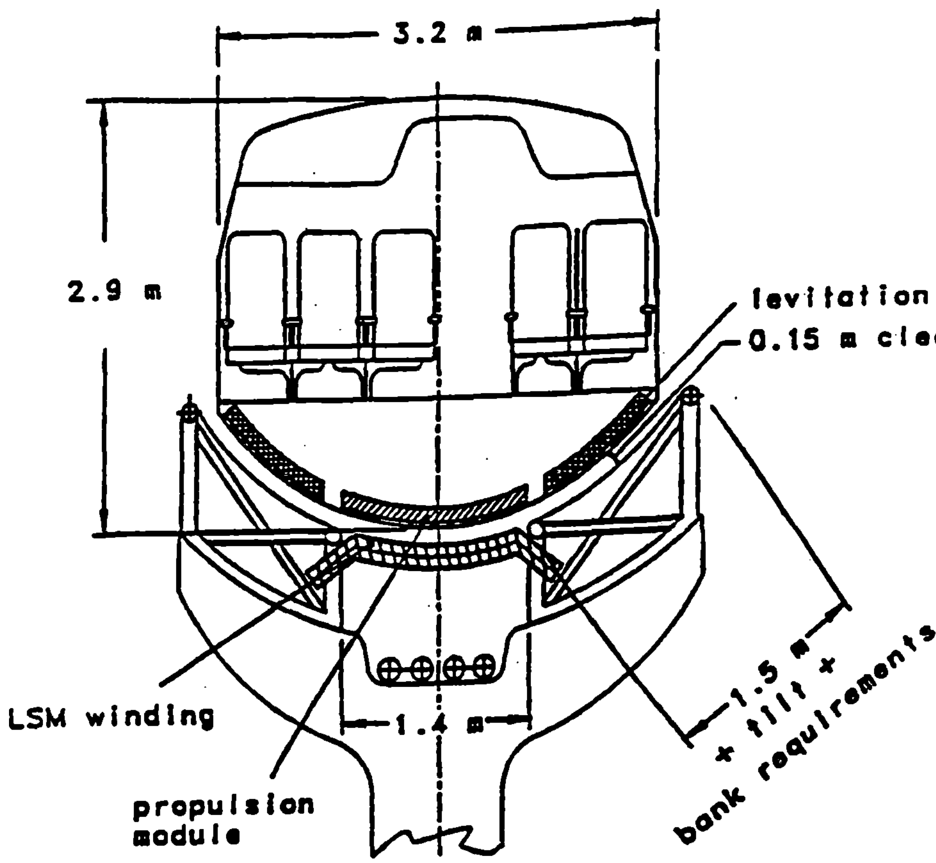


Figure 4. M.I.T./Bechtel Beam Guideway Configuration



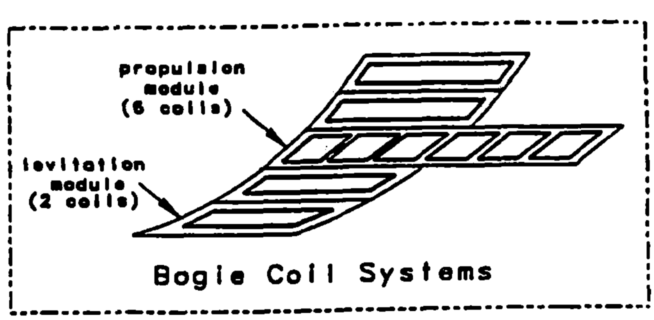


Figure 5. Magneplane Trough Shaped Guideway Configuration

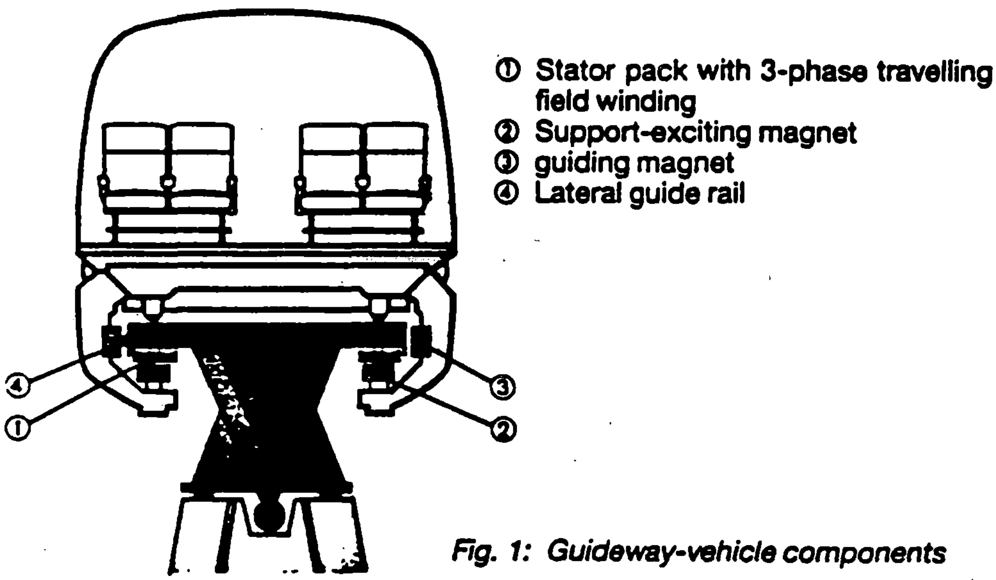


Fig. 1: Guideway-vehicle components

Figure 6. Transrapid T-Shaped Guideway Configuration

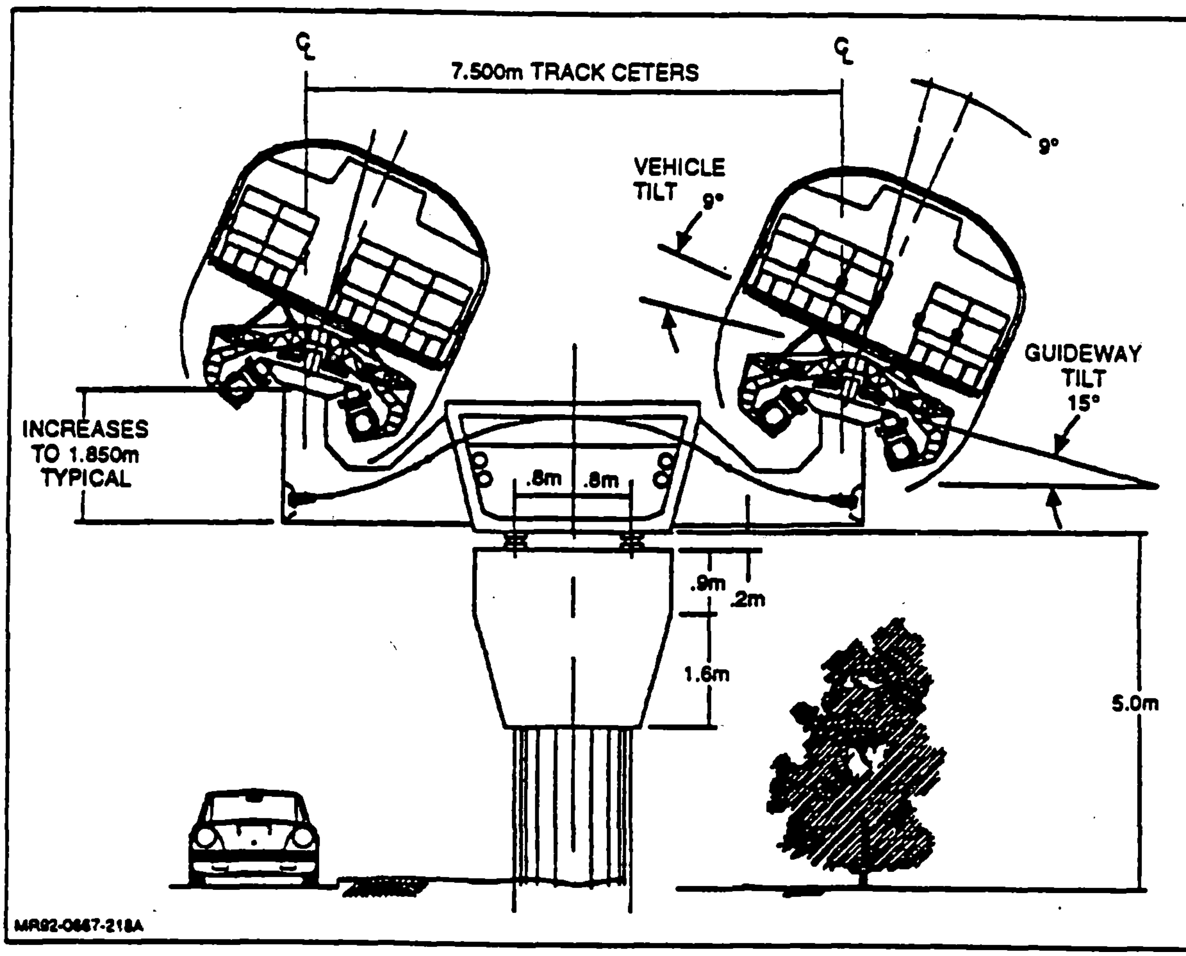


Figure 7. Grumman Y-Shaped Guideway Configuration

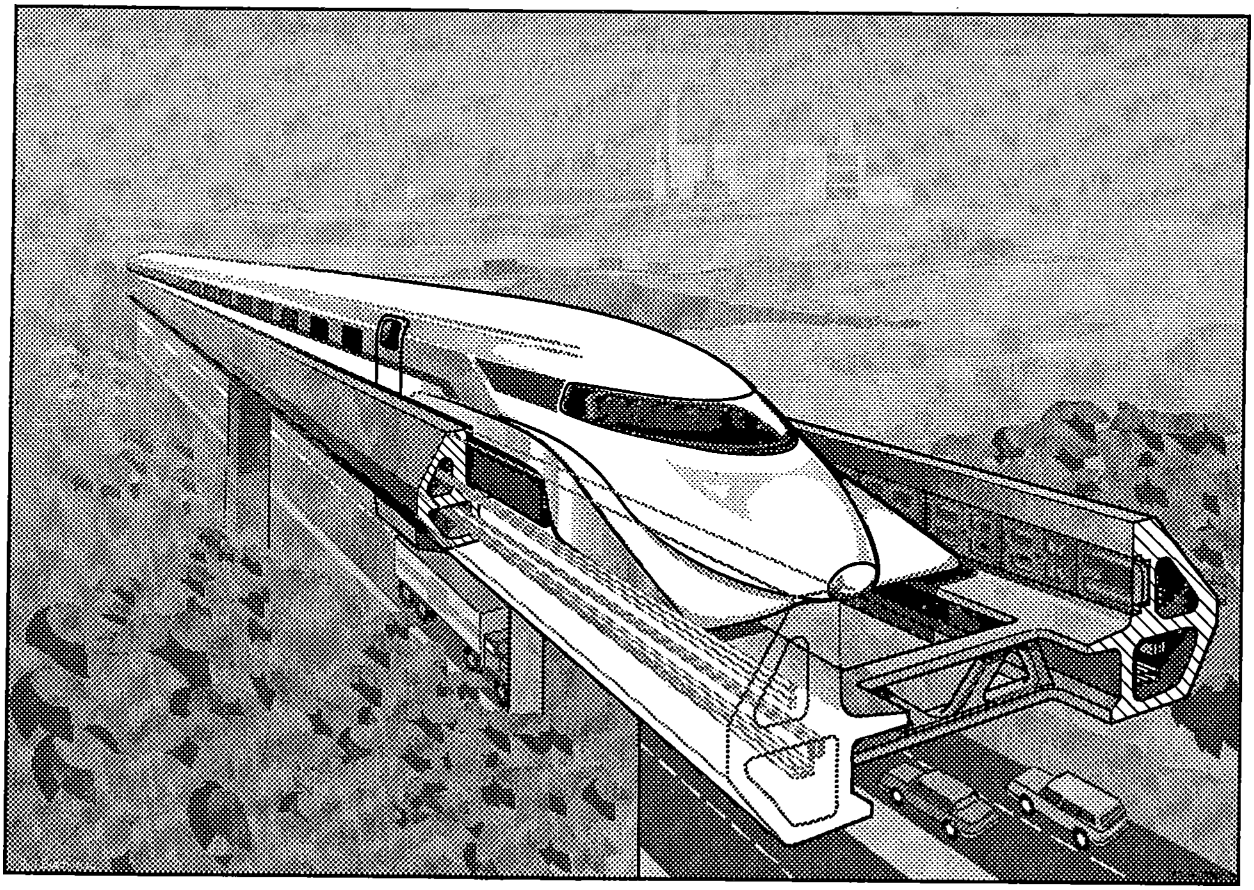


Figure 8a. Foster-Miller Sidewall Levitated Open Bottom Guideway Configuration

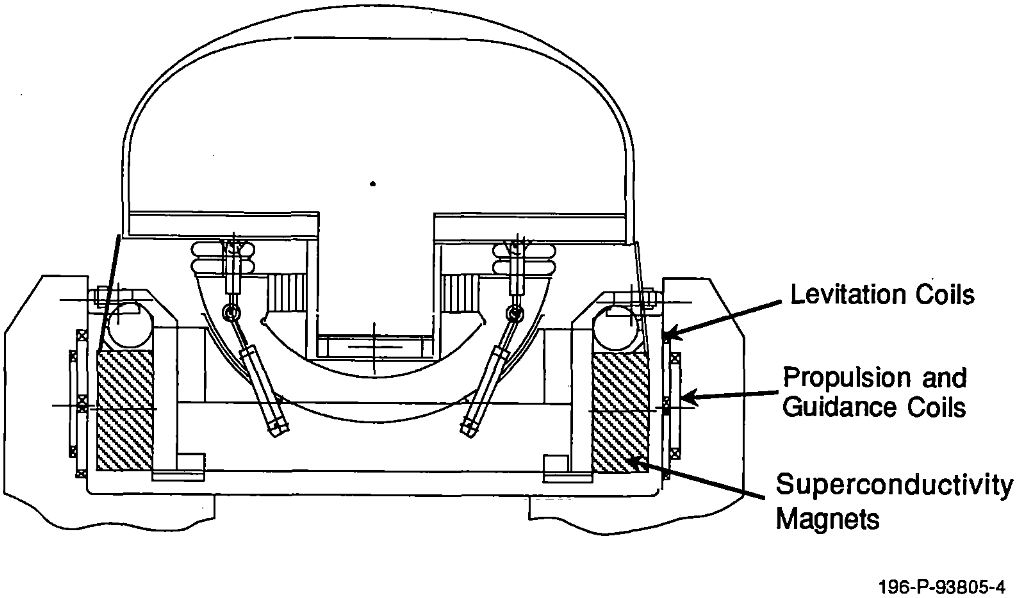


Figure 8b. Foster-Miller Bogie Section View

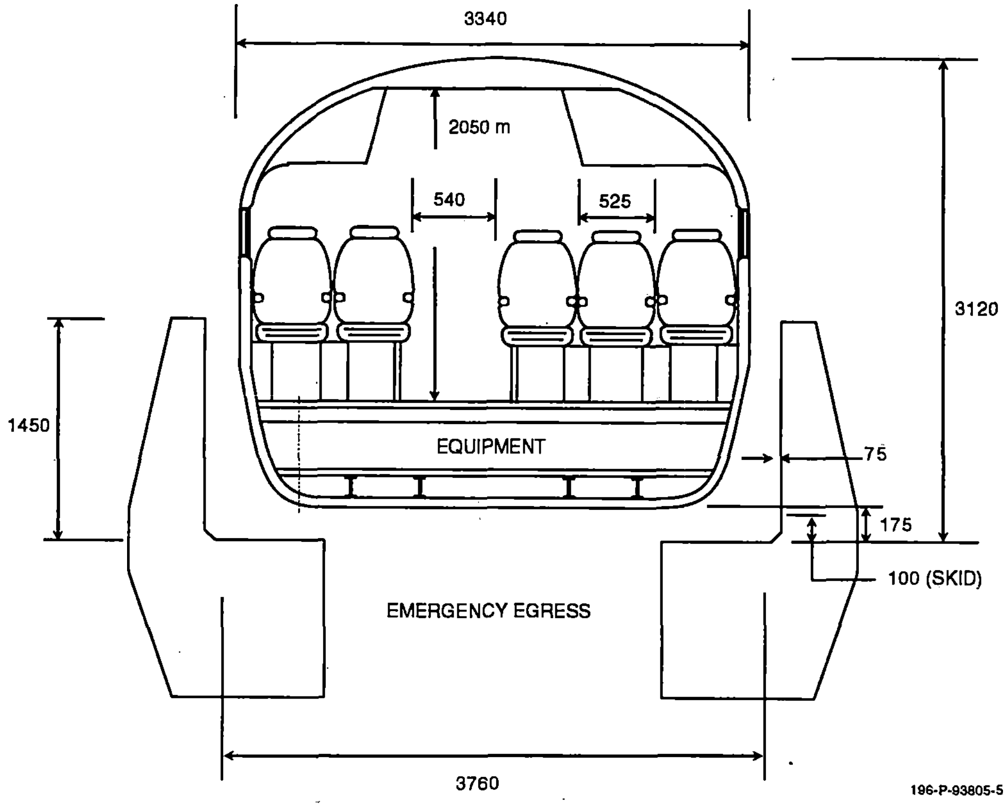


Figure 8c. Foster-Miller Vehicle Dimensions

2.4. Overview of Switch Configurations

This section includes descriptions some of the basic switch concepts.

2.4.1. Foster-Miller High Speed Vertical Switch

2.4.1.1. Basic operation of FMI vertical switch

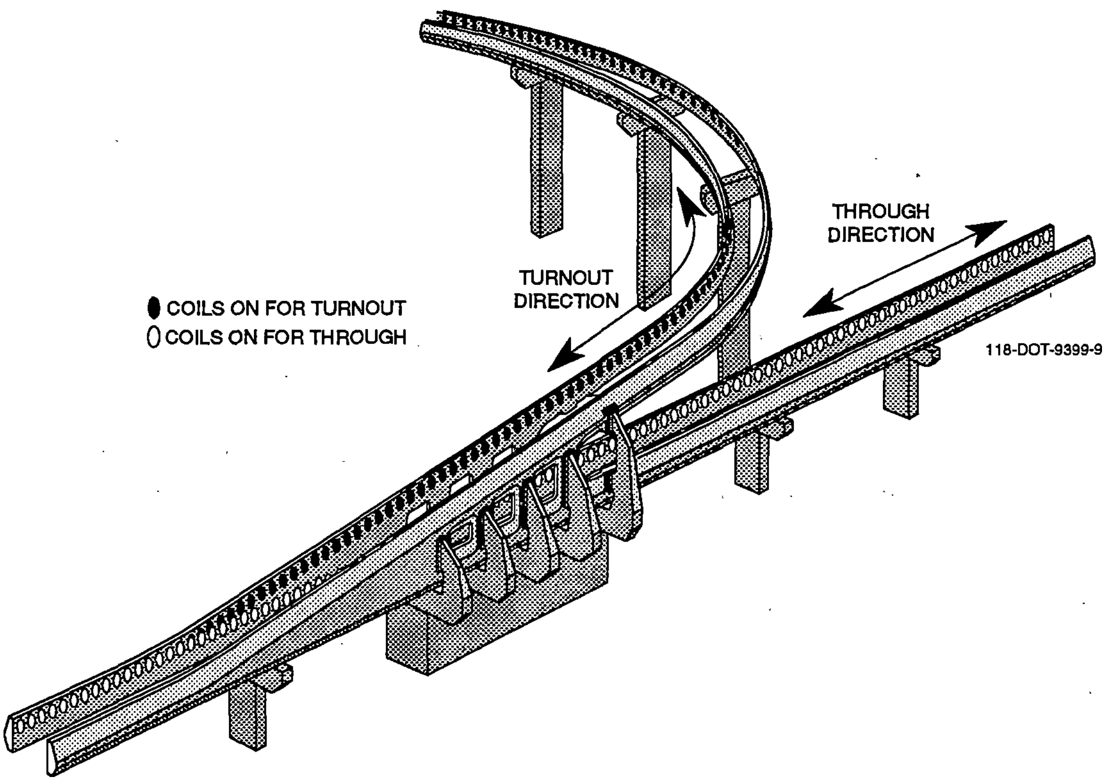


Figure 9. Foster-Miller Vertical Switch Using Null-Flux Sidewall Levitation and Sidewall Propulsion Coils (with Up Direction Switchout and Length Scale Greatly Reduced For Illustration)

The Foster-Miller open bottomed guideway with null flux sidewall suspension concept lends itself naturally to a high speed vertical switch configuration as shown in Figure 9. Although many switch configurations are possible with the Foster-Miller system, the vertical switch is the best. In normal operation, the vehicle is levitated, guided, and propelled by coils in the sidewall of the guideway. By overlapping switched coils as shown schematically in Figure 10 two paths are possible. Switching one set of coils on guides the vehicle along one path and switching that set off and the other set on guides the vehicle along the other. The vehicle is switched vertically and there is no change in the basic operation of the vehicle. Interleaved coils can be produced by tap changes and interleaved windings for the initial coils and by an offset coil configuration when the horizontal conductors are widely separated as shown in Figure 11.

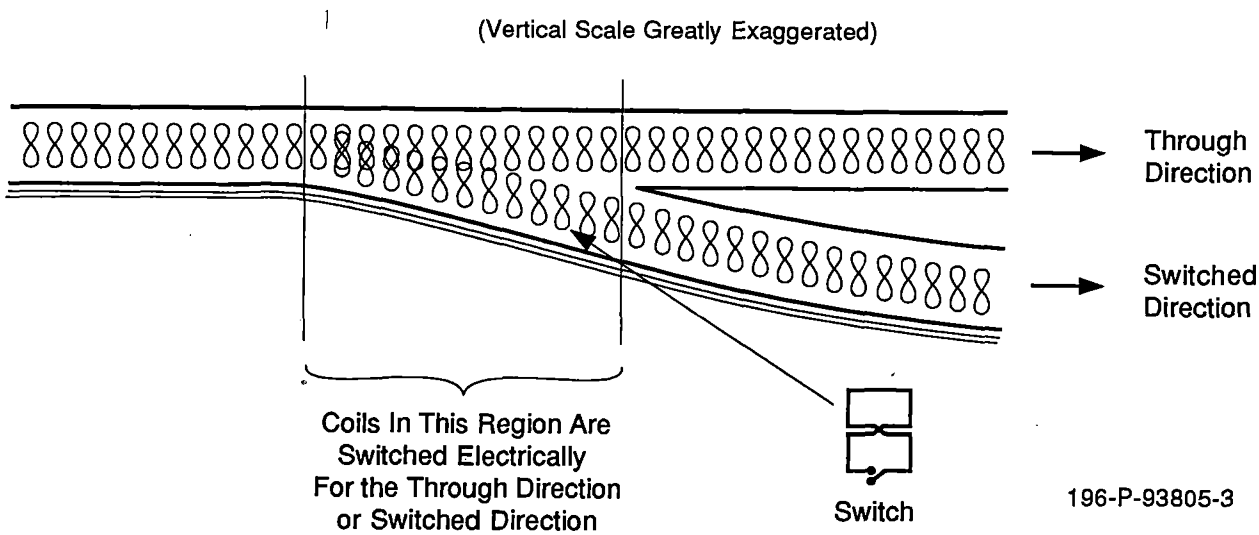


Figure 10. Null-Flux Sidewall Levitation Schematic (with Down Direction Switchout)

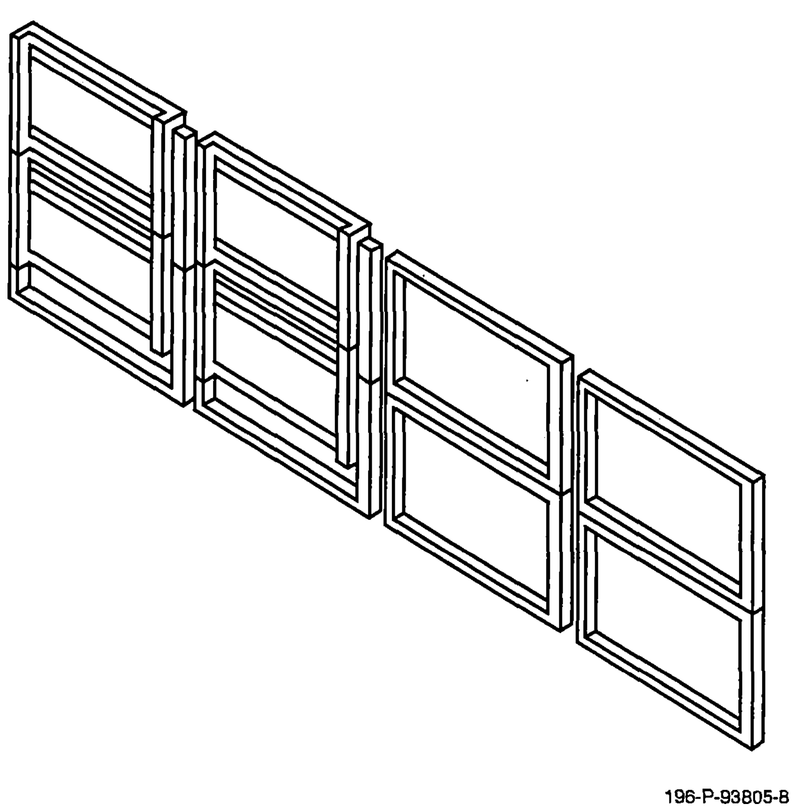


Figure 11. Schematic of Offset and Interleaved Coils

The key feature of this switch is the fact that there is no difference in levitation, guidance, or propulsion from the normal operating configuration. The switch is bi-directional and can be used for bi-directional traffic if required. This is possible because the physical and electromagnetic topology of the system lends itself naturally to this type of switch.

2.4.1.2. Safety and backup systems for FMI vertical switch

Safety can be assured by several methods. The first is that the integrity of the switched coils can be checked electromagnetically and reconfigured in milliseconds. Failure of several coils can be tolerated so fault tolerance is high. There are no moving mechanical guideway components to wear, service, or jam.

Backup systems provide fail safe operation so that even a massive failure of all the vehicle magnets while the vehicle is in the switch section can be tolerated. There is normally a small ledge on the inside sidewall that safely catches the vehicle in the guideway in case of failure as shown in Figure 12. In the switch section this ledge continues on the lower level of the switch. The lower level is traversed with no changes in vehicle configuration since the normal safety system is in place.

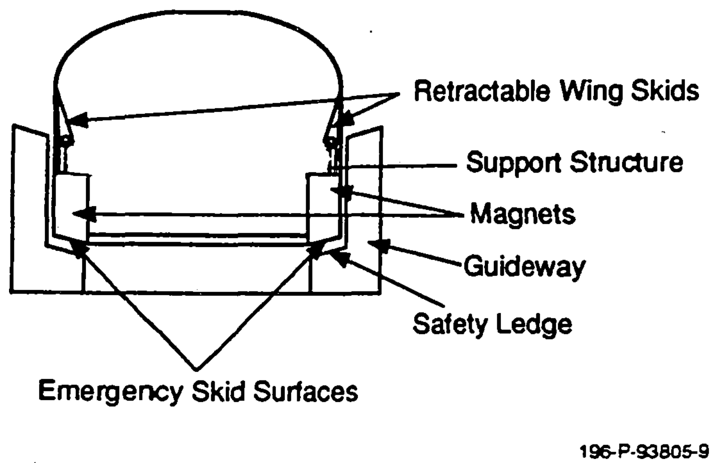


Figure 12. Foster-Miller Safety Ledge in Guideway

For the upper switch route, small wing like skids (or wheels) are deployed from the vehicle as shown in Figure 13. If there is a catastrophic levitation system failure, the vehicle is supported by the wings which slide (or roll) along the top surface of the guideway. This is done well before the switch section so that if there is a problem the wings (or wheels) can be retracted and the vehicle switched down for safety. If some safety wings fail locked out and some locked in then the vehicle can be stopped before the switch section. The vehicle can operate normally with the wings extended. They could be retracted only when switching down, but they are folded most of the time to reduce noise and drag. Sensors on the guideway can be used to sense the wing position to ensure that the guideway switch setting matches the vehicle configuration. The vehicle traverses the upper part of the switch with the safety skid/wings extended. When the lower ledge safety surface is available after crossing the gap, the wings can be safely retracted to reduce noise and drag. There are no moving guideway components. All moving safety components are very simple and located on the vehicle where they are easily serviced at stations if required. Additional operating flexibility is obtained if the wing is provided with multiple positions combined with a guideway with three switch directions and a small step for safety on the middle path. These components are located over the vehicle bogies where they do not interfere with passenger space. This location provides efficient mounting to the bogie structure. Safety is ensured with this system.

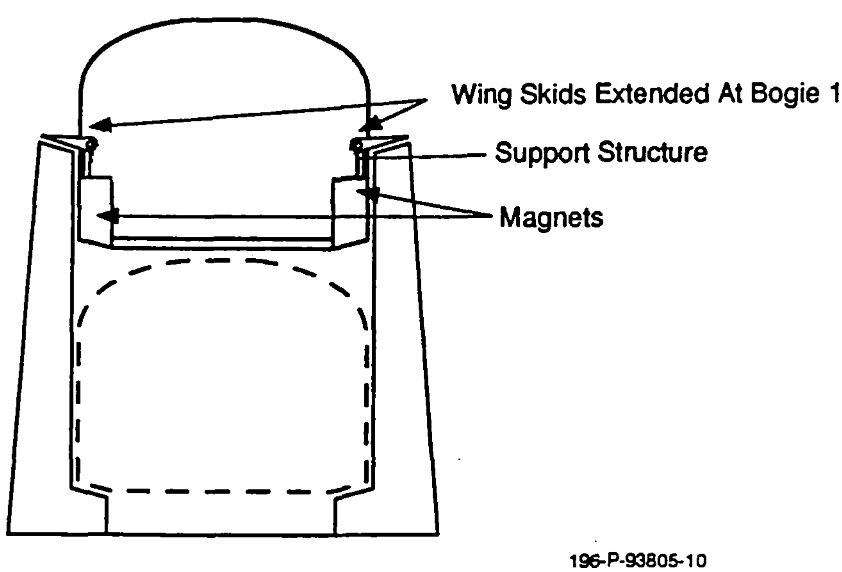


Figure 13. 'Wing' Skids in Vehicle for Upwards Switch Direction

2.4.1.3. Vertical switch configuration system issues

System logistics requirements are also well met by the vertical switch. Switches can be located almost anywhere along the route and do not take up any additional real estate since the motion is vertical. This allows the switch to be very long for good ride comfort without requiring additional right of way and the associated real estate. Once on the exit guideway, the vehicle can be slowed for a sharp turnout without adversely affecting traffic on the main line and without requiring a wider right of way for the long braking section. This is very beneficial since areas that require a sharp turnout tend to be the areas that have the highest right of way cost. In less congested areas the vertical motion can be used to reduce turnout radius without slowing the vehicle as shown in Figure 9. The upwards switch direction can be followed by a tight turn using a Chandel motion so that the downward acceleration available can be used to reduce g levels in a tightened coordinated turn. The vertical switch also makes in line, vertically stacked stations possible in which through vehicle speed remains unaffected. This further reduces real estate cost and simplifies route and station placement.

2.4.1.4. FMI vertical switch summary

In summary, the Foster-Miller sidewall levitation system is naturally suited to vertical switching. There is no change in suspension or propulsion in the switch. There are no moving guideway components, and the system has many levels of safety and reliability built into the switch. System wide issues such as right of way and logistics also benefit from this vertical switch arrangement. The Foster-Miller concept is a good example of a well developed switch concept and is a standard by which other switch concepts can be compared.

2.4.2. High Speed Switches for the EMS Systems - Transrapid T-Shaped Guideway and Grumman Y-Shaped Guideway

Transrapid is based on an attractively levitated small gap (1 cm) system utilizing a T-shaped guideway and wraparound vehicle configuration as shown in Figure 6 and more schematically in Figure 14. Grumman's concept is similar but uses combined levitation and guidance with super conducting coils and a larger gap (~ 6 cm) with a Y-shaped guideway as shown in Figure 7. Some Transrapid switch concepts will be discussed along with some Grumman examples where appropriate for discussion.

2.4.2.1. Powered ground coils in flat guideway for EMS systems

Figure 15 illustrates the basic features of the flat channel type switch for the Transrapid type system. The basic configuration of the system shown is similar in concept to the system described for the beam guideway. Since there are no superconducting magnets with large external fields in the Transrapid system, ground coils mounted in the guideway must be powered to produce a magnetic field which interacts with a sheet, ladder, or coil set mounted to the bottom surface of the outer bogies. The concept is basically an inversion of the standard sheet guideway system. For this switching system the sheets are mounted on the vehicle and the magnets in the guideway. This approach requires that the ground coils generate high fields. The coils are mounted in the guideway so they can be heavy, transient rated, actively cooled, or even powered superconducting designs. Again the coils must be overlaid or interlaced in overlapping portions, and the two paths must be held either powered or open circuited to control the path taken by the vehicle. Such an approach may even allow vertical switch configurations, and this basic concept can be adapted to most Maglev configurations.

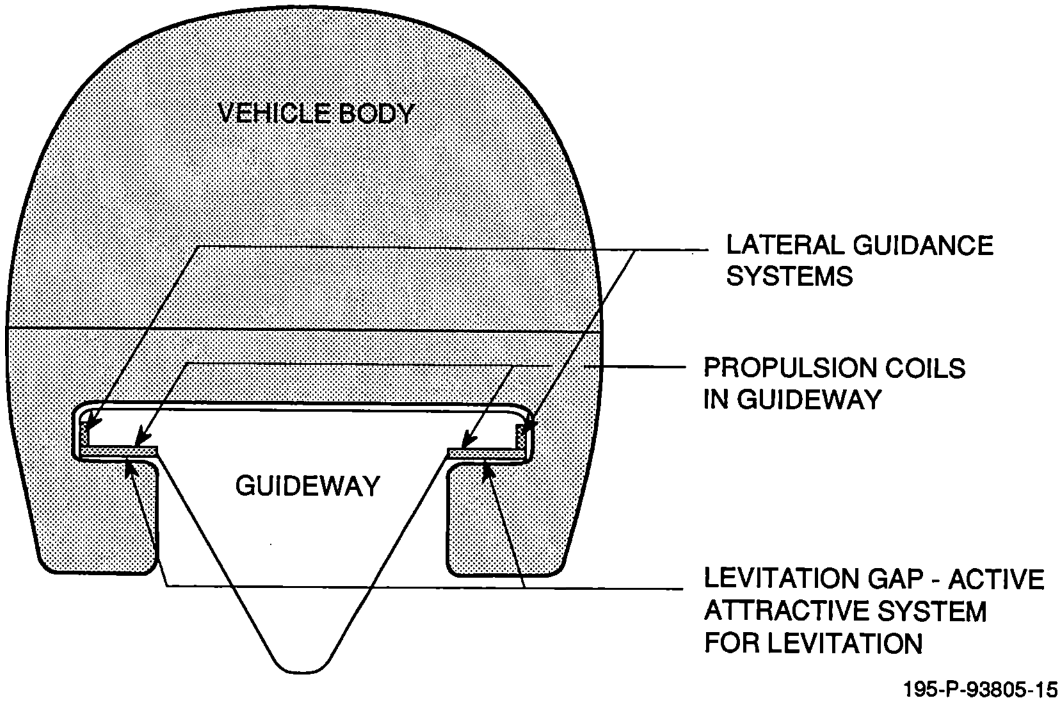


Figure 14. Transrapid Type Attractive Magnetic Levitation, Guidance, and Propulsion Configuration

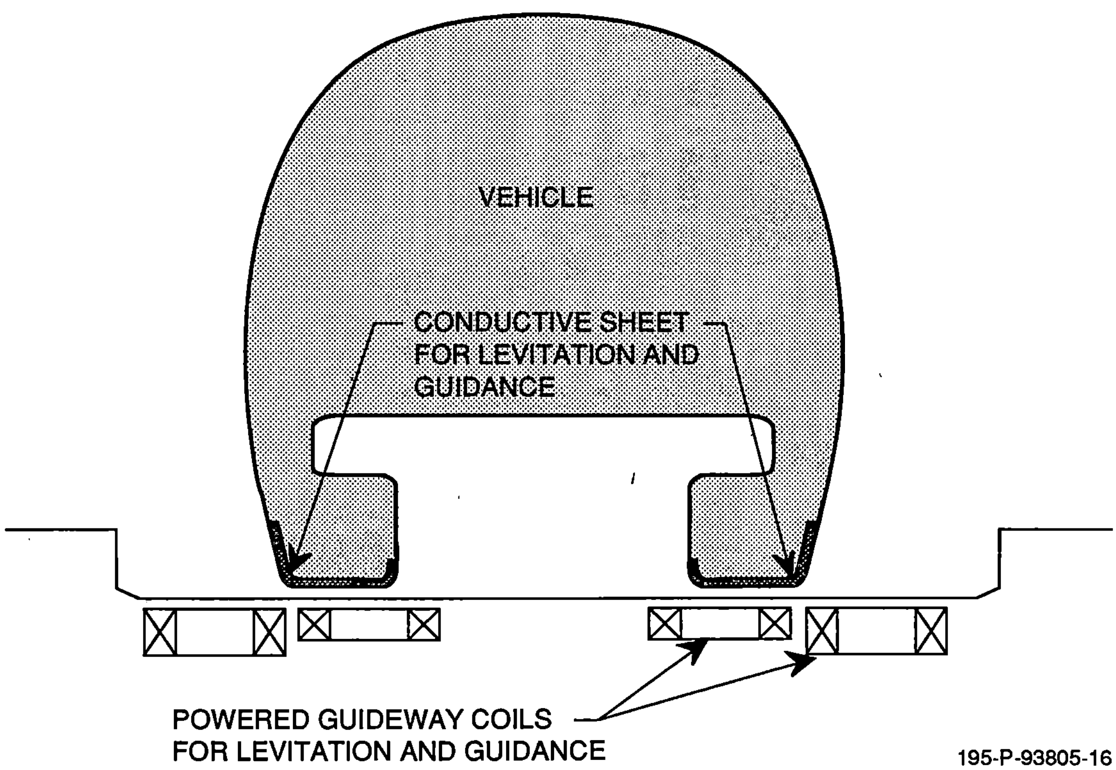


Figure 15. Flat Switch Section with Powered Ground Coils for the Transrapid Type Vehicle

Another possibility for controlling the levitation and guidance characteristics for this concept is to utilize active control for the ground coils. Active control is required for the basic operation of the Transrapid system; however, the very high power requirements for the ground coils would be similar for active or passive repulsive technology and investigation of the passive system will provide information on whether the approach is worth pursuing. The coils must be configured to provide levitation, guidance, and roll stability. In addition to these considerations, the power requirements for such a system must be considered. Calculations show that power requirements for a normal copper coil configuration for such a system are on the order of 5 to 10 MW. This is comparable to the vehicle power requirements and makes this approach less practical if the vehicle is also powered. However, if the vehicle is coasting through the switch, the power is available from the propulsion supply. The powered guideway levitation system could be designed to match the motor drive impedance requirements to reduce the need for additional electrical components. The Transrapid system is relatively heavy and it is possible that the deceleration level coasting through a switch could be within ride comfort requirements. The disadvantage is that the loss of thrust reduces the ride quality since the deceleration could range from 0.05 to 0.15 or more g's; however, if the deceleration is at the lower end of this range the reduced ride quality may be acceptable. This is one of the few concepts that allows the normal vehicle configuration to be utilized. The only modifications are mounting the conducting sheets or coils on the bottom of the vehicle. Thus, this concept may be feasible in spite of the high power required.

2.4.2.2. Slotted guideway for EMS systems

Another possible configuration is shown in Figure 16. This configuration maintains as much of the normal operating levitation and guidance as possible. Troughs are cut in the guideway that allow the wrap-around bogie to follow either of the two paths shown. Lateral guidance in the Transrapid system is attractive, so it is necessary to levitate and push toward the center of the vehicle on the bogie as it crosses the gaps in the guideway. A bogie is always normally levitated on one side, and must be levitated by some means on the other side as the gaps are crossed. This can be done in a manner similar to that described in Figure 15, but in this case the number of guideway coils is greatly reduced and the requirements on thrust and guidance control are reduced since thrust and guidance can be provided by the half of the bogie still operating in the normal manner. This approach is probably more cost-effective than that of Figure 15. The basic calculations of the two systems' guideway based levitation system are similar. Power requirements are reduced by a factor of 2 or more, partial propulsion is possible throughout the switch and the approach appears to be practical.

2.4.2.3. Mechanical switches based on slotted guideway

It is worth noting that the geometry shown in Figure 16 is also well suited for a mechanical switch. The spans and distances over which guideway parts must be moved are much less than that required for a bending guideway system although they are still on the order of 200 m long. The bulk of the structure is stationary, and those parts that move only support half of the bogie load and need to move only a small lateral distance. Figure 17 shows mechanical configurations using this approach. The problem is that the tapers are extremely long and

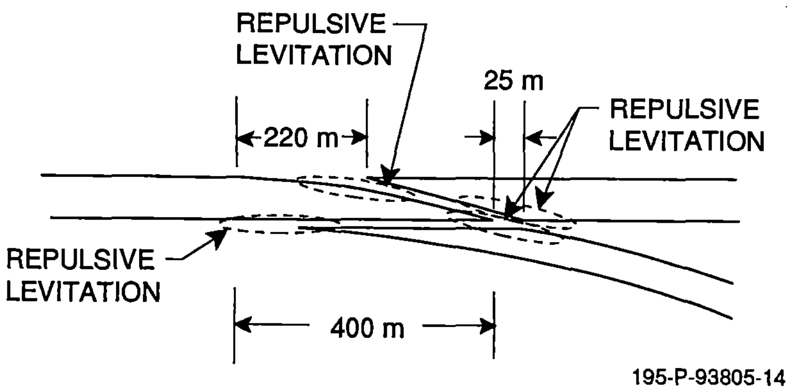


Figure 16. Slotted Guideway Configuration Using Powered Ground Coils (Top View)

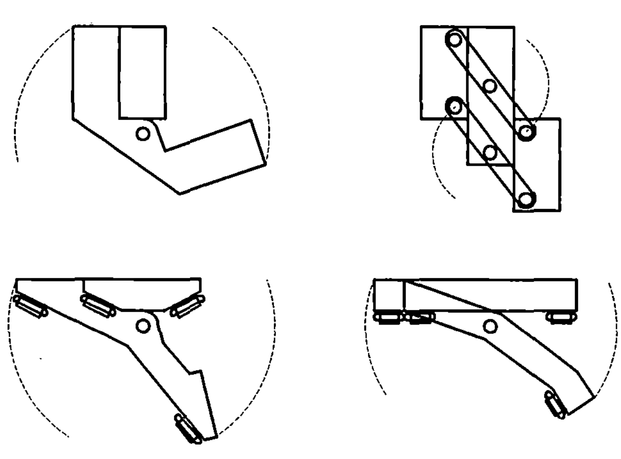


Figure 17. Implementation of Slotted Guideway Configuration Using Mechanical Moving Guideway Components (Side View). MIT/Bechtel Shown on Top, Grumman at Lower Left, and Transrapid at Lower Right.

require very thin components in some places. For the Transrapid system the gaps are very small which means that the parts must also be very thin. Even with the thin mechanical parts this approach may be attractive in some situations. Although such a mechanical system is not suited for high speed switching in an outdoor environment, it may still be a suitable system for lower speed switching off of the main high speed guideway sections in station areas and feeder lines.

2.4.2.4. Operational description of electromagnetic / electrodynamic slotted guideway switch for EMS systems

A more detailed view of the grooved guideway with powered ground coils that repel sheet, ladder, or coils on the vehicle is shown in Figure 18. Although the switch is bi-directional, assume the vehicle travels from left to right in the branching direction for the following description.

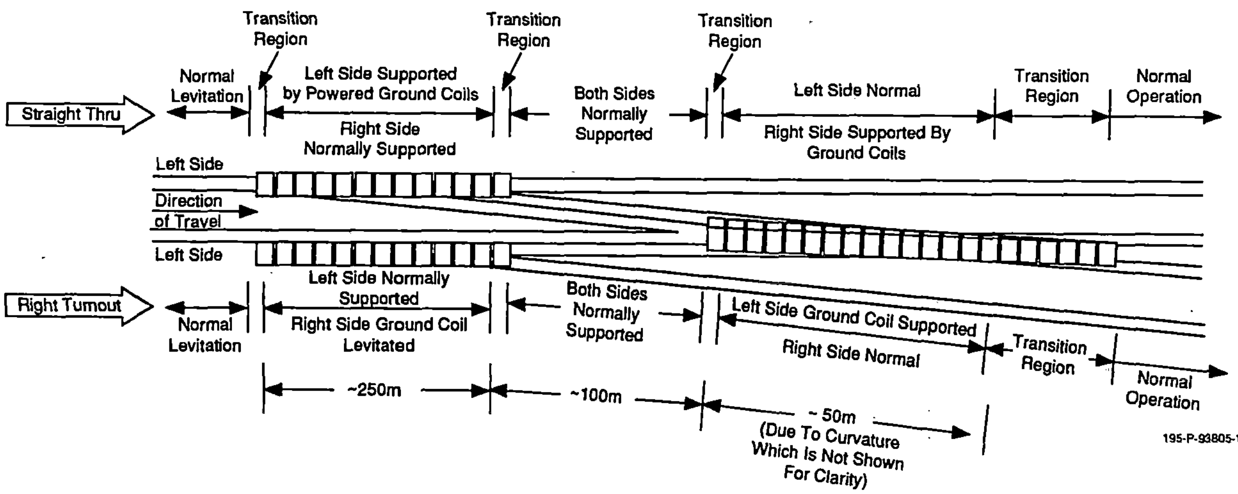


Figure 18. Slotted Powered Ground Coils Combined with Normal Operation (Horizontal Scale Greatly Compressed)

For a vehicle passing straight through the switch, levitation on the left side of the vehicle must be maintained over the cut away section while the right side operates normally. This is done by powered ground coils in the left side of the guideway that repel the bottom surface of the vehicle. Guidance is provided by normal operation of the right side while the levitation ground coils on the other side provide an offset side force (towards the center). The length of this section for full speed operation is approximately 250m. (The scale of any high speed switch must be compressed in the direction of travel for illustration as shown since a 1 in. wide drawing would have to be about 400 in. long to show the full switch.)

The vehicle then enters a central region and picks up the left guideway, which is ramped and tapered to allow gradual pickup. The vehicle is in normal operating mode in the central section of the switch. Next, the right side is levitated by powered ground coils as it traverses the cutout for the direction. Then the right side picks up and normal operation continues. For the exit guideway the operation is essentially the same except the sides are reversed. A summary of the operation is shown in Figure 18. This approach is also usable for the Grumman system as shown in cross section in Figure 19. Power requirements for the ground coils are high using normally conducting materials, at approximately 5 MW; however, this is not out of the realm of feasibility due to power constraints since a high speed switch is very important for an operational system. A major consideration is the difference in the stiffness and drag of the coil and sheet levitation compared to the active attractive suspension. This affects ride quality, stability, propulsion and feasibility of achieving switching transitions without physical contact. For the Grumman system, the effect on the superconducting coil due to the rapid removal and replacement of the guideway in the ramped and tapered section, which serves as a magnetic circuit return path, must be considered. The basic physics and characteristics of the levitation, guidance, and propulsion system change while switching. This produces a change in suspension characteristics and transition regions which may adversely affect ride quality.

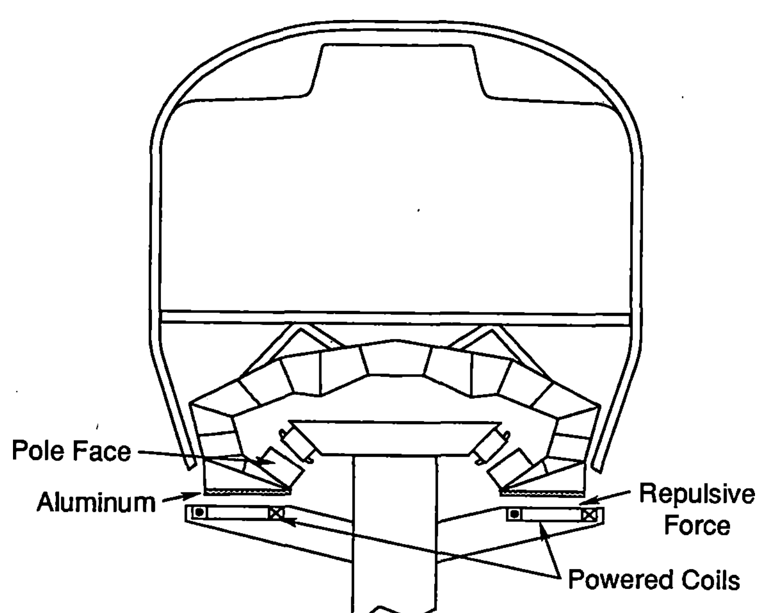


Figure 19. Grumman Configuration with Powered Ground Coils (Note: Substantial Lateral Forces Must be Generated and Controlled for Stability)

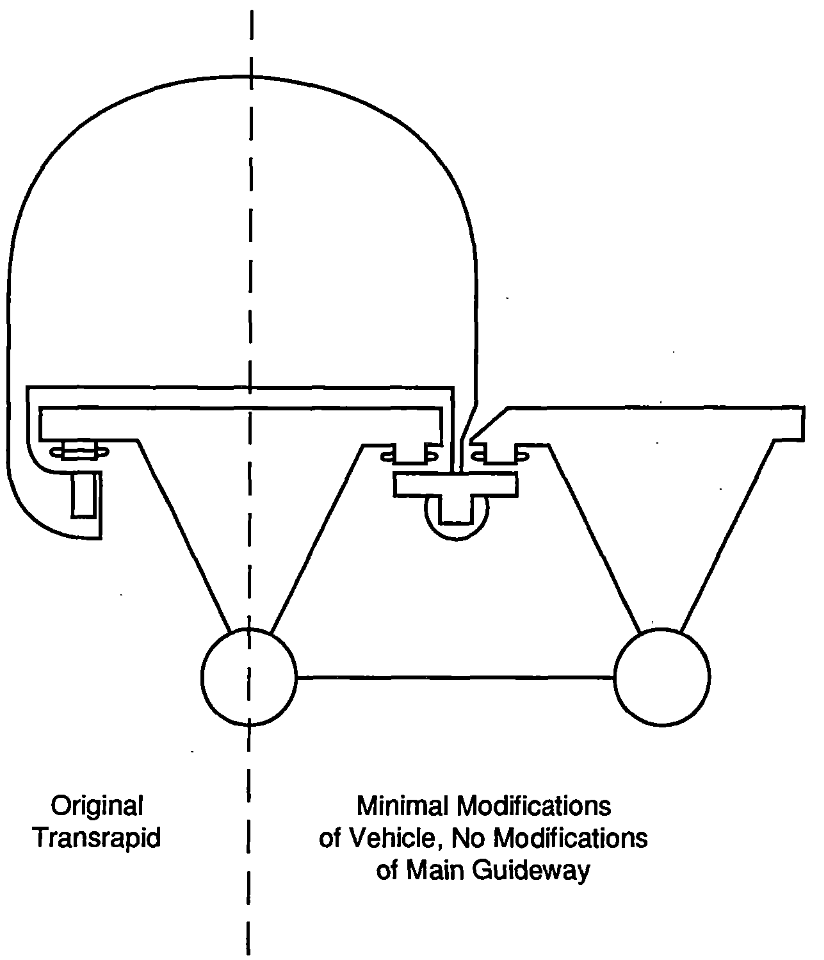


Figure 20. Modified Transrapid Configuration for Normal Electromagnetic Levitation and Guidance in the Switch (Original Configuration Shown on the Left and Modifications Shown on the Right)

<u>2.4.2.5. Switch using normal levitation and guidance by modification the EMS vehicle configuration</u>

A system which utilizes the same attractive magnetic suspension through the switch can be developed with a modification to the vehicle configuration as shown in Figure 20. In this case there are two levitation and guidance positions available on each side of the vehicle, one inside and one outside. A more detailed concept drawing is shown in Figure 21. Levitation, guidance, and propulsion can be achieved with either side of the inverted-T magnet arrangement on the vehicle acting on the guideway components. The guideway configuration and a table of what attractive coils are active is shown in Figure 22. Each side of the vehicle is always supported in the normal mode of attractive levitation with the guideway providing propulsion. Support, guidance and propulsion functions are passed from the inner coil to the outer coil or visa versa as required. Guideway components are ramped and tapered to provide relatively smooth traditions from one side to the other. There is no major difference in the levitation or propulsion technology using this approach except that the steep angle of the pole faces in the Grumman system must be made flatter to achieve adequate clearance for lateral motion.

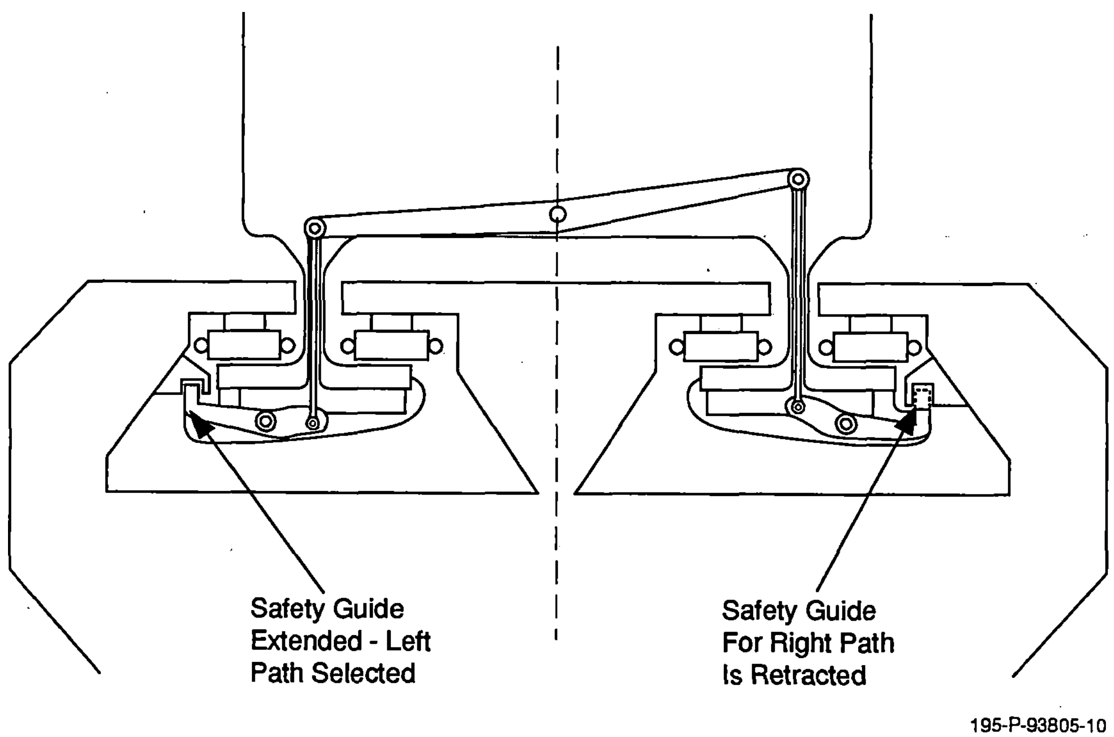


Figure 21. Details of the Modified Vehicle for Attractive Magnetic Levitation and Guidance in the Switch

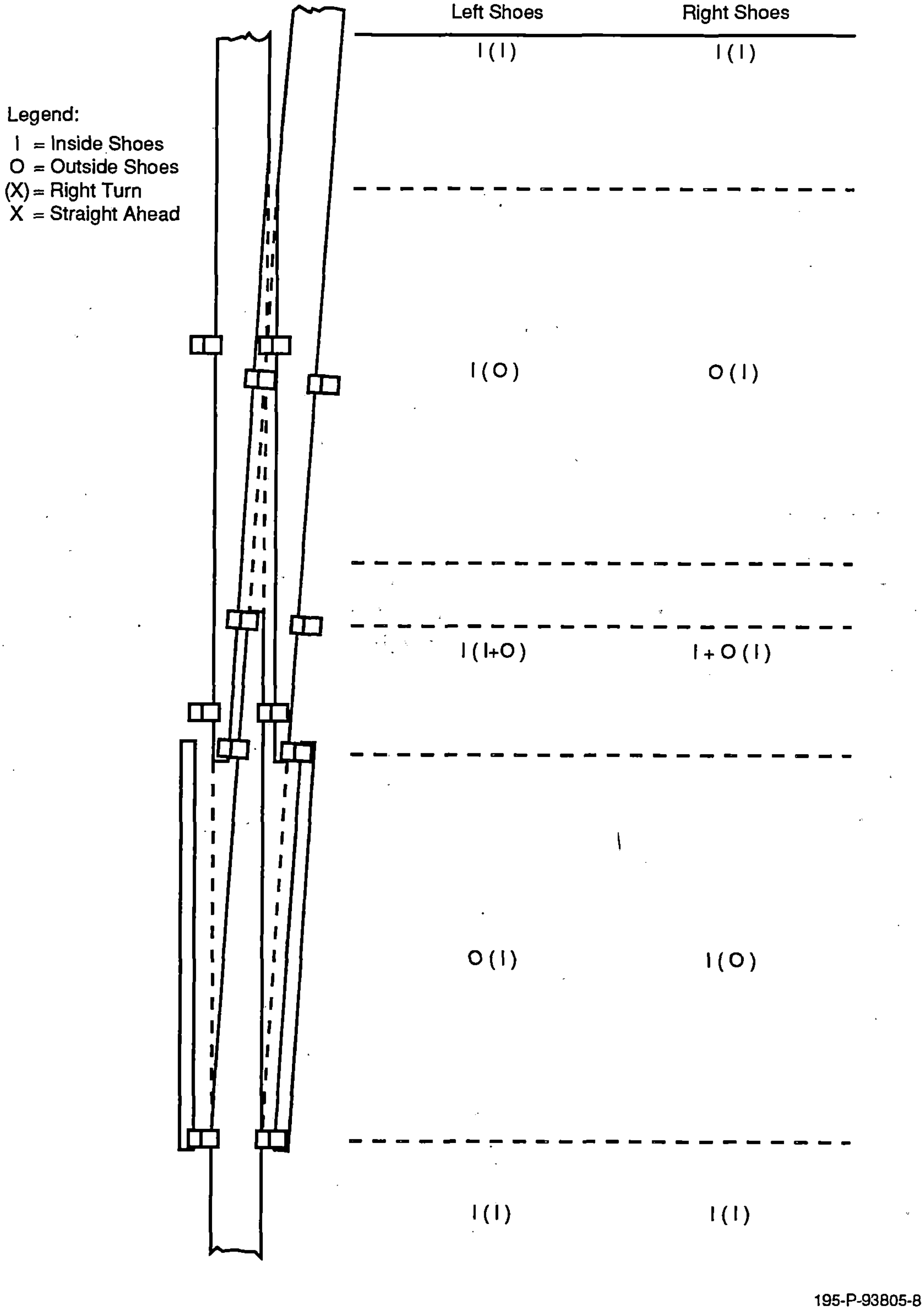


Figure 22. Always Attractive Switch Configuration and Operation (Top View)

2.4.2.6. Issues related to electromagnetic levitation and guidance

The Grumman system uses staggered coils for roll control. This approach is also suited to application in several of the EMS switch concepts and is described in more detail here. Several of the switch concepts can use alternating staggered magnets for lateral guidance in an approach similar to what Grumman uses for roll control. For this reason analysis was done for the Grumman configuration based on data available in the Executive Summary Report. The pole faces are staggered in pairs to provide a lateral component to the attractive force. This effectively provides a controllable shear force as long as there is a levitation force on the vehicle.

For example, to provide the maximum restoring shear force in one direction, half of the magnets are turned off, the half to the left of the centerline for example, and the other half, the half to the right of the centerline, are turned up to maintain lift. This provides a leftwards force on the vehicle as the pole faces to the right of the centerline try to line up with the stator block. However, use of this technology can produce substantial reductions in linear motor performance. Because the lift is related to the square of the magnetic field in the gap and there are half as many active pole faces, the motor back EMF is reduced when roll control is active. Under maximum roll control input the voltage reduction is essentially 30%. This reduction in motor EMF results in reduced motor efficiency and increased motor control electronics requirements.

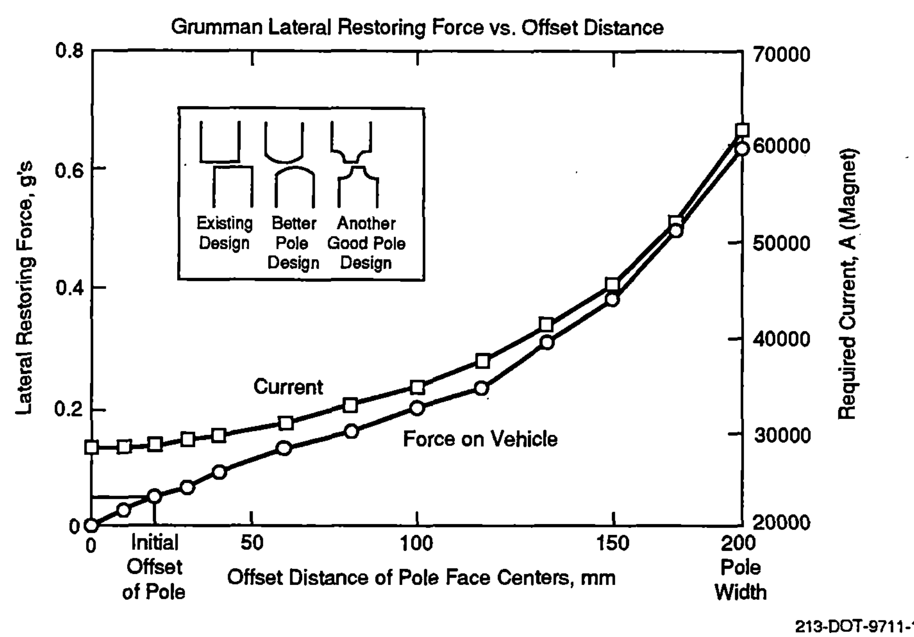


Figure 23. Shear Force Capabilities for the Grumman System of Offset Poles

The shear force capacity of this system is also limited. Figure 23 shows the lateral force as a function of pole center displacement for a magnetic configuration shown in Figures 24 and 25 similar to that shown by Grumman in the executive summary. The levitation force is held

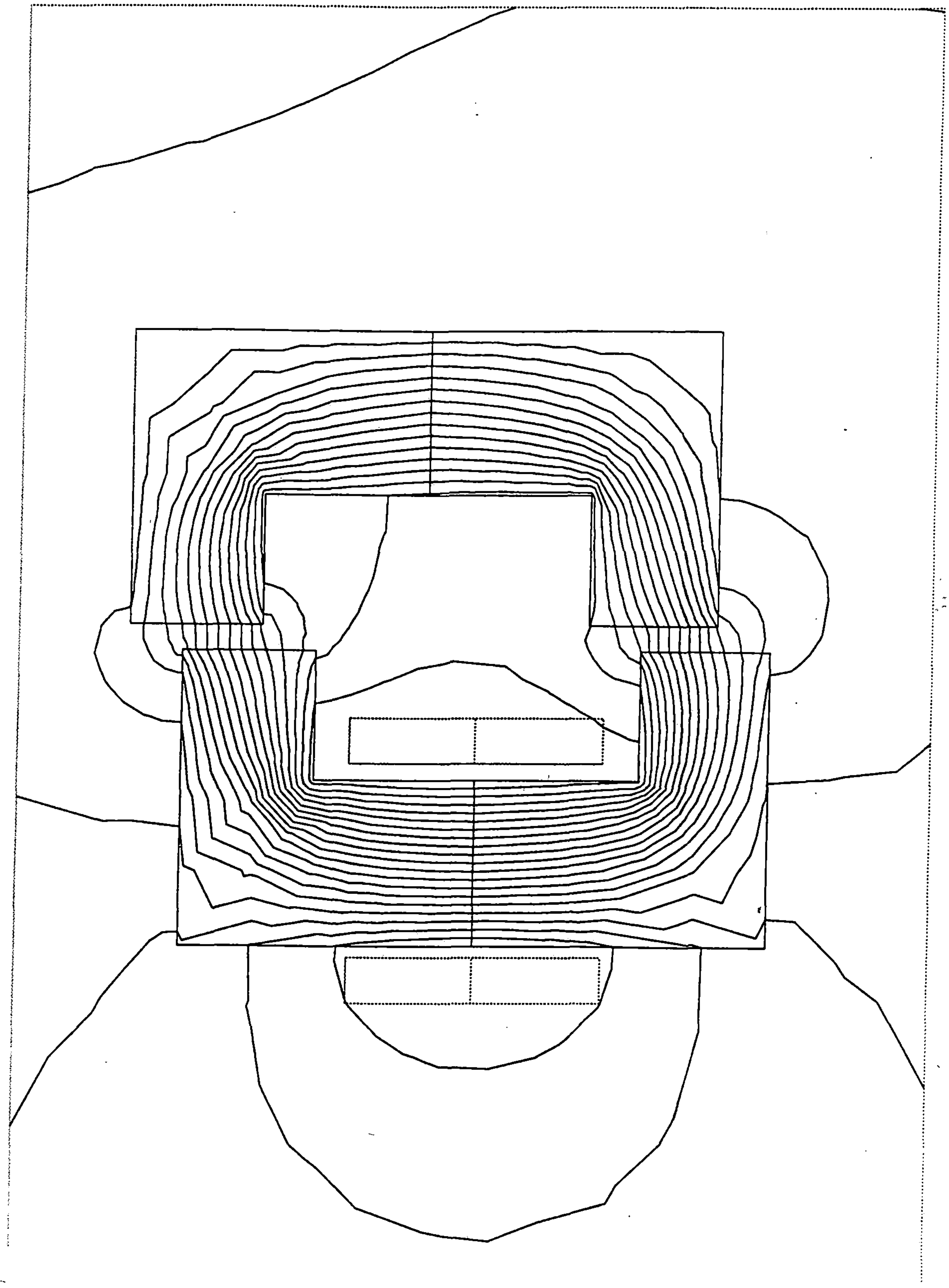


Figure 24. Magnetic Configuration and Field Lines from Analysis of Shear Force Capacity of the Grumman System with Moderate Displacement

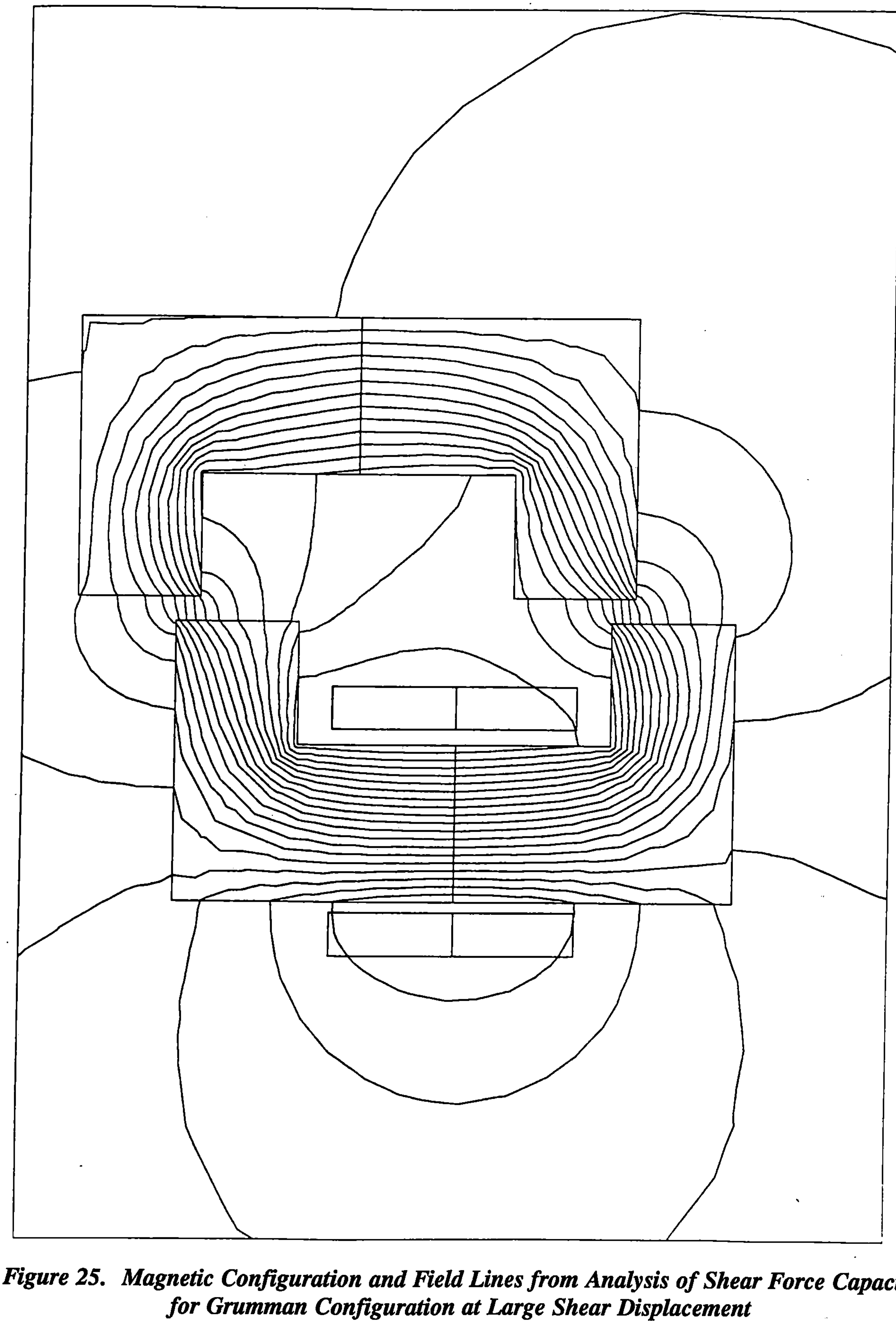


Figure 25. Magnetic Configuration and Field Lines from Analysis of Shear Force Capacity for Grumman Configuration at Large Shear Displacement

constant and the offset coils are turned off for this analysis so that the results represent the maximum lateral force for a given displacement. The geometry is also slightly modified for the calculation, but this has little effect on the results. For the Grumman system the initial offset is 20 mm so that the centering stiffness is set by the control system up to the maximum force available at 20 mm displacement. Lateral forces above this level require motion of the magnets relative to the centerline of the stator. The lateral force capacity of this system can be improved. The field lines shown in Figures 24 and 25 cross the gap primarily perpendicular to the gap which produces little restoring force. Only the fringing fields are contributing significantly to the centering action. For the shear type action of the pole faces, modified pole faces (rounded, for example) can provide improved lateral capacity and stiffness compared to the flat faces currently used by effectively changing the angle of the gap as the pole faces are displaced. This gain comes at the expense of a slight increase in the required levitation current due to the effective increase in the gap.

2.4.2.7. Safety systems for EMS switches

Safety is provided by the movable peg shown in Figure 21. The peg fits into a slightly wider slot in the guideway. The right side peg is used for the switch to the right guideway and the left for the left guideway for the system shown. The pegs are connected across the vehicle with a bar to prevent accidental engagement of both pegs which would cause damage. In the event of a failure the vehicle slides on the surface of the guideway and the peg slides in the slot to prevent the vehicle from contacting any of the structure in the transition regions of the switch.

Although this concept provides the same form of levitation and propulsion in the switch, it does require more vehicle mounted levitation components. This increases vehicle weight, frontal area, and complexity which results in lower capacity and higher operating costs. In addition, the lateral switch requires wider right of ways. The lateral motion reduces perceived ride quality compared to pure vertical or coordinated motion. Additional technical considerations indicate that lateral guidance might be achieved more easily using pole faces with alternating lateral offset similar to the Grumman approach rather than the system used now.

2.4.2.8. Alternative configurations for EMS systems

Other alternatives to be considered include replacing the outer levitation system on the vehicle with a bar of slotted steel and putting the active levitation and guidance components in the guideway to reduce the impact on vehicle weight. For a small gap system it may also be possible to use a set of downward facing poles to produce controlled small gap repulsive levitation using the same coil components as for normal operation as shown in Figure 26. A centrally located large area repulsive system might also be used as shown in Figure 27. By combining these techniques, it may be possible to produce a vertical switch for these systems in which the outer slotted bar ledges are used to pick the vehicle up and one of the bottom repulsive systems is used to continue on the level. The performance of these switch configuration concepts and their effect on system performance characteristics is considered in the trade off analysis.

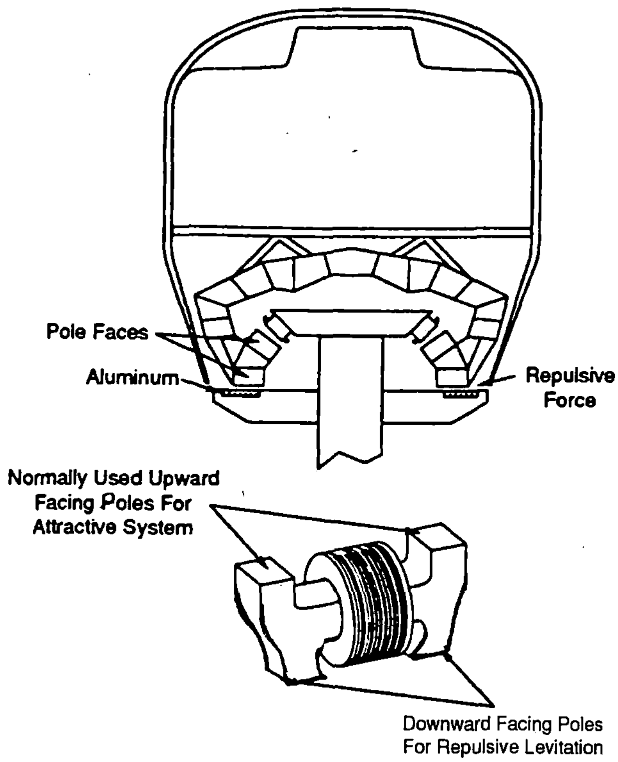


Figure 26. Grumman System with Active Repulsive Small Gap Levitation for Switching

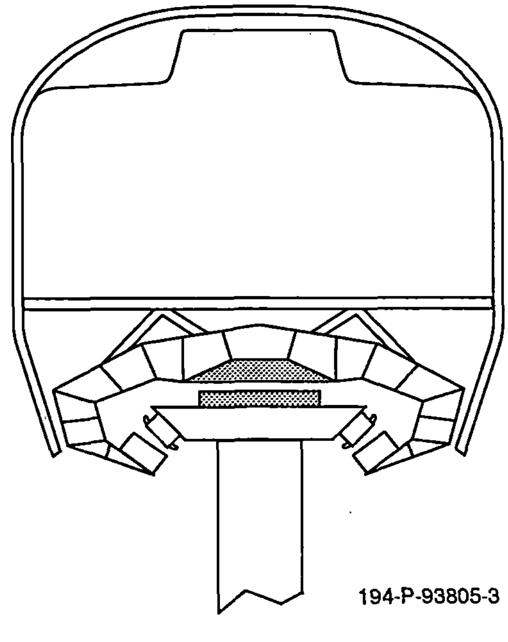


Figure 27. Grumman System with "Keel" Concept for Levitation

2.4.2.9. The roof switch

The roof switch (Figure 28) can be used for any of the major system configurations. A slotted steel piece is mounted on the roof of the vehicle. An EMS levitation and guidance system is installed on the underside of the roof over the vehicle. This active attractive system picks up the vehicle as it passes underneath. The guideway is terminated and the vehicle is switched by the laterally separated and controllable levitation magnets of the guideway. Once displaced laterally the guideway is started with a taper and normal operation is resumed. Safety is provided by slots and hooks above the vehicle configured for the proper path. The steel in the roof can be wound to provide excitation for propulsion as well. The mass of steel in the roof must be on the order of 5% of the vehicle weight to avoid saturation. In addition, the body must be strengthened to accommodate the stress of levitation and guidance from the roof and magnetic shielding may be required.

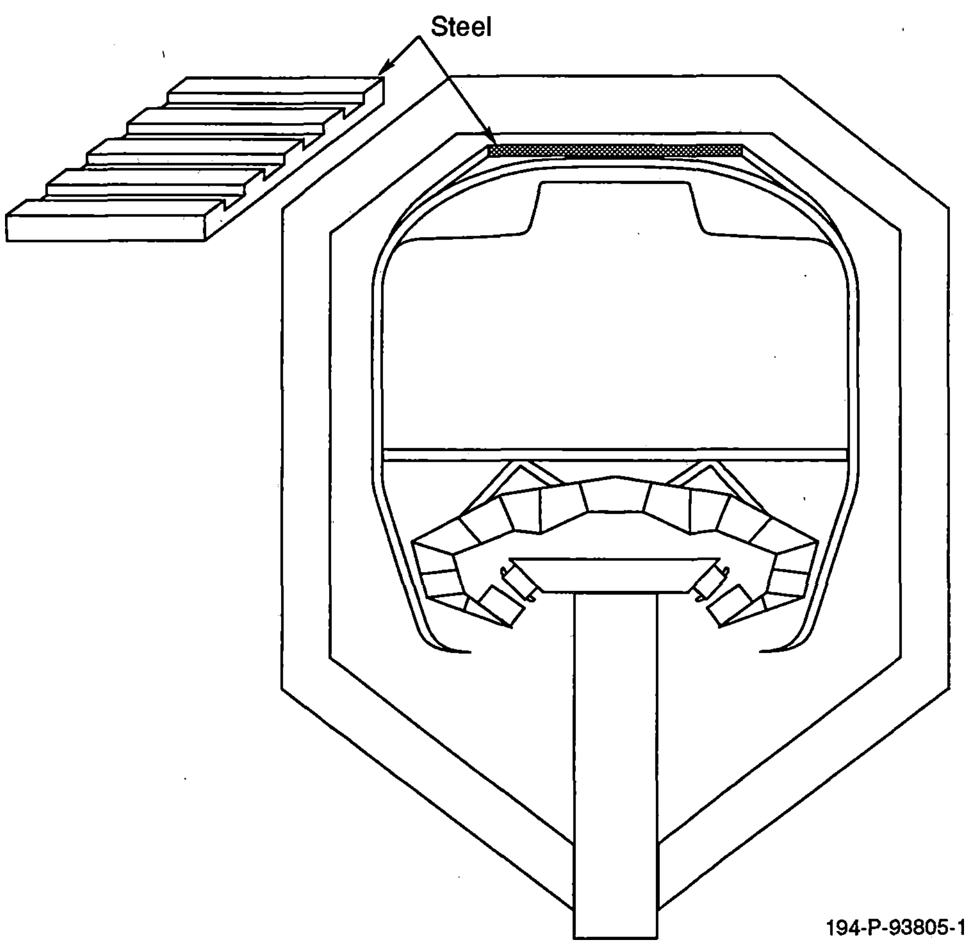


Figure 28. Roof Mounted Switch with Active Attractive Guideway Components

2.4.2.10. Summary of switch concepts for the EMS systems

Many switch configurations have been generated for switching the EMS configurations. None of these utilizes the normal levitation, guidance, and propulsion systems without substantial modification of the vehicle. The roof switch is the most general; however, it requires very small gaps to be maintained and requires a significant increase in the structural strength of the cabin roof and walls. Additional passenger shielding may be required for this configuration. The heavily modified vehicle in which the outer ledge or suspension is added is another option. The repulsive powered guideway coil systems do not use EMS suspension, so suspension response characteristics are not maintained. The coils require substantial drive power which leads to safety issues in case of a power failure. None of the EMS systems is well suited to electromagnetic switching without some modification.

2.4.3. High Speed Switches for the EDS Systems - MIT/Bechtel Beam Guideway and Magneplane Trough Shaped Guideway

High speed switch configurations developed for the Electro-Dynamic Suspension (EDS) configurations of the MIT/Bechtel and Magneplane concepts are presented in this section. These systems are characterized primarily by the use of superconducting magnets which provide a very high field with an air core. Currents induced in sheets or coils of conductors mounted on the guideway as the superconducting vehicle magnets pass by produce levitation and guidance forces. The relatively large gaps and natural stability of the EDS configuration combined with the fact that there is no need to wrap the vehicle around the guideway to provide levitation and guidance makes these systems potentially more easily adapted to a variety of simple switch configurations. With modifications, both systems can be configured to provide a vertical switch with its inherent advantage of low right of way cost and high ride quality.

2.4.3.1. MIT/Bechtel Beam Guideway Switch Configurations

The M.I.T./Bechtel configuration utilizes null flux sidewall levitation, propulsion, and guidance similar in many respects to the Foster-Miller system except that the vehicle straddles a box beam guideway. Currently configured as shown in Figure 4, the configuration is very difficult to switch electromagnetically although concepts similar to the flat guideway described for Transrapid might work. However, with slight modifications there are many possible electromagnetic switch arrangements with this system.

2.4.3.2. Switched coils on flat guideway for the MIT / Bechtel system

The flat guideway with switched coils approach requires eliminating some of the lower structure of the vehicle so the superconducting coils are near the bottom surface to provide substantial fields that extend below the vehicle bottom surfaces. The basic configuration assumed for the M.I.T./Bechtel beam guideway and vehicle configuration is shown in Figure 29. The superconducting magnets are located in the vehicle bogie. The passenger compartment is mounted above the bogie system and is not included in the figure. This magnet configuration allows the use of simple sheet, ladder, or coil levitation and guidance configurations in an efficient null-flux mode of operation. The bogie straddles a relatively compact beam which contains the levitation, guidance, and propulsion coils. There are many variations on the details of the location of the guideway components and the size and dimensions of the system, but the key concept incorporated is the configuration of the superconducting magnets into a "null-flux" octupole arrangement which allows a simple and efficient null-flux ladder levitation and guidance system with low shielding requirements. If the magnets are near the outer edge of the vehicle, the system will also work with a sidewall levitation system; it can incorporate vertical switching in a relatively straightforward manner and such a simple switching system does not warrant inclusion here. Configurations in which the vehicle projects laterally beyond the effective range of the magnetic fields are discussed here since vertical switching would not be practical for that case without supplementary components onboard.

One switch configuration is based on a wide flat section of guideway on which the beam is removed. Levitation and guidance are achieved by ground coils located in the guideway as shown in Figure 30. The switching section of the guideway consists of a flat stationary portion of guideway which has ground coils for levitation and guidance mounted in the surface. There is a transition zone over which both the beam and the floor overlap and allow a smooth transition to the flat section of guideway. The ground coils have switches which allow them to be either open or short circuited. When open circuited the coils produce no interaction with the vehicle magnets. When short circuited, they provide a levitation and guidance force which constrains the vehicle to follow the path desired. Divergence from the main line or convergence from a branch line are achieved by overlapping and interleaving the coils of the two paths. Only one path would be short circuited to control the path of the vehicle. Once the vehicle is clear of the overlapping sections of the switch paths, it enters a transition zone where the beam guideway emerges from the floor. Transition to normal operation begins at this point. Ground coils provide a relatively soft suspension, so the influence of coil positioning variations which are inherent in such a system are reduced in the switching section. The guideway might also contain small mechanical guidance features such as stringers that normally pass freely under the vehicle, but control vehicle trajectory to a safe path in the event of loss of levitation. It may also be feasible to mount a backup component on the vehicle that ensures safe guidance in the event of a failure. The key feature however is the high speed switching in normal operation. This capability must be verified before details and backup systems can be developed.

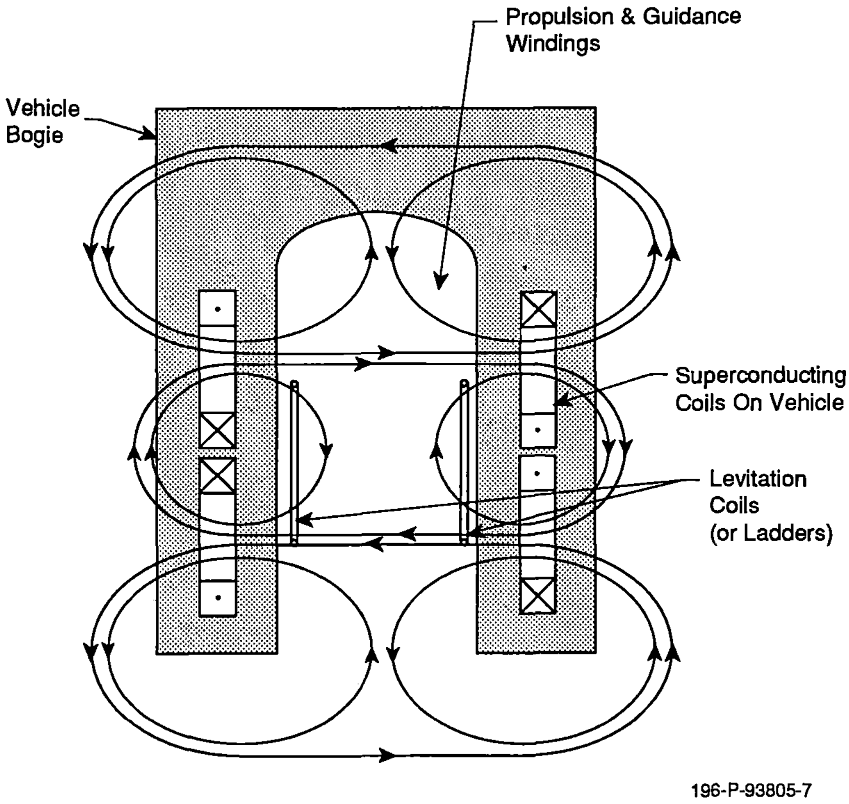


Figure 29. Probable Configuration of MIT/Bechtel Null-Flux Magnet Arrangement

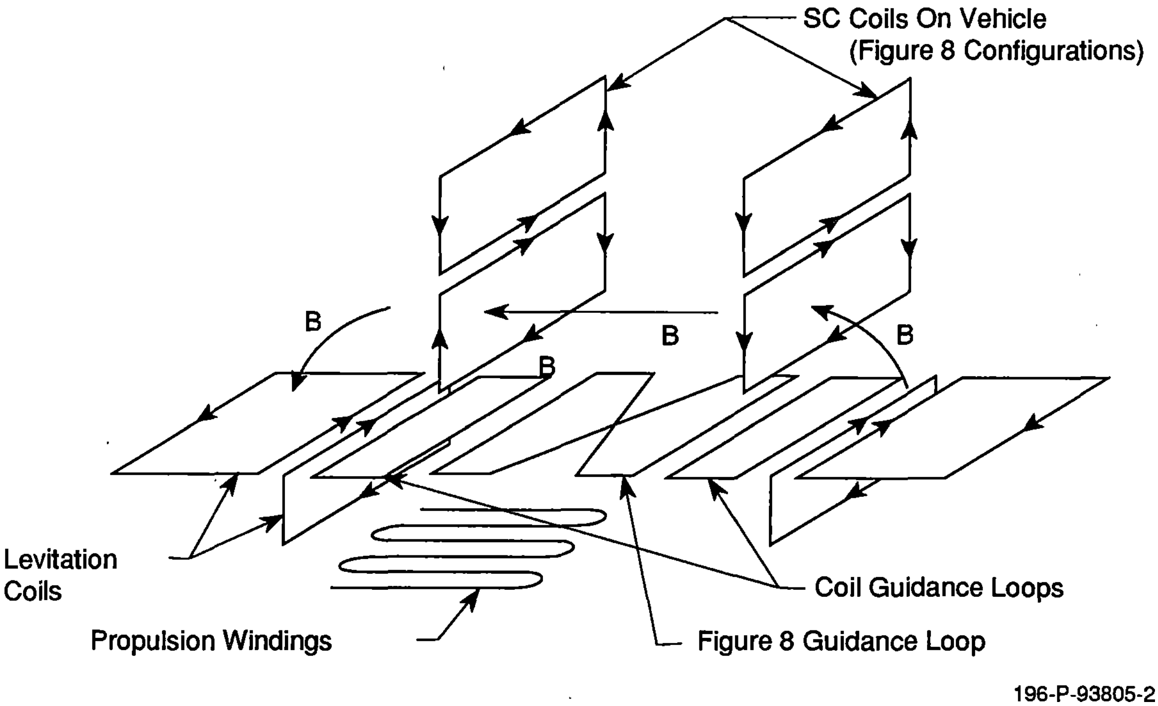


Figure 30. Switched Passive Coil Levitation and Guidance Configuration of a Flat Switching Section for the MIT/Bechtel Magnet Configuration

In order to determine the feasibility of such a levitation scheme, an approximate analysis was done on the levitation capacity of such a system. For the configuration and dimensions shown in Figure 31, an analysis based on two-dimensional geometry was performed to investigate the ability of such a configuration to generate adequate lift and centering force for lateral guidance.

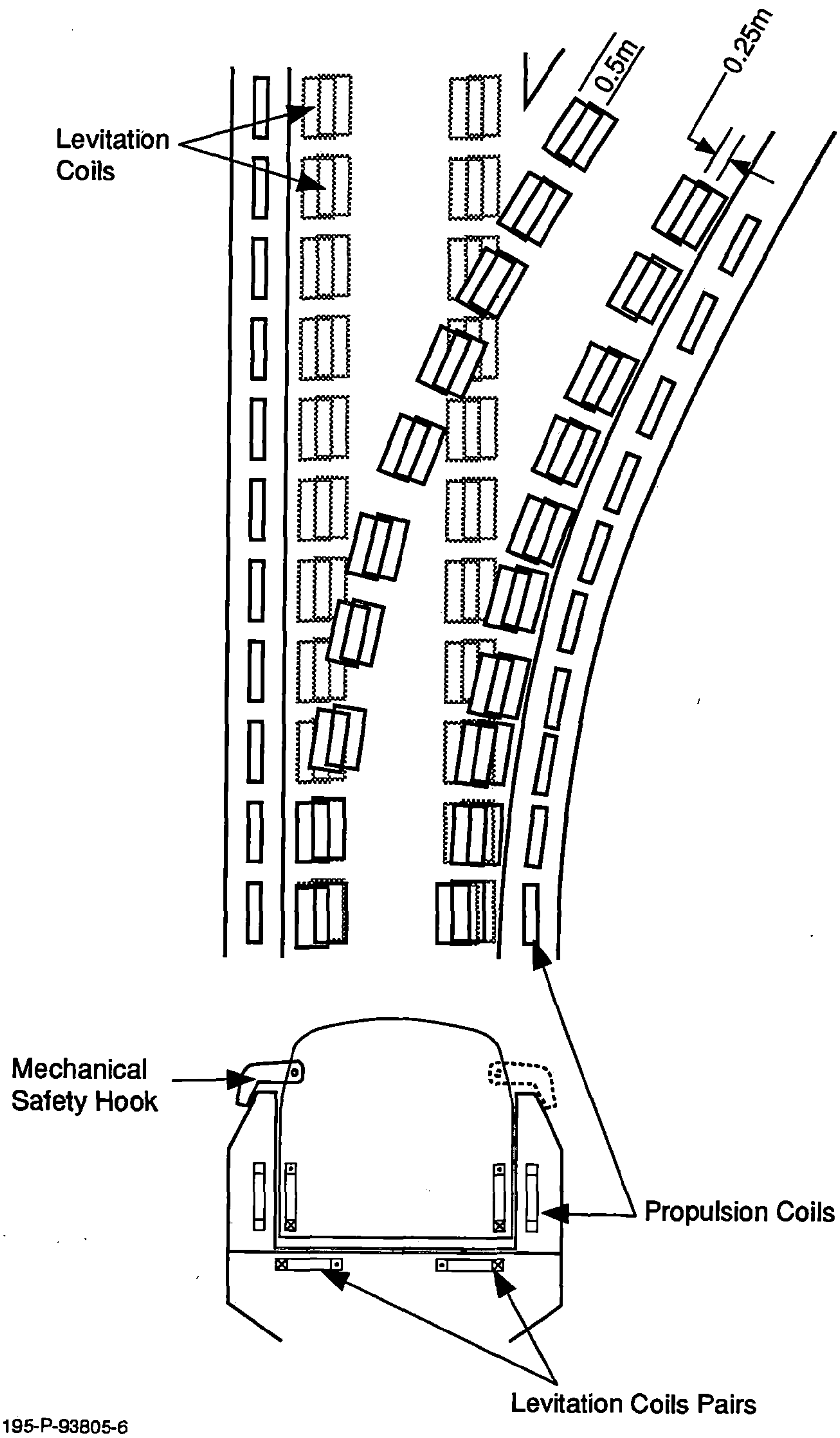
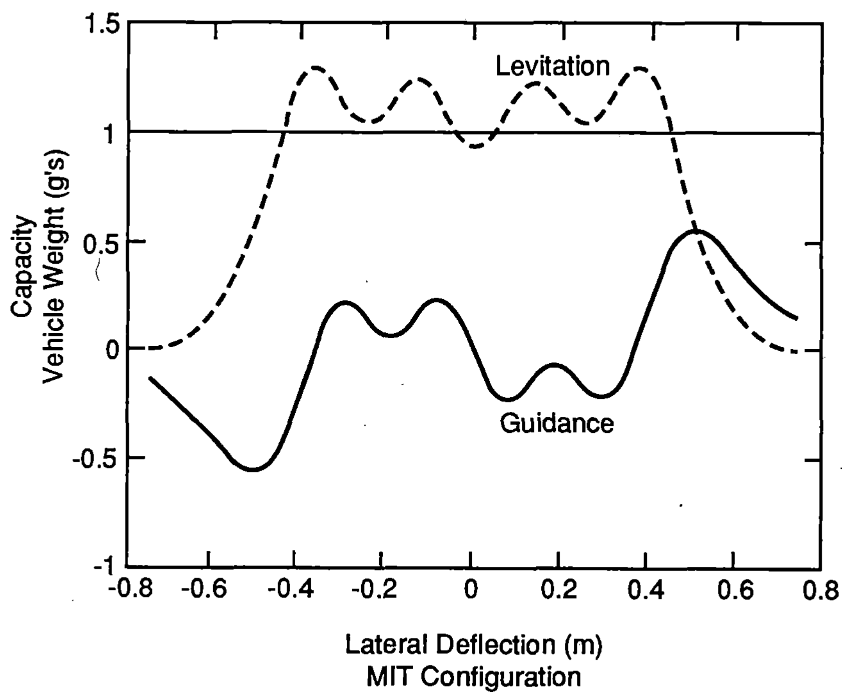


Figure 31. Geometry Used to Calculate the Levitation and Guidance Capacity of a Passive Ground Coil Switch for the MIT/Bechtel System

Results of the analysis are shown in Figure 32. The 20 cm center to center gap is marginal for a real system and the two dimensional analysis over predicts the force since the actual 3-D field values are lower. The levitation performance is poor primarily because the superconducting magnet has a very low 400 Kamp turn specification. Figure 33 shows the results when the superconducting magnets are operated at 1Mamp-turns. This provides adequate levitation. If the higher amp-turn superconducting magnet is used, it appears that this concept is practical from a levitation force capacity standpoint. The issues that need to be investigated to determine the feasibility of the system are: levitation, roll stiffness, guidance stiffness, magnetic drag, and propulsion requirements. Documentation of levitation and guideance calculation for this and other systems is included in Appendix B



Amp turns on Superconductor $Isc = 4 \cdot 10^5 \cdot amp$

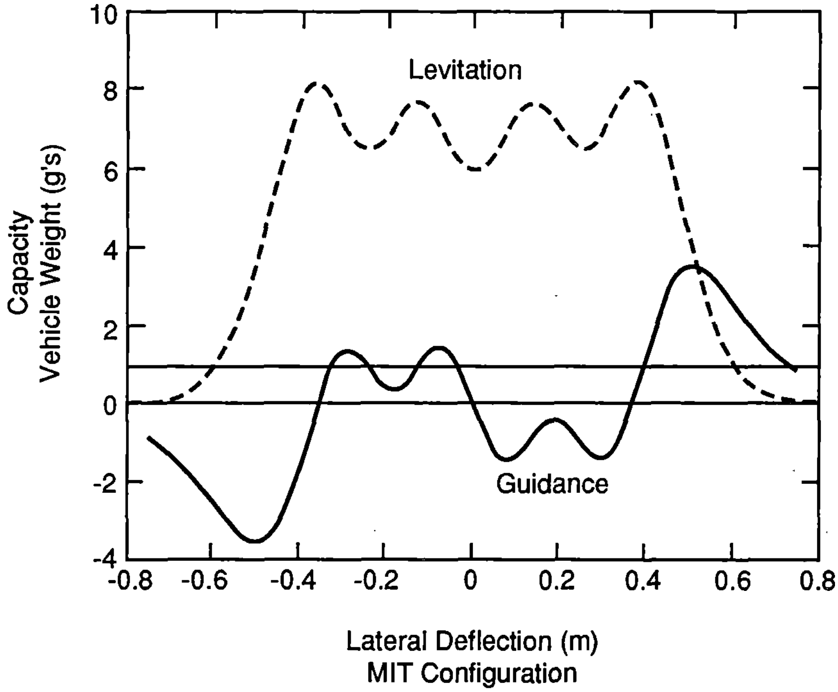
Vehicle Weight per meter $WPM = 1.771 \cdot 10^4 \cdot \frac{N}{m}$

Levitation height h = 0.2m

Coils: 0.5m wide
0.25 m Center to Center Spacing

213-DOT-9711-2

Figure 32. Calculated Levitation and Guidance Forces for 400 Kilo amp-Turn Magnets for MIT/Bechtel System



Amp turns on Superconductor Isc = $1 \cdot 10^6 \cdot$ amp

Vehicle Weight per meter WPM = $1.771 \cdot 10^4 \cdot \frac{N}{m}$

Levitation height h = 0.2m

Coils: 0.5m wide
0.25 m Center to Center Spacing

213-DOT-9711-3

Figure 33. Calculated Levitation and Guidance Forces for 1 Mega amp-Turn Magnets for MIT/Bechtel System

An approach that requires even more modification of the vehicle is shown in Figure 34. This configuration requires thinning the structure on the outside of the superconductors and eliminating the components in that area so that the vehicle magnetic fields are accessible from both the inside and outside. This allows the vehicle to be supported by either or both the inside and outside surfaces as required to pass through the switch in a manner similar to that described for other slotted guideway systems such as shown in Figure 18 . Obtaining adequate levitation and guidance with such a large gap is not feasible however, so this is not a workable system without the addition of switched ground coils for added levitation and guidance.

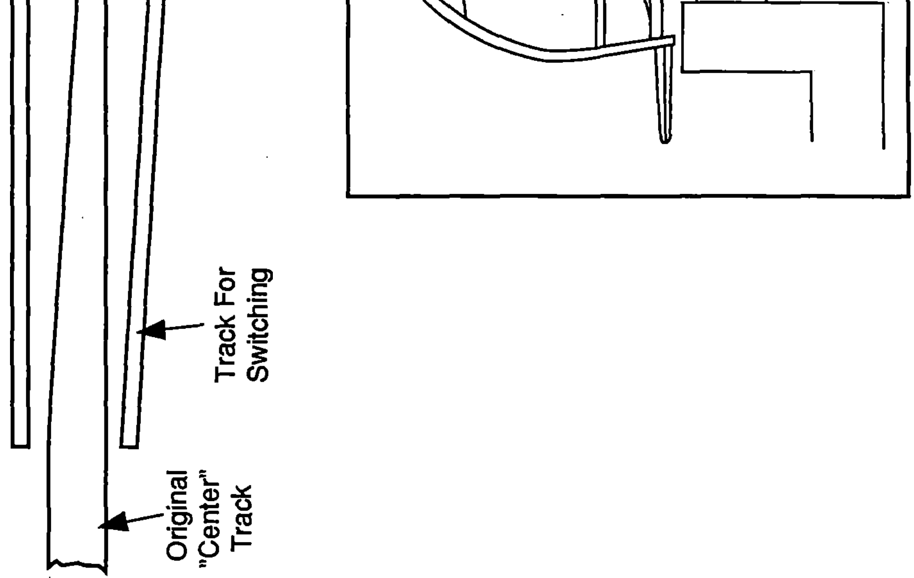
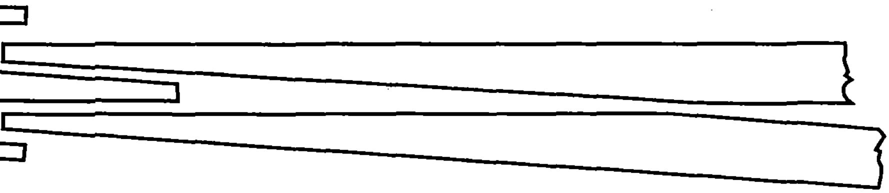
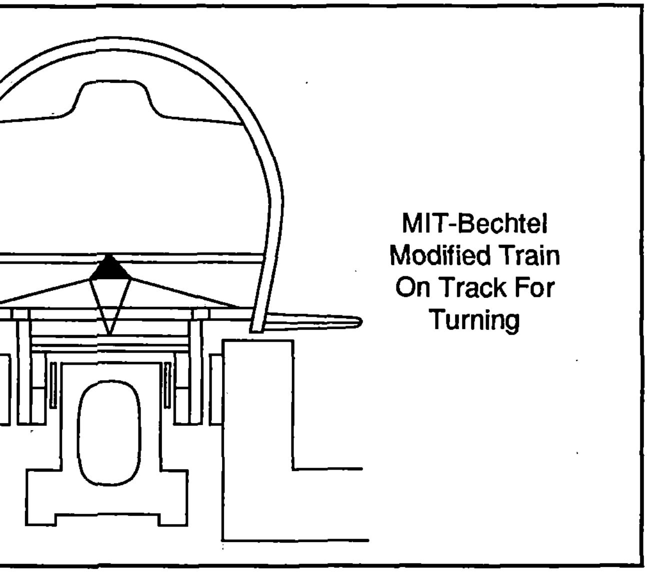


Figure 34. Slotted Guideway for M.I.T./Bechtel System (Not Effective)





MIT-Bechtel Modified Train On Track For Turning

195-P-93805-11

2.4.3.3. Flat sheet guideway switches for the MIT/Bechtel system (and other EDS systems)

The modified MIT/Bechtel system, like the Foster-Miller system and the Magneplane system, has large external magnetic fields to provide repulsive levitation and guidance on a sheet guideway. Levitation magnets on the bottom sides of the bogies act on a sheet guideway and magnets in the center of the vehicle provide the magnetic field for vehicle propulsion. One such configuration is shown in Figure 35. The flat sheet allows the vehicle to move to the right or left. Coils in the sidewall force the vehicle to move along the selected wall. The difficulty with this switch is controlling the position of the vehicle where the guideway is wide. Figure 36 shows the arched sheet which utilizes gravity to aid in directing the vehicle in a banked lateral switch. The initial selection of the right or left path is made by electrically switchable passive coils in the sidewall which repel the vehicle towards the other side of the guideway. This system will work for the modified MIT/Bechtel and Foster-Miller systems. For the Magneplane system the curvature of the bottom of the vehicle may cause roll stability problems. Appendix C contains some of the switch concepts that are not included in the body of the text. Switches similar to these have been presented in various references and are not analyzed in detail here.

Figure 35. Flat Sheet Guideway

2.4.3.4. Vertical switching for the MIT/Bechtel system

The most extreme modification to the MIT/Bechtel system is also the approach most suited to switching. The best switching configuration for this system is obtained by moving the magnets to the edge of the vehicle so that either an internal box beam or external open bottom guideway with sidewall levitation can be used. Then a vertical switch is feasible. Although this requires substantial modification, there are many benifits of this configuration since it provides vertical switching with very little change in levitation or propulsion response and may actually reduce the frontal area of the vehicle.

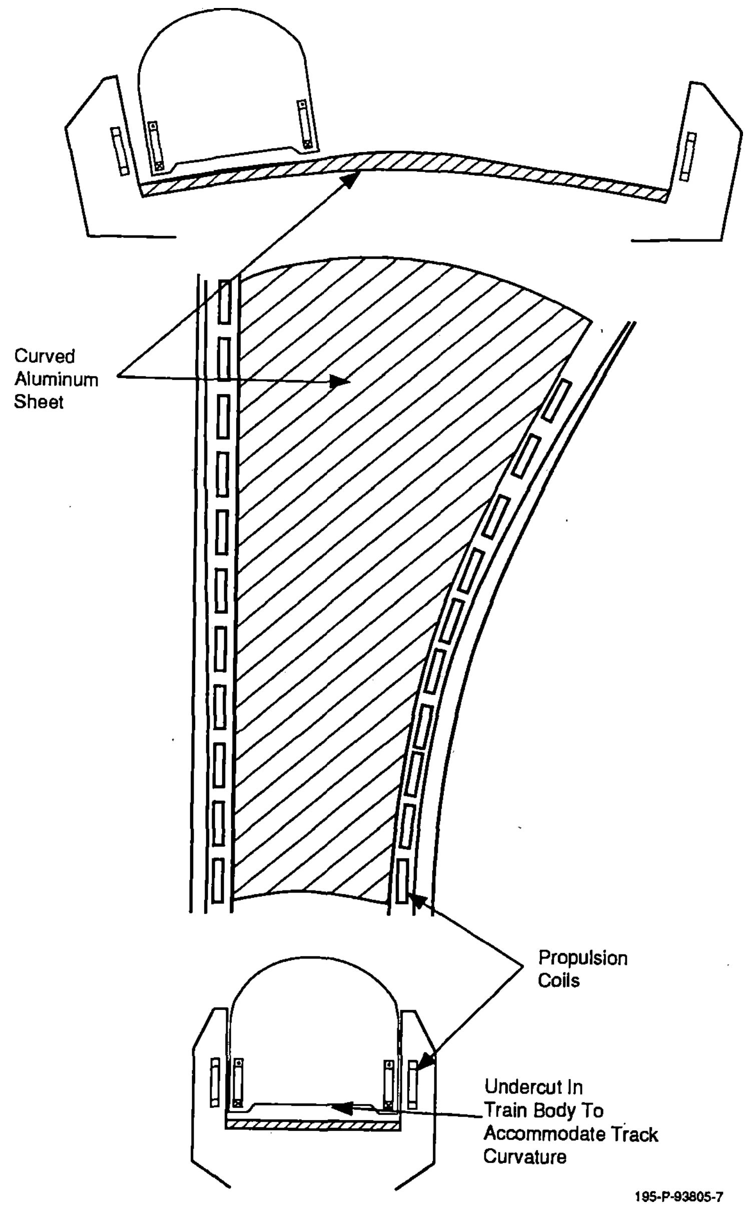


Figure 36. Arched Sheet Guideway (Foster-Miller Configuration Shown)

2.4.3.5. High Speed Switches for the Magneplane Trough Shaped Guideway Configuration

Many flat switch configurations similar to that shown for the MIT/Bechtel system in Figure 30 may be feasible for the Magneplane system, but a new vertical switch arrangement is described in this section. There are roll stability issues associated with the magnet configuration of the Magneplane vehicle in the flat lateral switches. Rather than investigate a number of schemes for producing a stable and propelled lateral switch configuration, a vertical switch that utilizes many of the features of the Foster-Miller system is developed. This results in a Magneplane concept with the benefits of vertical switching. Figure 37 shows a cross section of the key components for a vertical switch for the Magneplane system based on null-flux levitation from the sidewall. Figure 38 shows a sketch of the side view of the system. Operation is similar to that of the Foster-Miller vertical switch arrangement described at the beginning of Section 3.

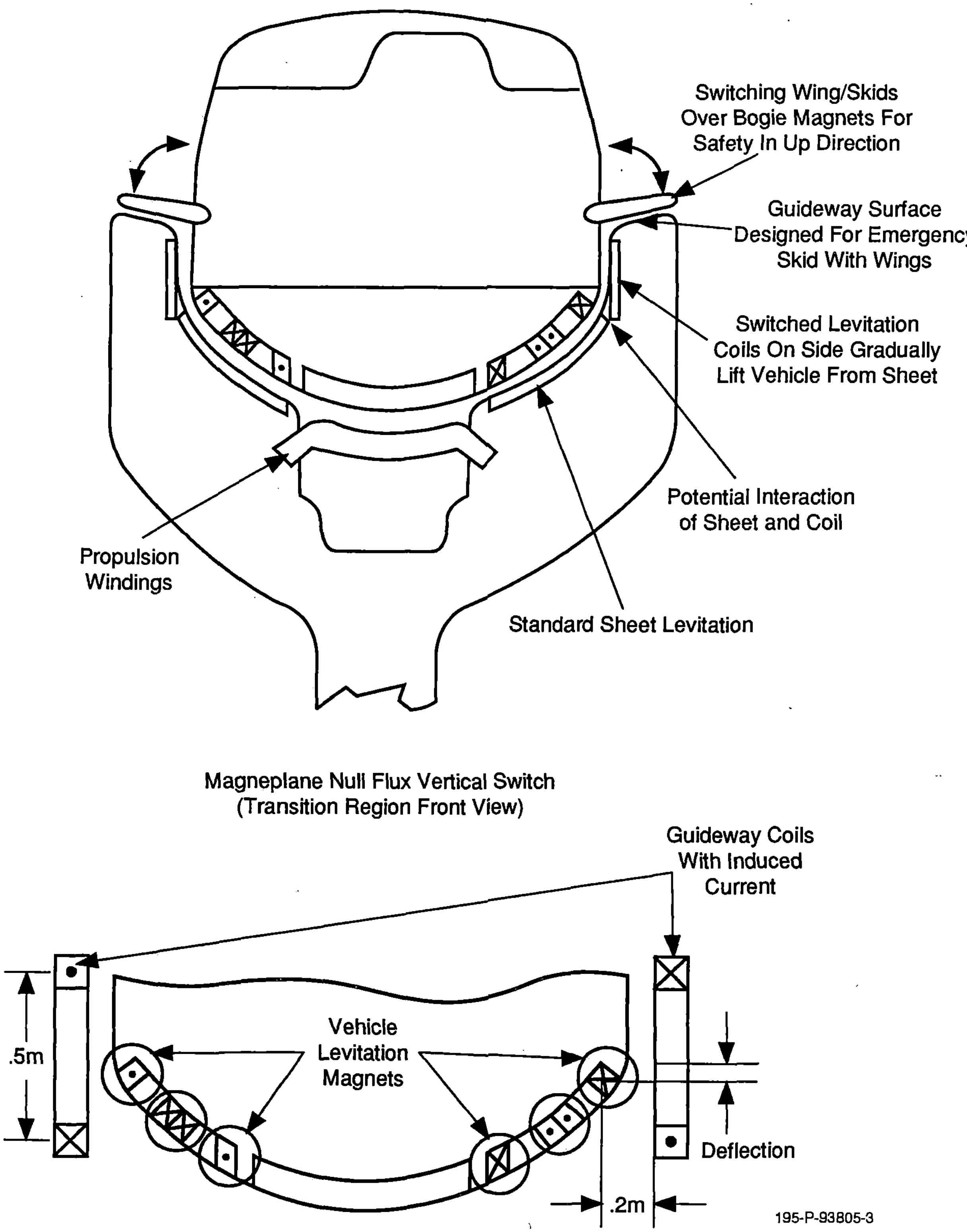


Figure 37. Vertical Switch for the Magneplane Configuration

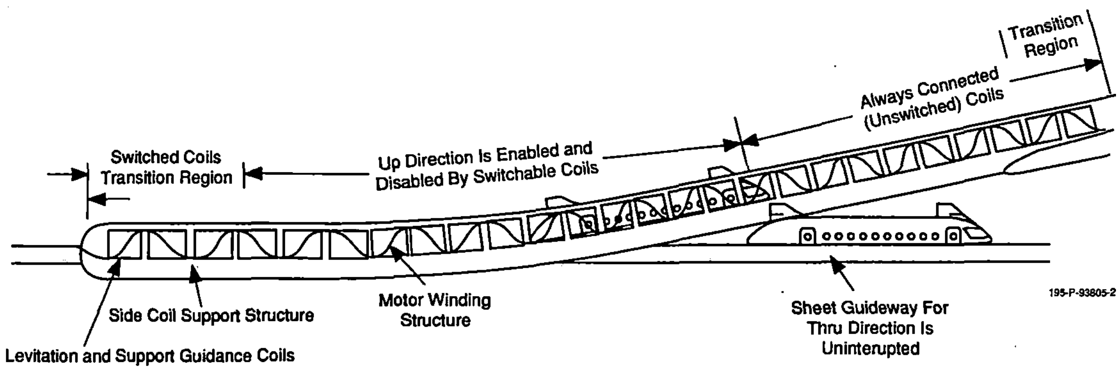


Figure 38. Magneplane Null-Flux Vertical Switch (Side View with Vertical Scale Greatly Expanded)

The vehicle passing straight through the switch on the lower guideway does not feel any effect from the sidewall coils because they are switched off (open circuit). When the coils are switched on a current is induced in the coils that produces levitation and guidance forces. Figure 39 shows a superposition of the calculated vertical and lateral coil force per meter as a function of vertical displacement. A downwards displacement of the vehicle is considered a negative displacement over the range of vertical displacements for the configurations shown in Figure 37. The region of potentially stable lateral and vertical levitation is boxed, and the operating point for a typical vehicle is starred. The centering force as a function of lateral displacement for vertical offsets in the operating range is shown in Figure 40. (Note that these calculations and many others shown are based on position and not a one g levitation. This is adequate for determining the feasibility of the approaches). Safety features are similar to those of the Foster-Miller vertical switch. The characteristics of this parameter null-flux system of levitation and guidance are not expected to match the system's sheet guideway, but the pickup and set down can probably be made smoothly by starting the coils at a wide gap and tapering the entry section of the switch so that the lift from the null-flux coils picks the vehicle up gradually.

2.4.3.6. Summary of the Magneplane configuration

Like the Foster-Miller system, the Magneplane concept has large external fields and is a relatively easily switched system. The concept described is not necessarily the best but serves to illustrate the flexibility available at the concept stages. Many switch concepts have been generated for the Foster-Miller, Magneplane, and modified MIT/Bechtel systems. These systems utilize high magnetic fields which allows large gaps and a variety of stable passive electrodynamic switch configurations.

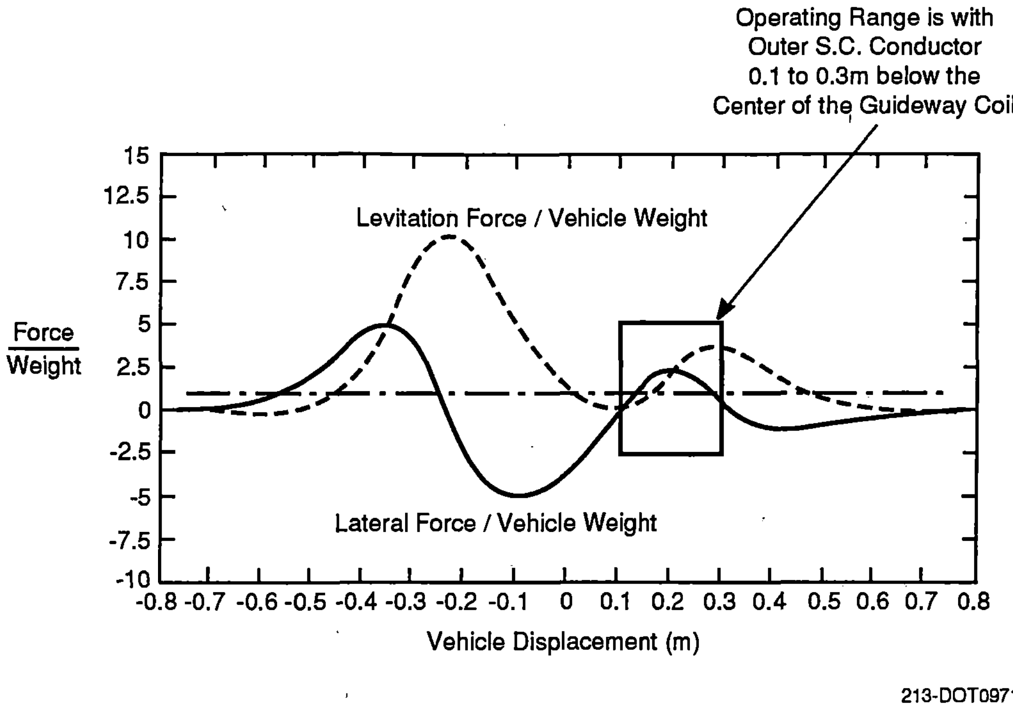


Figure 39. Force as a Function of Displacement on a Single Side of the Vertically Switched Magneplane. Results Used to Determine Stable Operating Configurations

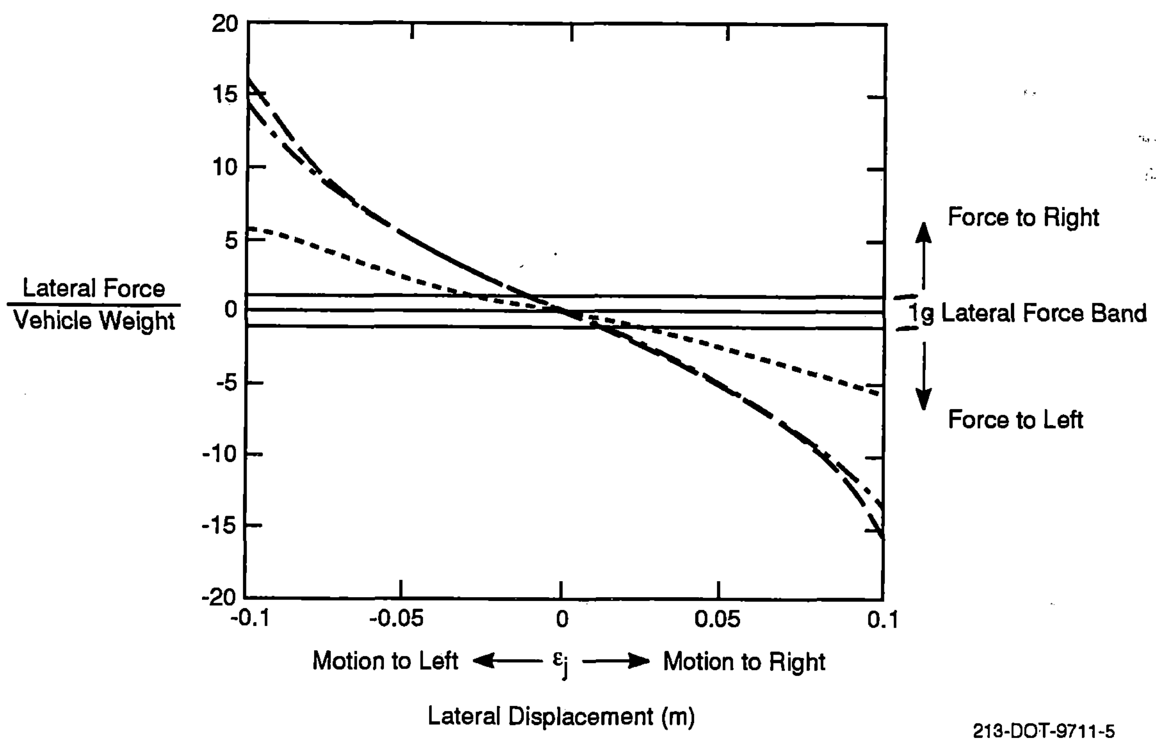


Figure 40. Stabilizing Lateral Force as a Function of Lateral Displacement for the Vertically Switched Magneplane Used to Determine the Stable Operating Configurations

2.5. Compatibility of Switch Designs with System Configurations

2.5.1. Summary and Brief Description of the Basic Switch Types

Most switch concepts can be characterized by a few basic approaches which are summarized below.

Roof switch -- The roof switch is based on a steel insert on the roof of the vehicle that is attracted to an EMS levitation system with most of the active parts located in the guideway. For vehicles that wrap the guideway vehicle is levitated by the roof, the normal guideway is cut off, and the vehicle is switched laterally by overlapping coils in the guideway levitation system to the appropriate guideway. For vehicles that do not wrap the guideway (all of the EDS systems) the normal guideway can be the lower path and the switch can operate as a vertical switch. The roof switch is a very flexible design; however, it has a large impact on the vehicle design.

Vertical Switch -- The vertical switch uses sidewall levitation, guidance, and propulsion based on switchable coils in the guideway to support the vehicle as it travels over the upper section of a switch. The lower section can be traversed by whatever normal levitation system is used.

Flat Guideway with Switched Coils -- For this system the vehicles are levitated by repulsive forces generated by ground coils combined with null flux guidance. Overlapping switched coils control the vehicle path.

Flat Guideway with Powered Coils -- Passive sheets or coils are mounted on the underside of the vehicle and powered ground coils are located on a flat guideway section. The powered ground coils levitate the vehicle by repulsion. By using an AC excitation of the guideway low speed levitation is possible; however, the power cost is high.

Slotted guideway with powered coils -- Similar to the Flat Guideway with Powered Coils except normal levitation is used wherever possible and only the places where the guideway must be cut away for clearance utilize the repulsive powered guideway coils acting on conductors in the vehicle.

Slotted Guideway with Modified Vehicle Attractive System -- For electromagnetic systems the vehicle is reconfigured to provide levitation on either an inner or outer guideway. Slots are cut to provide different path possibilities and the direction is controlled by proper control of the operation of the vehicle magnets.

Slotted with Modified Attractive Guideway -- In this case a simple steel ledge is added to the outside of the vehicle and an actively controlled guideway is used to levitate those portions of the vehicle not supportable by normal means.

Repulsive Keel with Powered Guideway -- Repulsive levitation is provided primarily at the center of the vehicle instead of the sides.

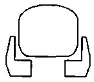
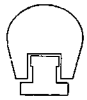
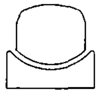
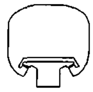
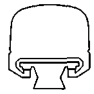
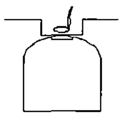
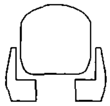
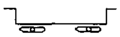
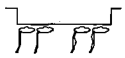
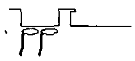
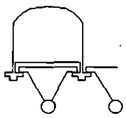
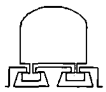
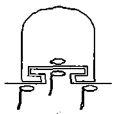
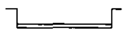
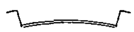
Flat Sheet -- An EDS system where the vehicle is driven towards one side or the other of a flat switching section by repulsion from the sidewalls. Similar the flat guideway with switched coils.

Arched Sheet -- Another EDS system except that once the initial push to one side or the other is given, gravity aids in holding the vehicle to one side or the other. This switch idea can provide coordinated turnouts since banking is inherent in its operation.

2.5.2. Compatibility Summary Chart

The suitability of the basic switch configurations to each system concept are summarized in Table 3.

Table 3. Switch Compatibility Matrix

Switch Concepts	Configuration Compatibility Chart	 FMI	 MIT	 Magnepln	 Grumman	 Transrapid
	Roof Switch	√	√	√	√	√
	FMI Vertical Switch	√	Modify Vehicle	√		
	Flat Guideway with Switched Coils	√	Modify Vehicle	√		
	Flat Guideway with Powered Coils	√	√	√	√	√
	Slotted Guideway with Powered Coils		√		√	√
	Slotted Guideway with Modified Vehicle Attractive System				Modify Vehicle	Modify Vehicle
	Slotted with Modified Attractive Guideway				Modify Vehicle	Modify Vehicle
	Repulsive Keel Powered Guideway		√		√	√
	Flat Sheet	√	Modify Vehicle	√		
	Arched Sheet	√	Modify Vehicle	√		

2.6. Selection of the Best Switch Types for Each System Configuration

2.6.1. Major Criteria For Switch Concept Selection

GENERAL CRITERIA	SPECIFIC CASE	DEFINITION OF THE CRITERIA
Speed	max.	Is the upper speed capability limited
	min.	Is the low speed capability limited
Susceptibility interference	snow /ice	Is the design resistant to interference from snow and ice
	debris	Is the design resistant to interference from branches, etc.
Cost	guideway	Cost associated with guideway structure in switch region
	land	Cost associated with land required to implement switch
	vehicle	Increased cost associated with vehicle to match switch
	power	Increased power costs due to switch
	electronics	Increased electronics cost due to switch
Ride Comfort	coordinated turns	Is motion similar to aircraft
	stiffness, suspen.	Is levitation and guidance stiffness the same in the switch
	uses secondary	Is the same secondary suspension used in the switch
	propulsion	Is propulsion practical in the switch
	propulsion type	What type of propulsion modes are feasible
Comfort in Transitions	entry	Is entry into the switch liable to cause a bump
	switch	Is the switch section itself likely to have a degraded ride
	exit	Is returning to the guideway likely to cause a bump
Related performance factors		
VEHICLE impact	frontal area (drag)	Do vehicle modifications related to switching increase drag
	max. width	Is the width increased or restricted
	weight	Is the weight of the vehicle increased substantially
	interior space used	Is space taken from the passenger region of the vehicle
	extra power used	Is more onboard power required
	complexity	Is the complexity increased
	ease of maintenance	Are vehicle components more difficult to maintain
	vehicle cost	Are modifications required for switching expensive
	noise	Are modifications likely to increase operating noise levels
SYSTEM impact	right of way	Is a large right of way required for the switch
	speed	Does the switch reconfigure quickly/provide continuos op.
	reliability	Is the switch inherently reliable
	maintenance	Will maintenance intervals be high
	spacing of next switch	Can switches be closely spaced to provide a multiple branch capability in a smaller space
	branch number	How many branches can be made in one switch region
	cost	What is the switch impact on the system cost
SAFETY		
normal operation	wind	Is the design sensitive to cross-winds
	high speed	Is the switch safe at high speed
	low speed	Is the switch safe at low speeds
emergencies	power loss	Is the switch safe if propulsion power levels are lost
	levitation capacity	Is there excess levitation capacity
	braking surfaces	Is there a substantial and suitable braking surface
failure modes		Are there many possible dangerous failure modes
restarting after a problem		Is it difficult to restart if the vehicle stops in the switch

2.6.2. Tradeoff Analysis

Pugh charts were used to determine the best switch concept for each of the system configurations. The basis of this technique is that all comparisons are based on a one to one comparison with a single concept which serves as the datum. The basis of this approach is a same, better, or worse comparison for each switch concept with the datum switch concept for each criteria. The net number of plusses, minuses, and sames can be compared to determine the best configuration; however, this does not account for the fact that some factors may be more important than others. A better approach is to look at the most important criteria in particular and select the best switch primarily on this basis. This approach often leads to ways to incorporate some of the best features of each design where possible. The Pugh chart analysis was done for the applicable switches for each system configuration. In this case the roof switch was used as a datum since it can be used for any configuration and provides a consistent basis of comparison.

Two versions of the charts are presented. The charts for the full list of criteria are presented in detail in Appendix D. Charts including only the most important criteria are presented here. The MIT/Bechtel Pugh chart, Table 4, shows that the best switch is the vertical switch with the vehicle reconfigured. This switch configuration provides the best emergency performance and ride quality. There are no disadvantages among the major performance criteria to the vertical switch configuration for the MIT/Bechtel system.

Table 4. Critical Criteria Pugh Chart for MIT/Bechtel Configuration

For the Bechtel MIT Syste	DATUM =	flat	arched	roof	switched	switched	vertical	powered	powered
	roof mounted	sheet	sheet	mounted	guideway	guideway	switch	guideway	guideway
	switch			switch	flat	slotted		flat ac	slotted ac
Criteria		MOD	MOD	powered r	MOD	MOD	MOD	STOCK	STOCK
		comp	comp	comp	comp	comp	comp	comp	comp
Susceptability interference		-	-	vehicle	-	-	+	-	-
Cost	guideway	+	+	reasonabl	+	+	+	s	s
	land	s	s	lateral	s	s	+	s	s
	vehicle	+	+	moderate	+	+	+	+	+
	stiffness, suspen.	-	-	controllabl	-	-	+	-	-
	uses secondary	+	+	no	+	+	+	+	+
	Propulsion	s	s	syncreluct	s	s	+	s	s
Transitions	entry	-	-	good	-	-	+	-	-
VEHICLE impact	Frontal area (drg)	s	s	small	s	s	s	s	s
	Weight	+	+	moderate	+	+	+	+	+
	complexity	+	+	od to hig	+	+	+	+	+
SYSTEM impact	Right of way	-	-	vertical	-	-	s	-	-
	reliability	+	+	moderate	+	+	+	s	s
	cost	+	+	moderate	+	+	+	-	-
emergencies	p power loss	+	+	eed backu	+	+	+	-	-
	braking surfaces	-	-	backups	-	s	+	-	s
comp	plusses	8	8	0	8	8	14	4	4
+	minusses	5	5	0	5	4	0	7	7
comp	sames	3	3	2	3	4	2	5	5

Table 5 is the Pugh chart for the Magneplane system and is very similar to the MIT/Bechtel system in that the vertical switch is superior. It was assumed that the sheet and switched coil guideway systems were stable for this configuration even though this may not be the case. Some of the sheet guideway type switches are well suited to this design provided that the design is stable in roll for these configurations. Because the vertical switch is better and appears to provide adequate and stable levitation and guidance, it is not necessary to analyze the performance of these other concepts in detail.

Table 5. Critical Criteria Pugh Chart for Magneplane Configuration

For the Magnaplane Syste	DATUM =	flat	arched	roof	switched	switched	vertical	powered	powered
	roof mounted	sheet	sheet	mounted	guideway	guideway	switch	guideway	guideway
	switch			switch	flat	slotted		flat ac	slotted ac
Criteria				powered r					
		comp	comp	comp	comp	comp	comp	comp	comp
Susceptability interference	snow /ice	-	-	vehicle	-	-	+	-	-
Cost	guideway	+	+	reasonabl	+	+	+	s	s
	land	s	s	lateral	s	s	+	s	s
	vehicle	+	+	moderate	+	+	+	+	+
	stiffness, suspen.	-	-	controllabl	-	-	+	s	s
	uses secondary	+	+	no	+	+	+	+	+
	Propulsion	s	s	syncreluct	s	s	+	s	s
Transitions	entry	s	s	good	s	s	+	-	-
VEHICLE impact	Frontal area (drg)	s	s	small	s	s	s	s	s
	Weight	+	+	moderate	+	+	+	+	+
	complexity	+	+	od to hig	+	+	+	+	+
SYSTEM impact	Right of way	-	-	vertical	-	-	s	-	-
	reliability	+	+	moderate	+	+	+	s	s
	cost	+	+	moderate	+	+	+	-	-
emergencies	p power loss	+	+	eed backu	+	+	+	-	-
	braking surfaces	+	+	backups	-	-	+	-	-
comp	plusses	9	9	0	8	8	14	4	4
+	minusses	3	3	0	4	4	0	6	6
comp	sames	4	4	2	4	4	2	6	6

The Transrapid and Grumman systems are included in the same chart, Table 6, since they are very similar at this level of analysis. In this case the modified double levitation switch in which outer magnets are mounted to the vehicle, as shown in Figure 21, has many advantages relative to the roof switch. However, the disadvantages of increased frontal area and similar or higher vehicle weight relative to the roof switch are important considerations. These factors may outweigh the advantages in a system analysis. The modified track levitation is similar to the roof mounted switch in that the guideway is active in attracting a steel ledge on the outside of the vehicle. The mass of the ledge itself is similar to that required for the roof switch. The major advantage is that the ledge can be mounted on the secondary suspension which may provide improved ride quality and reduce structural weight since the forces are applied to the vehicle structure in a normal manner. There is no need to build a strong structure into the roof to support the vehicle with these approaches. None of the concepts shown provide an overwhelmingly satisfactory switch. They are not well suited to switching due to the mechanical wrap of the vehicle around the guideway structure to provide a means of levitating the vehicle by attractive forces. One way around this difficulty is to make the baseline vehicle based on a roof mounted system; this would be a new configuration and is not a developed system configuration.

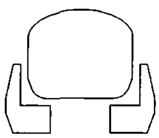
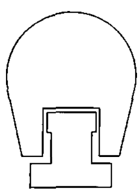
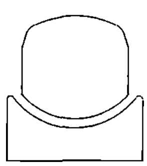
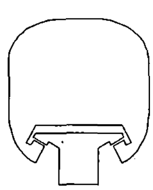
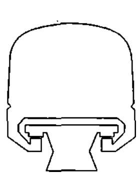
Although no good vertical switch configurations were developed for these configurations, a vertical switch can be developed for these systems by utilizing a combination of some of the switching concepts presented. For example, the powered guideway repelling sheets or coils on the vehicle can be combined with the roof mounted switch to produce a vertical switch. The powered guideway provides levitation when the vehicle takes the lower switch direction, and the roof switch picks up the vehicle and raises it vertically to a new guideway for the up switch direction. The active or passive outer ledge can replace the roof switch for lifting the vehicle in this application. The hybrid switch would have serious drawbacks in terms of generally having the flaws associated with the powered ground coil levitation system which is inherently different from normal operation since it is based on dynamic levitation. Even so this hybrid approach may provide the best solution in spite of the complexity involved if the right of way and other system performance issues are of overriding concern.

Table 6. Critical Criteria Pugh Chart for the Grumman and Transrapid Configurations

For the modified Grumman or the Transrapid	DATUM = roof mounted switch	powered guideway flat AC	powered guideway flat DC	powered guidewa slotted	roof mounted switch	modified double levitation	modified track levitation	repulsive keel	powered flat iron core	powered slotted iron core
Criteria		G	G	G	G	MG	G	G	G	G
		comp	comp	comp	comp	comp	comp	comp	comp	comp
Susceptability interference	snow /ice	-	-	-	vehicle	+	+	-	-	-
Cost	guideway	-	-	-	reasonabl	s	s	-	-	-
	land	s	s	s	lateral	s	s	s	s	s
	vehicle	+	+	+	moderate	s	-	-	-	+
	stiffness, suspen.	-	-	-	controllabl	+	s	-	-	-
	uses secondary	+	+	+	no	+	+	+	+	+
	Propulsion	-	-	-	syncreluct	+	s	-	-	-
Transitions	entry	-	-	-	good	+	s	-	-	-
VEHICLE impact	Frontal area (drg)	s	s	s	small	-	-	s	s	s
	Weight	+	+	+	moderate	s	+	+	+	+
	complexity	+	+	+	od to hig	+	+	+	+	+
SYSTEM impact	Right of way	s	s	s	lateral	s	s	s	s	s
	reliability/redunda	-	-	-	moderate	+	s	-	-	-
	cost	-	-	-	moderate	+	+	-	-	-
emergencies	p power loss	-	-	-	eed backu	+	s	-	-	-
	braking surfaces	-	-	-	backups	+	+	-	-	-
comp	plusses	4	4	4	0	10	6	3	3	3
+	minusses	9	9	9	0	1	2	10	10	10
comp	sames	3	3	3	2	5	8	3	3	3

Table 7 summarizes each system configuration, the key characteristics of each system, and the best switch concept for each configuration based on the trade off analysis.

Table 7. System configuration key characteristics and best switch concept

CONFIGURATION	SYSTEM CHARACTERISTICS	HIGH SPEED SWITCH OPTIONS
 FMI	<u>Advantages</u> Low frontal area & wetted surface High stiffness guideway <u>Disadvantages</u> Requires alternate levitation at low speed	1. Standard Operating Levitation & Guidance: vertical switch 2. Without Reconfiguring Vehicle: induced current switches 3. With Reconfiguration: roof switch 4. Best Switch: vertical with switched figure eight coil levitation provides standard operation throughout the switching operation
 MIT	<u>Advantages</u> Simple box beam guideway Aesthetic guideway <u>Disadvantages</u> High frontal area & wetted surface Requires modification for switching Requires alternate levitation at low speed	1. Standard Operating Levitation & Guidance: none 2. Without Reconfiguring Vehicle: lateral with powered ground coils 3. With Reconfiguration: Move magnets flush to the sides and use the null flux vertical switch. 4. Best Switch: Vertical switch based on switched null flux coils
 Magneplane	<u>Advantages</u> Low frontal area <u>Disadvantages</u> High magnetic drag Requires alternate levitation at low speed	1. Standard Operating Levitation & Guidance: lateral without propulsion 2. Without Reconfiguring Vehicle: lateral & vertical switching is possible 3. With Reconfiguration: not amenable to reconfiguration 4. Best Switch: Vertical switch, or flat sheet lateral switches
 Grumman	<u>Advantages</u> Levitated at all speeds with active suspension control and moderate gap <u>Disadvantages</u> AC superconductor High mass High frontal area & wetted surface Requires substantial modifications for normal mode switching	1. Using Standard Operating Levitation & Guidance: none 2. Without Reconfiguring Vehicle: powered ground coils 3. With Reconfiguration: reconfigure levitation and guidance with horizontal or slightly angled pole faces and add outer shoes 4. Best Switch: Reconfigured - dual shoe slotted lateral Not Reconfigured - powered guideway or roof switch
 Transrapid	<u>Advantages</u> Levitated at all speeds <u>Disadvantages</u> Small gap High mass High frontal area & wetted surface Requires modification for normal mode switch	1. Using Standard Operating Levitation & Guidance: none 2. Without Reconfiguring Vehicle: powered ground coils 3. With Reconfiguration: reconfigure levitation and guidance and add outer shoes 4. Best Switch: Reconfigured - dual shoe slotted lateral Not Reconfigured - powered guideway or roof switch

2.7. Summary of Technical Discussion

High speed switch concepts are described for all of the major system configurations. Of these, the best switch configurations for each system configuration are determined. Some vehicle/guideway/electromagnetic suspension configurations are well suited to safe, smooth, and cost effective high speed switching. Vertical switching provides the shortest switch length, least system cost, and most flexible configuration. Although concepts were generated for the EMS systems, the EMS systems are not as well suited to switching due to the mechanical constraints created by the vehicle wrapping around the guideway, the lack of a means of achieving a magnetic field across a large gap, and the poor shear capacity of EMS systems. Vertical switches for the EMS system require utilization of two different levitation and guidance systems. Reasonable modifications to the Magneplane and M.I.T./Bechtel configurations allow implementation of safe high speed vertical switches. The Foster-Miller configuration is naturally suited to high speed vertical switching with no changes in levitation, guidance, or propulsion.

Switch performance is critical to the success of a U.S. Maglev system. All of the system configurations are in the early development stage. Substantial modifications to system configurations to improve switching performance are warranted at this time.

3. CONCLUSIONS

Switching performance is critical to high speed Maglev system success. Major modifications to the proposed System Concept configurations are justified to provide electromagnetic high speed switches. The best switch configuration from a system flexibility and cost point of view is the vertical switch. The minimal additional structure, real estate, and reduced switch length of the vertical switch provide substantial advantages relative to lateral switch configurations.

The most easily adapted System Concept configuration for switching is the Foster-Miller system since it utilizes the vertical switch with no modifications or change in operation. With some modifications the MIT/Bechtel system provides vertical switch performance similar to Foster-Miller's. The Magneplane must change levitation characteristics from sheet guideway to null-flux levitation to utilize the vertical switch configuration developed here. This may impact ride quality adversely, but it is feasible to provide levitation, guidance, and propulsion for the Magneplane system in a vertical switch with minimal modifications to the vehicle. All of the EDS configurations can be configured to provide a high speed vertical switch because they can provide large external fields and are not mechanically constrained by encompassing the guideway.

The attractive electromagnetic suspension (EMS) systems are not well suited to vertical switching because the vehicle wraps around the guideway. Vertical switches for these systems require a combination of different levitation and guidance techniques. A roof mounted switch provides a consistent and flexible means for switching these configurations and is the only approach suitable for switching the Grumman system without substantial modification due to the steep angle of the pole faces. With substantial modification, the Grumman and Transrapid systems can be adapted to a slotted guideway type switch which utilizes the basic suspension system and secondary suspension so that ride quality can be maintained. The EMS configurations do not easily provide simple electromagnetic switches. Since they rely on a complex control system for levitation and guidance, a similar level of complexity is required in the switch.

4. RECOMMENDATIONS

High speed vehicle switching reduces overall system costs by improving usable guideway capacity, safety, and system flexibility. It is a requirement for a successful expandable Maglev system. Overall system safety, cost, maintenance, reliability, and expandability depend heavily upon the characteristics of the high speed switch. Further development, analysis, and evaluation of the system-wide impact of the best high speed switch configurations for each System Concept are recomended because high speed switching is a critical requirement for a successful and expandable Maglev system.

Switch concepts and safety systems must be refined. The effect of modifications to the vehicle and guideway on system performance and cost must be quantified. Analysis of the switch and system reliability must be performed. Failure modes and safety issues are of critical importance and need to be analyzed. This information will allow the impact of switches, which are a critical part of the system, to be accurately accounted for in the selection of the most suitable Maglev configuration.

5. REFERENCES

1. ***Compendium of Executive Summaries from the Maglev System Concept Definition Final Reports***, March 1993, DOT/FRA/NMI-93/02, Available Through the National Technical Information Service, Springfield, VA 22161.

2. ***Transrapid MagLev System***, Executive editors: Dr.-Ing. Klaus Heinrich, MVP Versuchs- Und Planungsgesellschaft für Magnetbahnsysteme mbH., and Dipl.-Ing. Rolf Kretzschmar, Transrapid International Gesellschaft für Magnetbahnsysteme, HESTRA-VERLAG Darmstadt.

APPENDIX A

Analysis of Guideway Path Constraints Due to Ride Quality Dynamic Limitations

A 1 Analysis Used to Determine Allowable Vehicle Trajectories in the Switch

For the small lateral displacements that occur during the initial few meters of lateral motion the normal acceleration vector does not change angle significantly. Therefore the effect of path curvature and the changing angle of the acceleration vectors can be ignored. A simple Cartesian frame with constant x-axis velocity and normal accelerations considered to occur only in the y or z-axis directions (lateral or vertical) is accurate for the conditions that occur during a switch.

The MathCad document used to calculate ride quality restrictions on the vehicle trajectory during switching follows for reference.

Look at the three g levels and the three basic switch modes. The basic assumption is that the lateral motion is small compared to the distance travelled and the speed is constant.

units: $m := 1L \quad s := 1T$

Set up the number of points to plot:

$M := 300 \quad i := 0..M \quad st := 3 \cdot s \quad t_i := \frac{st}{M} \cdot i$

Define velocity, 1g, etc.

$v := 134 \cdot \frac{m}{s} \qquad x_i := t_i \cdot v \qquad g := 9.81 \cdot \frac{m}{s^2}$

Set values for acceptable g levels, jerk, and roll rates:

parameter	design	min. req.	seat/belt
max bank angle	$mba_d := 24 \cdot \frac{\pi}{180}$	$mba_r := 30 \cdot \frac{\pi}{180}$	$mba_{sb} := 45 \cdot \frac{\pi}{180}$
roll rate	$rr_d := 5 \cdot \frac{\pi}{180 \cdot s}$	$rr_r := 5 \cdot \frac{\pi}{180 \cdot s}$	$rr_{sb} := 10 \cdot \frac{\pi}{180 \cdot s}$
roll acceleration alpha	$\alpha := 15 \cdot \frac{\pi}{180} \cdot \frac{1}{s^2}$	α is the same for all cases	
lateral acceleration	$la_d := .1 \cdot g$	$la_r := .16 \cdot g$	$la_{sb} := .2 \cdot g$
lateral jerk	$lj_d := .07 \cdot \frac{g}{s}$	$lj_r := .25 \cdot \frac{g}{s}$	$lj_{sb} := .25 \cdot \frac{g}{s}$
vertical acceleration (up)	$vau_d := .2 \cdot g$	$vau_r := .1 \cdot g$	$vau_{sb} := .1 \cdot g$
vertical acceleration (down)	$vad_d := .3 \cdot g$	$vad_r := .3 \cdot g$	$vad_{sb} := .4 \cdot g$
vertical jerk	$vj_d := .1 \cdot \frac{g}{s}$	$vj_r := .25 \cdot \frac{g}{s}$	$vj_{sb} := .3 \cdot \frac{g}{s}$

$\frac{vau_d}{vj_d} \cdot v = 268 \cdot m$

case1 pure lateral motion without roll

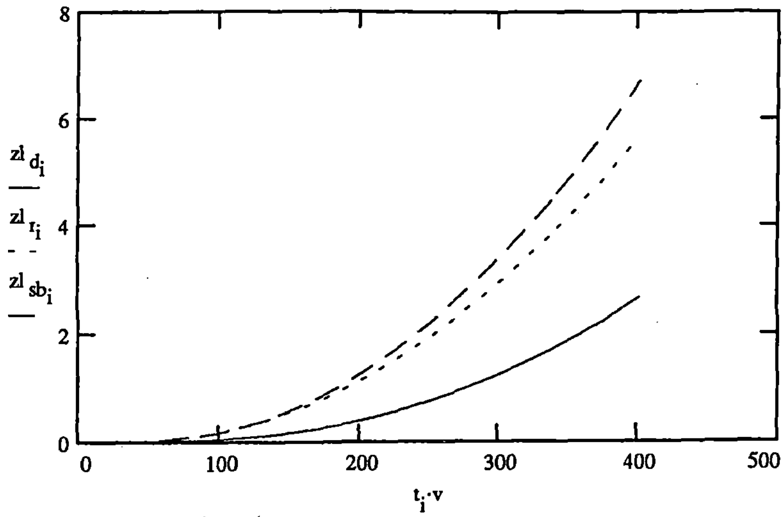
$$zl(t, tjerk, J, a) := \left[(t<tjerk) \cdot J \cdot \frac{(t)^3}{6} + (t \ge tjerk) \cdot \left[a \cdot \frac{(t - tjerk)^2}{2} + J \cdot \frac{(tjerk)^2}{2} \cdot (t - tjerk) + J \cdot \frac{(tjerk)^3}{6} \right] \right]$$

Set up the arrays of data for the different cases

for design $\quad zl_{d_i} := zl\left[t_i, \left(\frac{la_d}{lj_d} \right), lj_d, la_d \right]$

for min req $\quad zl_{r_i} := zl\left[t_i, \left(\frac{la_r}{lj_r} \right), lj_r, la_r \right]$

for seatbelt $\quad zl_{sb_i} := zl\left[t_i, \left(\frac{la_{sb}}{lj_{sb}} \right), lj_{sb}, la_{sb} \right]$



Case 2: Vertical switch. Again the limit is first set by jerk and then by acceleration

Same equation as for lateral motion applies which is function zl() and it is not copied here to avoid errors and redundancy.

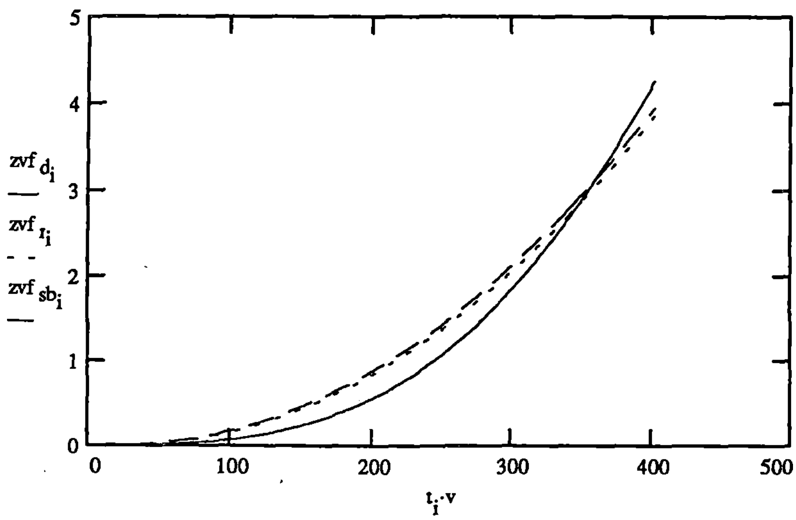
CASE2 a) switching with up values (which means going downwards!!!). I will call this falling

Set up the arrays of data for the different cases

for design $zvf_{d_i} := zl\left[t_i, \left(\frac{vau_d}{vj_d}\right), vj_d, vau_d\right]$

for min req $zvf_{r_i} := zl\left[t_i, \left(\frac{vau_r}{vj_r}\right), vj_r, vau_r\right]$

for seatbelt $zvf_{sb_i} := zl\left[t_i, \left(\frac{vau_{sb}}{vj_{sb}}\right), vj_{sb}, vau_{sb}\right]$



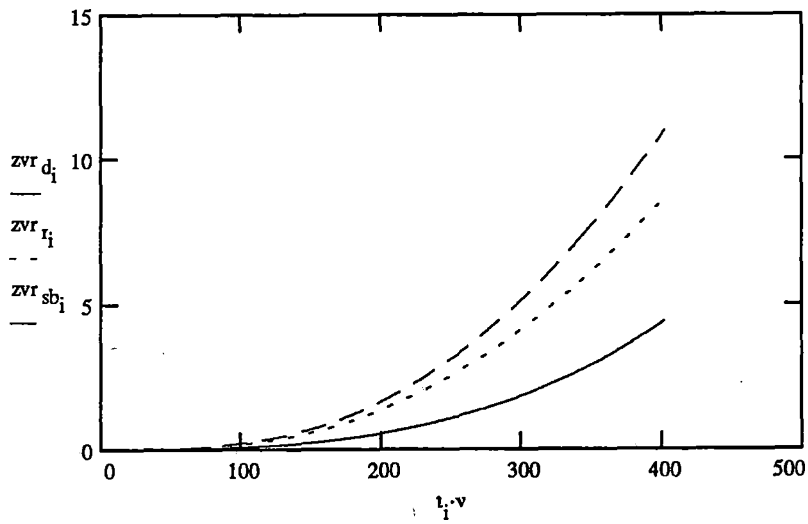
CASE2 b) switching with down values (which means going upwards!!!). I will call this rising.

Set up the arrays of data for the different cases

for design $zvr_{d_i} := zl\left[t_i, \left(\frac{vad_d}{vj_d}\right), vj_d, vad_d\right]$

for min req $zvr_{r_i} := zl\left[t_i, \left(\frac{vad_r}{vj_r}\right), vj_r, vad_r\right]$

for seatbelt $zvr_{sb_i} := zl\left[t_i, \left(\frac{vad_{sb}}{vj_{sb}}\right), vj_{sb}, vad_{sb}\right]$



Case 3. Rolling into a perfectly coordinated turn. This is taken from the old file (accel.mcd) and needs cleaning up and checking at some point. But I think it is right based on the fact that I probably checked it when I did it. It is confusing and need to be redone.

Case 3a. design values. $\omega := rr_d$

Roll accel considered

variable of convienience β

$$\beta := \frac{\alpha}{2}$$

tr is time required to reach roll rate limit.

$tr := \frac{\omega}{\alpha}$ $tr = 0.333 \cdot time$

q is pure roll accel

$$q_i := g \cdot \left[\beta \cdot \frac{(t_i)^4}{12} + \beta^3 \cdot \frac{(t_i)^8}{(21 \cdot 8)} + \beta^5 \cdot \frac{(t_i)^{12}}{(66 \cdot 15)}\right]$$

qr is dist at tr

$$qr := g \cdot \left[\beta \cdot \frac{(tr)^4}{12} + \beta^3 \cdot \frac{(tr)^8}{(21 \cdot 8)} + \beta^5 \cdot \frac{(tr)^{12}}{(66 \cdot 15)}\right]$$

$qr = 0.001 \cdot length$

Case 3a. max values. $\omega := rr_{sb}$

Roll accel considered

variable of convienience β

$$\beta := \frac{\alpha}{2}$$

tr is time required to reach roll rate limit.

$$tr := \frac{\omega}{\alpha} \qquad tr = 0.667 \cdot time$$

qdot is vel at tr

$$qdotr := g \cdot \left[\beta \cdot \frac{(tr)^3}{6} + \beta^3 \cdot \frac{(tr)^7}{(21)} + \beta^5 \cdot \frac{(tr)^{11}}{(11 \cdot 15)} \cdot 2 \right]$$

$$qdotr = 0.008 \cdot length \cdot time^{-1}$$

fdot is velocity at tr based on roll rate (actual solution)

$$fdot := -g \cdot \frac{(\ln(\cos(\omega \cdot tr)))}{\omega}$$

$$fdot = 0.048 \cdot length \cdot time^{-1}$$

$$K1 := fdot - qdotr \qquad K1 = 0.04 \cdot length \cdot time^{-1}$$

ytr is the postion from the roll equation at tr

$$T_i := \omega \cdot t_i$$

$$ytr := \left[\frac{g}{\left(\omega^2\right)} \right] \cdot \left[\frac{(tr \cdot \omega)^3}{6} + \frac{(tr \cdot \omega)^5}{60} + \frac{(tr \cdot \omega)^7}{315} + 17 \cdot \frac{(tr \cdot \omega)^9}{(9 \cdot 2520)} \right]$$

$$ytr = 0.005 \cdot length$$

$$K2 := qr - ytr - K1 \cdot tr \qquad K2 = -0.017 \cdot length$$

$$y_i := \left[\frac{g}{\left(\omega^2\right)} \right] \cdot \left[\frac{\left(T_i\right)^3}{6} + \frac{\left(T_i\right)^5}{60} + \frac{\left(T_i\right)^7}{315} + 17 \cdot \frac{\left(T_i\right)^9}{(9 \cdot 2520)} \right]$$

$$R(time) := \left[\frac{g}{\left(\omega^2\right)} \right] \cdot \left[\frac{(time \cdot \omega)^3}{6} + \frac{(time \cdot \omega)^5}{60} + \frac{(time \cdot \omega)^7}{315} + 17 \cdot \frac{(time \cdot \omega)^9}{(9 \cdot 2520)} \right]$$

alphaphi is roll accel solution

$$\alpha\phi(tr) := g \cdot \left[\beta \cdot \frac{(tr)^4}{12} + \beta^3 \cdot \frac{(tr)^8}{(21 \cdot 8)} + \beta^5 \cdot \frac{(tr)^{12}}{(66 \cdot 15)} \right] \qquad \alpha\phi(tr) = 0.001 \cdot length$$

Omega is the combined solution using singularity functions.

$$\Omega_i := \left(R\left(t_i\right) + K1\cdot t_i + K2\right)\cdot\left(t_i \geq tr\right) + \left(t_i < tr\right)\cdot\alpha\phi\left(t_i\right) \qquad \Omega_{100} = 0.165\cdot\text{length}$$

there were a bunch of graphs between these sections.

integral of tan(x)

$$I(x) := -\ln(\cos(x))$$

I2(t)

$$I2(t) := \frac{g}{\omega}\cdot I\left[\omega\cdot t - \frac{\omega^2}{(2\cdot\alpha)}\right]$$

integral of -ln(cos(s)) note s is going to be wt-w^/2a

$$II(s) := \left[\frac{g}{\left(\omega^2\right)}\right]\cdot\left[\frac{(s)^3}{6} + \frac{(s)^5}{60} + \frac{(s)^7}{315} + 17\cdot\frac{(s)^9}{(9\cdot 2520)}\right]$$

II2 use wt-w^2/2a

$$II2(t) := II\left[\omega\cdot t - \frac{\omega^2}{(2\cdot\alpha)}\right] \qquad II2(tr) = 6.606\cdot 10^{-4}\cdot\text{length}$$

integral of tan(at^2/2)

$$qdotr := g\cdot\left[\beta\cdot\frac{(tr)^3}{6} + \beta^3\cdot\frac{(tr)^7}{(21)} + \beta^5\cdot\frac{(tr)^{11}}{(11\cdot 15)}\cdot 2\right]$$

integral of integral of tan(at^2/2)

$$\alpha\phi(tr) := g\cdot\left[\beta\cdot\frac{(tr)^4}{12} + \beta^3\cdot\frac{(tr)^8}{(21\cdot 8)} + \beta^5\cdot\frac{(tr)^{12}}{(66\cdot 15)}\right]$$

temp function for t>tr

$$\psi(s) := (qdotr - I2(tr))\cdot s + II2(s) \qquad \psi(tr) = -6.605\cdot 10^{-4}\cdot\text{length}$$

constant of integration C

$$C := \alpha\phi(tr) - \psi(tr) \qquad C = 0.002\cdot\text{length}$$

Equation for t>tr

$$\Delta(t) := \psi(t) + C \qquad \Delta(tr) = 0.001\cdot\text{length}$$

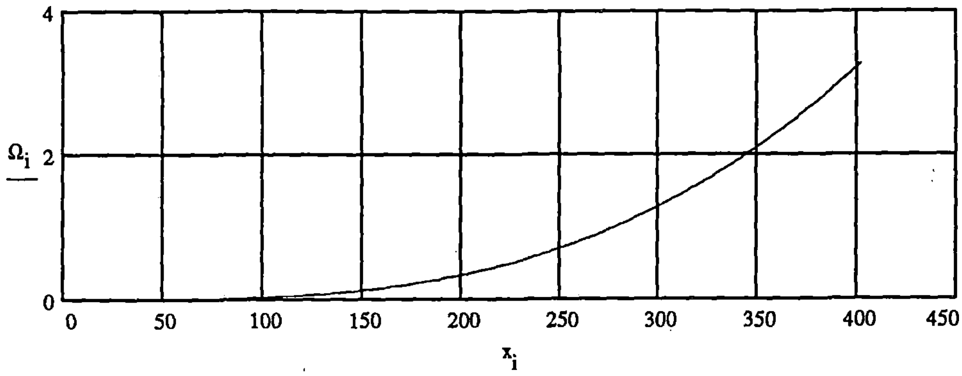
Equation for the whole curve

Omega is the combined solution using singularity functions.

$$\Omega_i := \Delta(t_i)\cdot(t_i \geq tr) + (t_i < tr)\cdot\alpha\phi(t_i)$$

$\Omega_{100} = 0.081\cdot\text{length}$

$Od_i := \Omega_i$



q is pure roll accel

$$q_i := g\cdot\left[\beta\cdot\frac{(t_i)^4}{12} + \beta^3\cdot\frac{(t_i)^8}{(21\cdot 8)} + \beta^5\cdot\frac{(t_i)^{12}}{(66\cdot 15)}\right]$$

qr is dist at tr

$$qr := g\cdot\left[\beta\cdot\frac{(tr)^4}{12} + \beta^3\cdot\frac{(tr)^8}{(21\cdot 8)} + \beta^5\cdot\frac{(tr)^{12}}{(66\cdot 15)}\right]$$

$qr = 0.021\cdot\text{length}$

qdot is vel at tr

$$qdotr := g\cdot\left[\beta\cdot\frac{(tr)^3}{6} + \beta^3\cdot\frac{(tr)^7}{(21)} + \beta^5\cdot\frac{(tr)^{11}}{(11\cdot 15)}\cdot 2\right]$$

$qdotr = 0.063\cdot\text{length}\cdot\text{time}^{-1}$

fdot is velocity at tr based on roll rate (actual solution)

$$fdot := -g\cdot\frac{(\ln(\cos(\omega\cdot tr)))}{\omega}$$

$fdot = 0.381\cdot\text{length}\cdot\text{time}^{-1}$

$K1 := fdot - qdotr$ $\quad$ $K1 = 0.318\cdot\text{length}\cdot\text{time}^{-1}$

ytr is the postion from the roll equation at tr

$T_i := \omega \cdot t_i$

$$ytr := \left[\frac{g}{(\omega^2)}\right] \cdot \left[\frac{(tr\cdot\omega)^3}{6} + \frac{(tr\cdot\omega)^5}{60} + \frac{(tr\cdot\omega)^7}{315} + 17\cdot\frac{(tr\cdot\omega)^9}{(9\cdot 2520)}\right]$$

$ytr = 0.085 \cdot length$

$K2 := qr - ytr - K1\cdot tr$ $\qquad K2 = -0.275 \cdot length$

$$y_i := \left[\frac{g}{(\omega^2)}\right] \cdot \left[\frac{(T_i)^3}{6} + \frac{(T_i)^5}{60} + \frac{(T_i)^7}{315} + 17\cdot\frac{(T_i)^9}{(9\cdot 2520)}\right]$$

$$R(time) := \left[\frac{g}{(\omega^2)}\right] \cdot \left[\frac{(time\cdot\omega)^3}{6} + \frac{(time\cdot\omega)^5}{60} + \frac{(time\cdot\omega)^7}{315} + 17\cdot\frac{(time\cdot\omega)^9}{(9\cdot 2520)}\right]$$

alphaphi is roll accel solution

$$\alpha\phi(tr) := g\cdot\left[\beta\cdot\frac{(tr)^4}{12} + \beta^3\cdot\frac{(tr)^8}{(21\cdot 8)} + \beta^5\cdot\frac{(tr)^{12}}{(66\cdot 15)}\right]$$

$\alpha\phi(tr) = 0.021 \cdot length$

Omega is the combined solution using singularity functions.

$$\Omega_i := \left(R(t_i) + K1\cdot t_i + K2\right)\cdot\left(t_i \ge tr\right) + \left(t_i < tr\right)\cdot\alpha\phi(t_i)$$

$\Omega_{100} = 0.329 \cdot length$

there were a bunch of graphs between these sections.

integral of tan(x)

$$I(x) := -\ln(\cos(x))$$

I2(t)

$$I2(t) := \frac{g}{\omega}\cdot I\left[\omega\cdot t - \frac{\omega^2}{(2\cdot\alpha)}\right]$$

integral of -ln(cos(s))   note s is going to be wt-w^/2a

$$\mathrm{II}(s) := \left[\frac{g}{\left(\omega^2\right)}\right]\cdot\left[\frac{(s)^3}{6}+\frac{(s)^5}{60}+\frac{(s)^7}{315}+17\cdot\frac{(s)^9}{(9\cdot 2520)}\right]$$

II2 use wt-w^2/2a

$$\mathrm{II2}(t) := \mathrm{II}\left[\omega\cdot t-\frac{\omega^2}{(2\cdot\alpha)}\right] \qquad \mathrm{II2}(tr) = 0.011\cdot\text{length}$$

integral of tan(at^2/2)

$$qdotr := g\cdot\left[\beta\cdot\frac{(tr)^3}{6}+\beta^3\cdot\frac{(tr)^7}{(21)}+\beta^5\cdot\frac{(tr)^{11}}{(11\cdot 15)}\cdot 2\right]$$

integral of integral of tan(at^2/2)

$$\alpha\phi(tr) := g\cdot\left[\beta\cdot\frac{(tr)^4}{12}+\beta^3\cdot\frac{(tr)^8}{(21\cdot 8)}+\beta^5\cdot\frac{(tr)^{12}}{(66\cdot 15)}\right]$$

temp function for t>tr

$$\psi(s) := (qdotr - \mathrm{I2}(tr))\cdot s+\mathrm{II2}(s) \qquad \psi(tr) = -0.011\cdot\text{length}$$

constant of integration C

$$C := \alpha\phi(tr) - \psi(tr) \qquad C = 0.032\cdot\text{length}$$

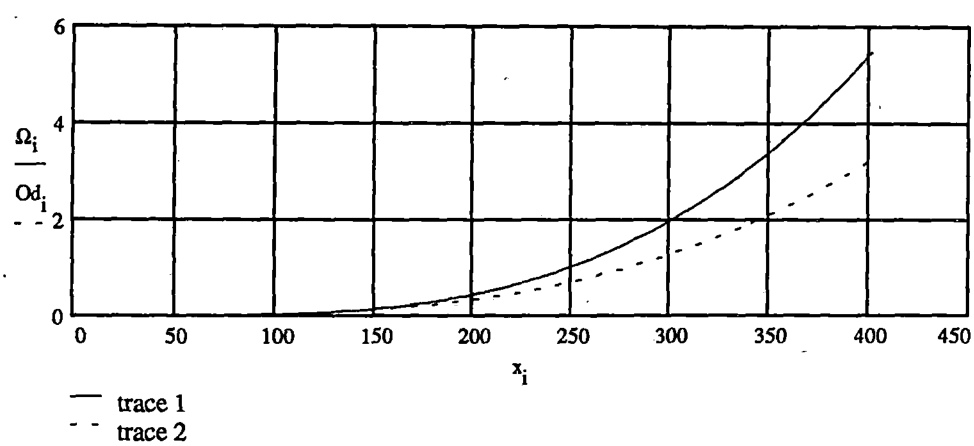
Equation for t>tr

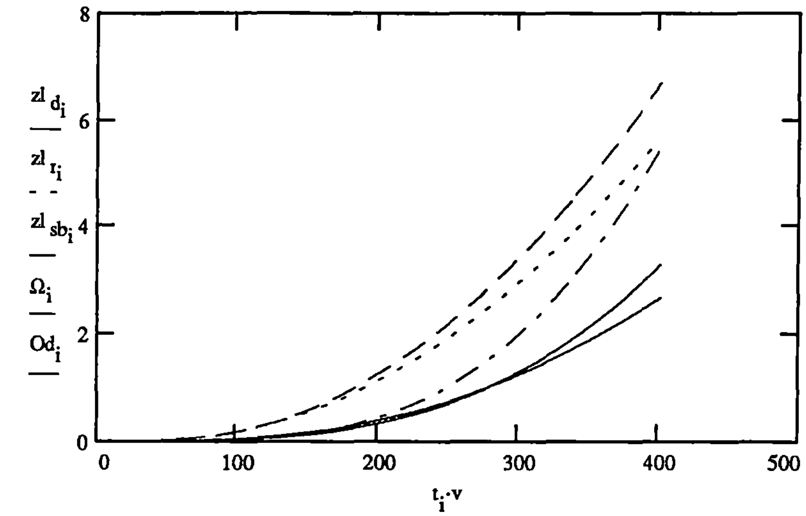
$$\Delta(t) := \psi(t) + C \qquad \Delta(tr) = 0.021\cdot\text{length}$$

Equation for the whole curve

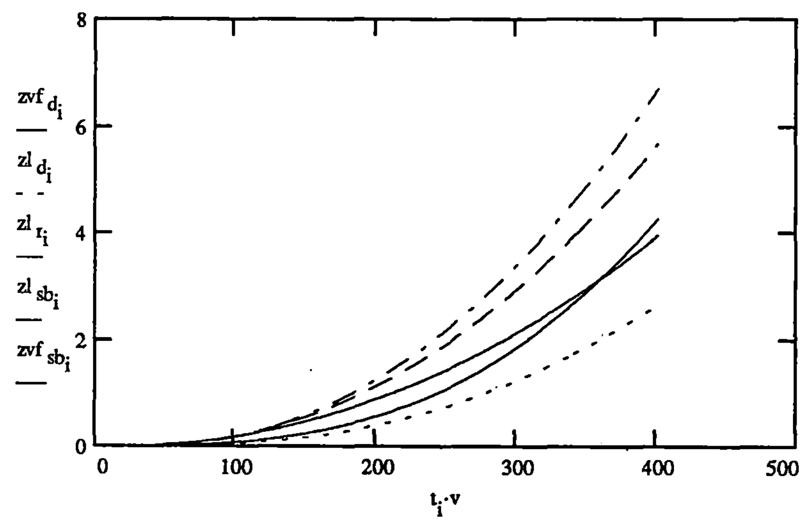
Omega is the combined solution using singularity functions.

$$\Omega_i := \Delta(t_i)\cdot(t_i \ge tr) + (t_i < tr)\cdot\alpha\phi(t_i) \qquad \Omega_{100} = 0.085\cdot\text{length}$$

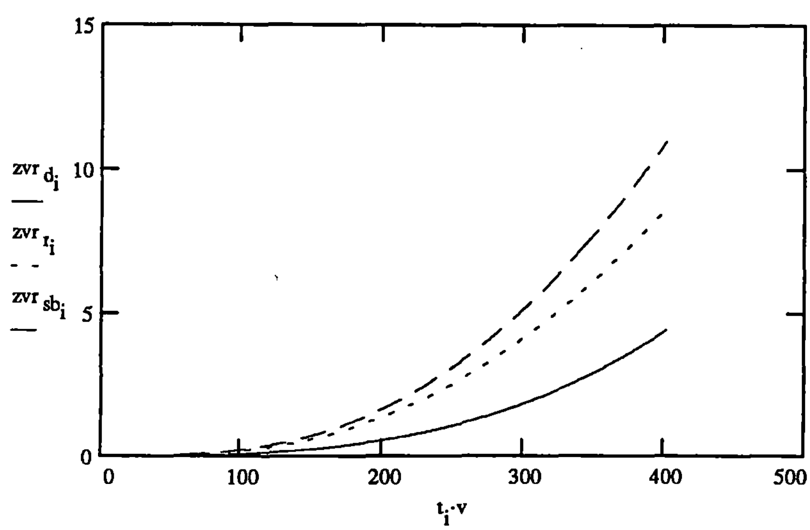




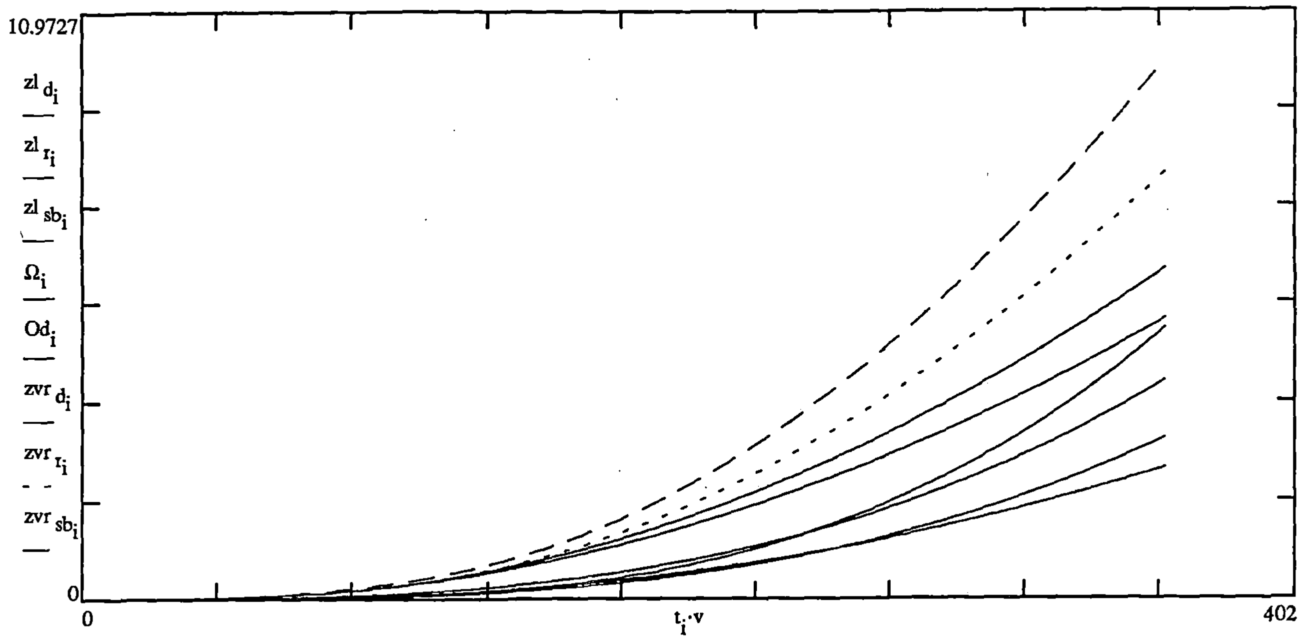
zl_{d_i}
zl_{r_i}
zl_{sb_i}
Ω_i
Od_i
0
2
4
6
8
0
100
200
300
400
500
$t_i \cdot v$



zvf_{d_i}
zl_{d_i}
zl_{r_i}
zl_{sb_i}
zvf_{sb_i}
0
2
4
6
8
0
100
200
300
400
500
$t_i \cdot v$



zvr_{d_i}
zvr_{r_i}
zvr_{sb_i}
0
5
10
15
0
100
200
300
400
500
$t_i \cdot v$


10.9727
zl d_i
zl r_i
zl sb_i
Ω_i
Od_i
zvr d_i
zvr r_i
zvr sb_i
0
0
t_i·v
402

new derivation of the rolling switch.

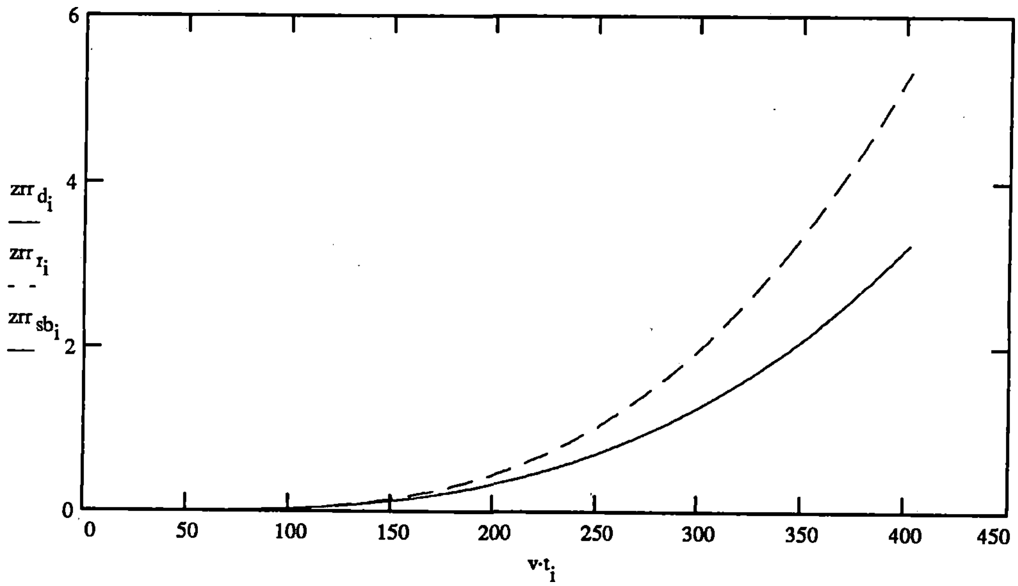
$$
\begin{aligned}
zr(t,\omega,a,t1) := g\cdot\Bigg[& (t<t1)\cdot\left(\frac{1}{12}\cdot a\cdot t^{4}+\frac{1}{168}\cdot a^{3}\cdot t^{8}+\frac{1}{990}\cdot a^{5}\cdot t^{12}+\frac{17}{75600}\cdot a^{7}\cdot t^{16}+\frac{31}{538650}\cdot a^{9}\cdot t^{20}+\frac{691}{43035300}\cdot a^{11}\cdot t^{24}\right)\ \ldots \\
& +(t\geq tr)\cdot\Bigg[\Bigg[\Bigg[\Bigg[\Bigg[\Bigg[\frac{1}{2}\cdot\frac{\ln\left(1+\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\right)}{\omega}\cdot t+\frac{1}{2}\cdot\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)\cdot t^{2}\ \ldots \\
& \quad +\frac{2}{3}\cdot\omega\cdot\frac{t^{3}}{\left(1+\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\right)}\cdot\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\ \ldots \\
& \quad +\frac{1}{2}\cdot\omega\cdot\frac{t^{3}}{\left(1+\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\right)}\cdot\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{4}\Bigg]\ \ldots \\
& \quad +\frac{1}{6}\cdot\omega\cdot\frac{t^{3}}{\left(1+\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\right)}\Bigg]-\frac{1}{3}\cdot\omega\cdot t^{3}\cdot\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\ \ldots \\
& \quad +\frac{1}{2}\cdot\omega^{2}\cdot\frac{t^{4}}{\left(1+\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\right)}\cdot\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{3}\Bigg]\ \ldots \\
& \quad +\frac{1}{4}\cdot\omega^{2}\cdot\frac{t^{4}}{\left(1+\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\right)}\cdot\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{5}\Bigg]\ \ldots \\
& \quad +\frac{1}{4}\cdot\omega^{2}\cdot\frac{t^{4}}{\left(1+\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)^{2}\right)}\cdot\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)\Bigg]\ \ldots \\
& \quad -\frac{1}{6}\cdot\omega^{2}\cdot t^{4}\cdot\tan\left(-\omega\cdot t1+a\cdot t1^{2}\right)-\frac{1}{6}\cdot\omega^{2}\cdot t^{4}\cdot\tan\left(-\omega\cdot t1+a\cdot t1\right)^{3}\Bigg]\Bigg]
\end{aligned}
$$

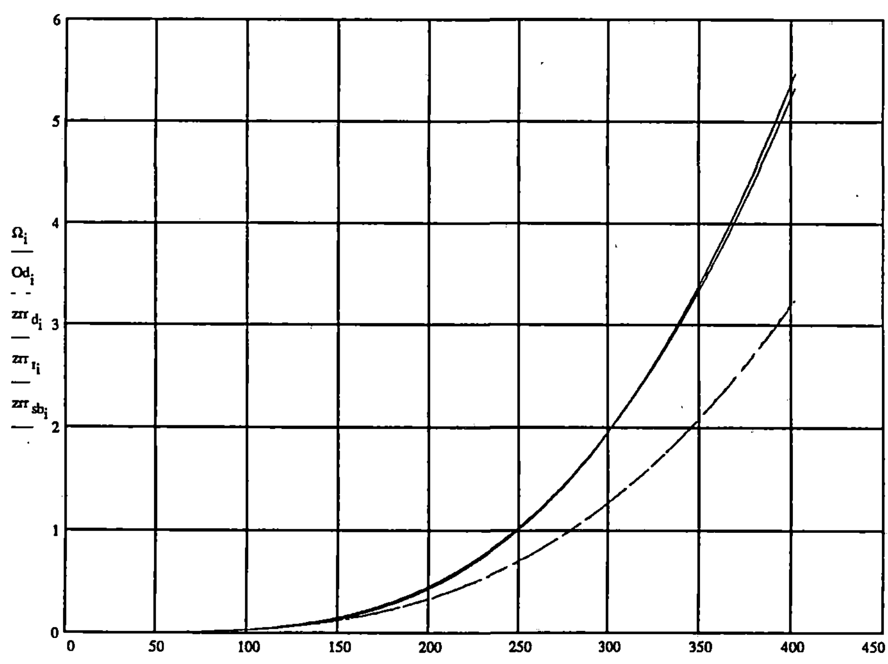
solution arrays:

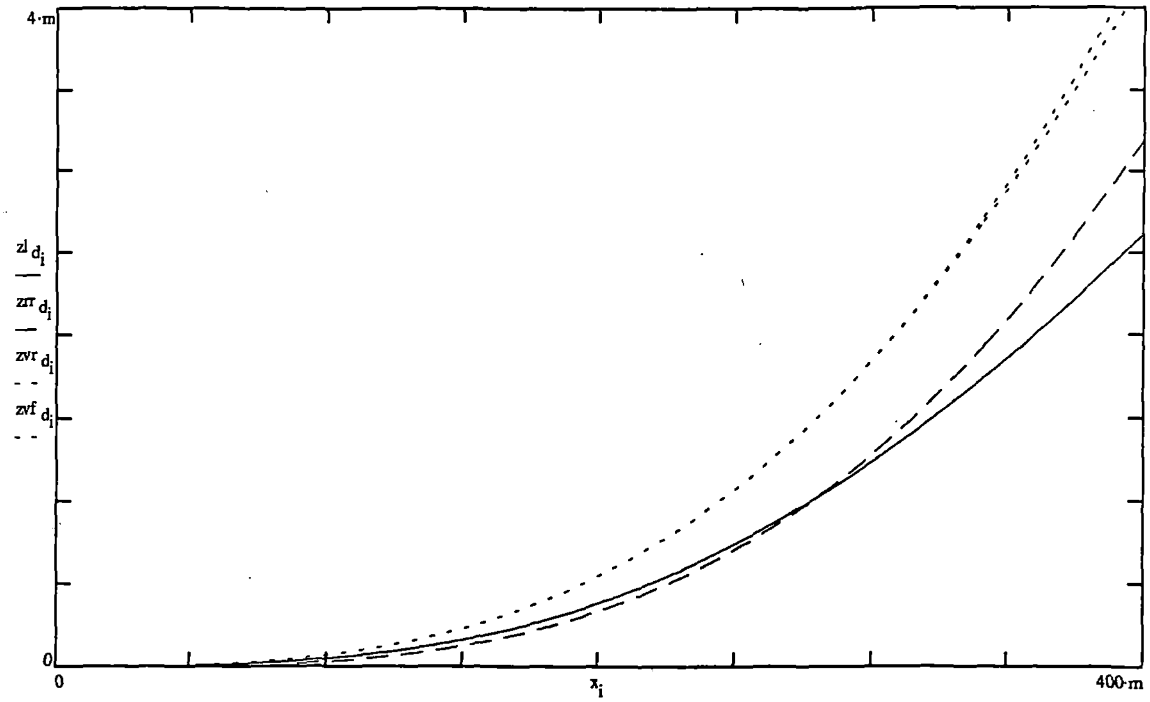
design roll $\quad zrr_{d_i} := zr\left(t_i, rr_d, \frac{\alpha}{2}, \frac{rr_d}{\alpha}\right)$ $\qquad zr\left(.3 \cdot s, rr_d, \frac{\alpha}{2}, \frac{rr_d}{\alpha}\right) = 8.668 \cdot 10^{-4} \cdot length$

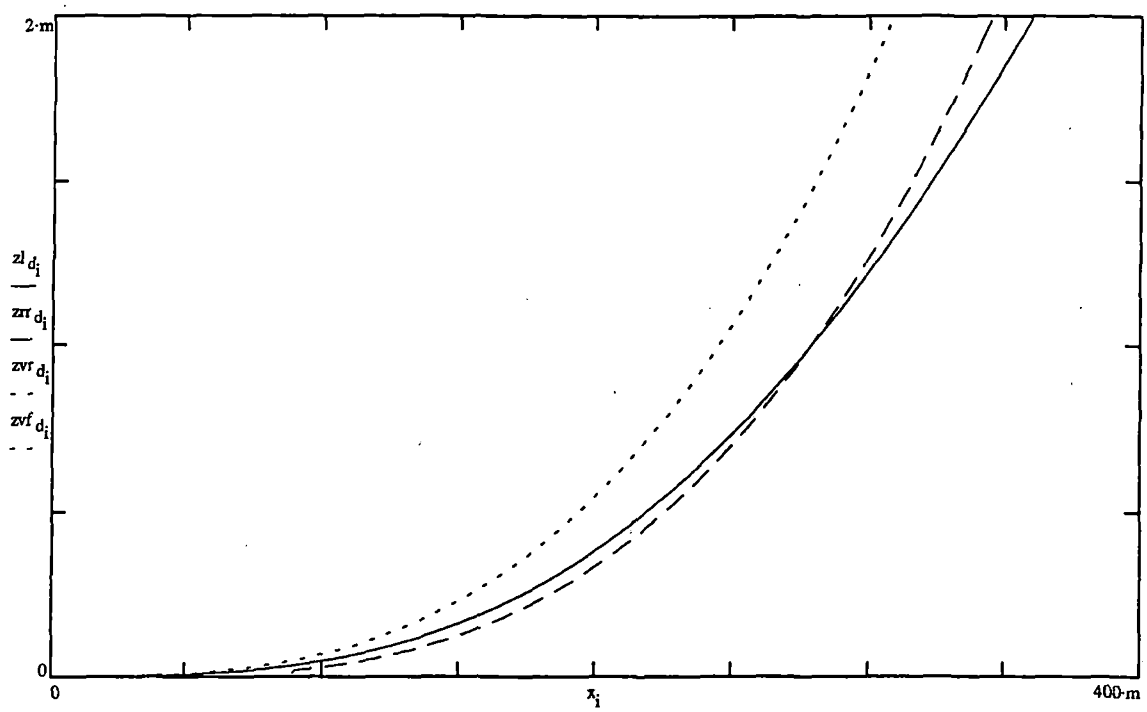
min req roll $\quad zrr_{r_i} := zr\left(t_i, rr_r, \frac{\alpha}{2}, \frac{rr_r}{\alpha}\right)$

seat belted roll $\quad zrr_{sb_i} := zr\left(t_i, rr_{sb}, \frac{\alpha}{2}, \frac{rr_{sb}}{\alpha}\right)$









$M = 300$

$MA_{i,0} := x_i \quad MA_{i,1} := zl_{d_i} \quad MA_{i,2} := zrr_{d_i}$

$MA_{i,3} := zvr_{d_i} \quad MA_{i,4} := zvf_{d_i}$

WRITEPRN(RQL) := MA

A 2 First Order Verification of Results

A first order numerical solution for the vehicle path including the change in angle of the path due to the normal acceleration was developed. This was used to verify the range of accuracy of the initial assumption of constant x velocity and only y direction accelerations. Since the solution is first order, it also underestimates the curvature somewhat; however, it does verify that, given the ride quality constraints, for the first 100 m of lateral motion the approximate solution is well beyond the accuracy required for analysis of switch length. The MathCad document follows for reference.

Look at the three g levels and the three basic switch modes. The basic assumption is that the lateral motion is small compared to the distance travelled and the speed is constant.

units: $m := 1L \quad s := 1T$

Set up the number of points to plot:

$M := 300 \quad i := 0..M \quad st := 100 \cdot s \quad t_i := \frac{st}{M} \cdot i$

Define velocity, 1g, etc.

$v := 134 \cdot \frac{m}{s} \qquad x_i := t_i \cdot v \qquad g := 9.81 \cdot \frac{m}{s^2}$

Set values for acceptable g levels, jerk, and roll rates:

parameter	design	min. req.	seat/belt
max bank angle	$mba_d := 24 \cdot \frac{\pi}{180}$	$mba_r := 30 \cdot \frac{\pi}{180}$	$mba_{sb} := 45 \cdot \frac{\pi}{180}$
roll rate	$rr_d := 5 \cdot \frac{\pi}{180 \cdot s}$	$rr_r := 5 \cdot \frac{\pi}{180 \cdot s}$	$rr_{sb} := 10 \cdot \frac{\pi}{180 \cdot s}$
roll acceleration alpha	$\alpha := 15 \cdot \frac{\pi}{180} \cdot \frac{1}{s^2}$	α is the same for all cases	
lateral acceleration	$la_d := .1 \cdot g$	$la_r := .16 \cdot g$	$la_{sb} := .2 \cdot g$
lateral jerk	$lj_d := .07 \cdot \frac{g}{s}$	$lj_r := .25 \cdot \frac{g}{s}$	$lj_{sb} := .25 \cdot \frac{g}{s}$
vertical acceleration (up)	$vau_d := .2 \cdot g$	$vau_r := .1 \cdot g$	$vau_{sb} := .1 \cdot g$
vertical acceleration (down)	$vad_d := .3 \cdot g$	$vad_r := .3 \cdot g$	$vad_{sb} := .4 \cdot g$
vertical jerk	$vj_d := .1 \cdot \frac{g}{s}$	$vj_r := .25 \cdot \frac{g}{s}$	$vj_{sb} := .3 \cdot \frac{g}{s}$

case1 pure lateral motion without roll

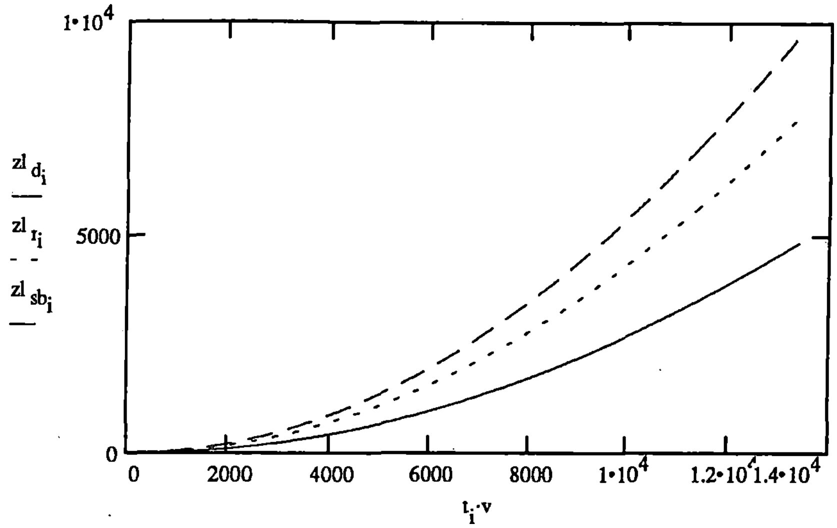
$$zl(t, tjerk, J, a) := \left[(t < tjerk) \cdot J \cdot \frac{(t)^3}{6} + (t \ge tjerk) \cdot \left[a \cdot \frac{(t - tjerk)^2}{2} + J \cdot \frac{(tjerk)^2}{2} \cdot (t - tjerk) + J \cdot \frac{(tjerk)^3}{6} \right] \right]$$

Set up the arrays of data for the different cases

for design $\quad zl_{d_i} := zl\left[t_i, \left(\frac{la_d}{lj_d} \right), lj_d, la_d \right]$

for min req $\quad zl_{r_i} := zl\left[t_i, \left(\frac{la_r}{lj_r} \right), lj_r, la_r \right]$

for seatbelt $\quad zl_{sb_i} := zl\left[t_i, \left(\frac{la_{sb}}{lj_{sb}} \right), lj_{sb}, la_{sb} \right]$



True pure lateral motion without roll with the actual curvature

$N := 500 \quad ind := 0..N \quad t_f := 100 \cdot sec \quad dt := \frac{t_f}{N} \quad t_0 := 0 \cdot sec \quad t_{ind+1} := t_{ind} + dt tt_{ind} := dt \cdot ind \quad dt = 0.2 \cdot s$

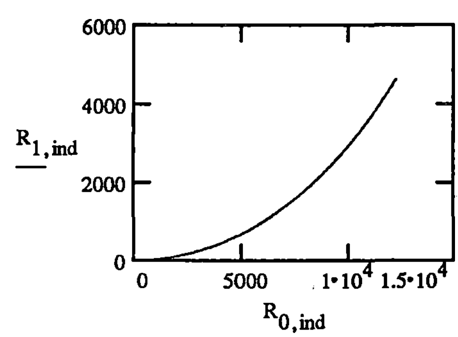
$j := 0..1 \qquad vyzero := 0 \cdot \frac{m}{s} \qquad R_{0,0} := 0 \cdot m \quad R_{1,0} := 0 \cdot m$

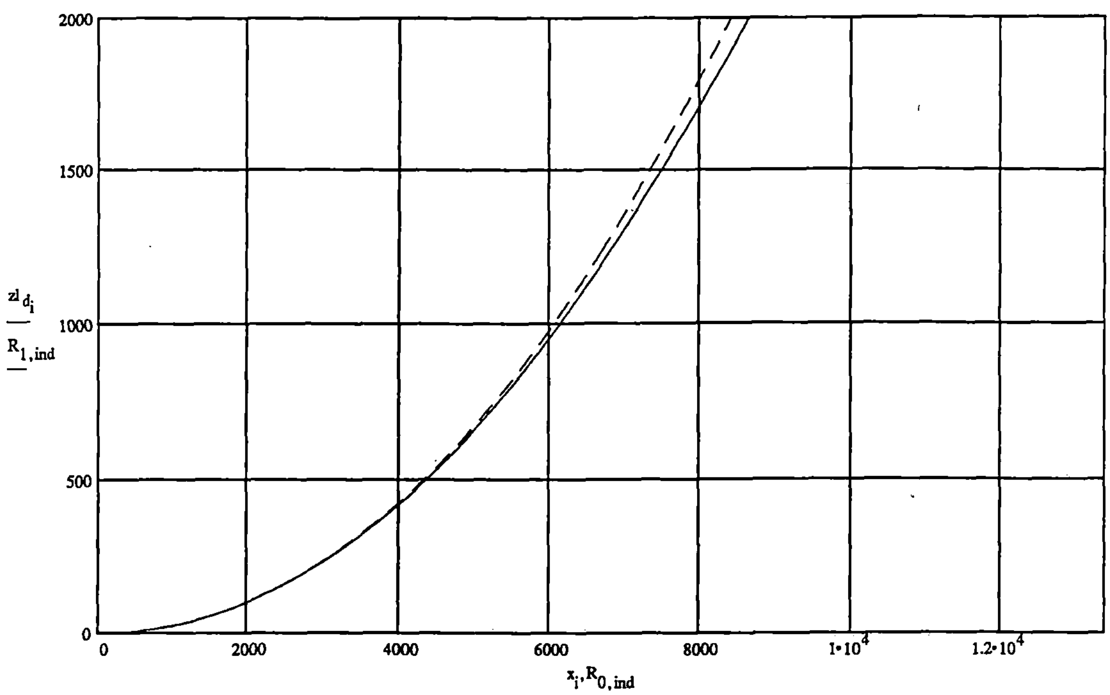
$a_0 := 0 \cdot \frac{m}{s^2} \quad a_{ind+1} := if\left(a_{ind} + lj_d \cdot dt \le la_d, a_{ind} + lj_d \cdot dt, la_d\right)$

$V_{0,0} := v \quad V_{1,0} := vyzero$

$$\begin{pmatrix} V_{0,ind+1} \\ V_{1,ind+1} \end{pmatrix} := \begin{pmatrix} V_{0,ind} \\ V_{1,ind} \end{pmatrix} + \frac{a_{ind} \cdot dt}{\left| \begin{pmatrix} V_{0,ind} \\ V_{1,ind} \end{pmatrix} \right|} \cdot \begin{pmatrix} -V_{1,ind} \\ V_{0,ind} \end{pmatrix}$$

$$\begin{pmatrix} R_{0,ind+1} \\ R_{1,ind+1} \end{pmatrix} := \begin{pmatrix} R_{0,ind} \\ R_{1,ind} \end{pmatrix} + \left[\begin{pmatrix} V_{0,ind} \\ V_{1,ind} \end{pmatrix} + \frac{a_{ind} \cdot dt}{\left| \begin{pmatrix} V_{0,ind} \\ V_{1,ind} \end{pmatrix} \right|} \cdot \begin{pmatrix} -V_{1,ind} \\ V_{0,ind} \end{pmatrix} \right] \cdot dt$$





2000
1500
1000
500
0
0
2000
4000
6000
8000
1·10^4
1.2·10^4
zl d_i
R_1, ind
x_i, R_0, ind

A 3 Analysis of Switching on Parallel Guideways

The first order numerical solution for the vehicle path including the change in angle of the path due to the normal acceleration was used to determine the length required to move to a parallel guideway. The MathCad document for this analysis follows.

Look at the three g levels and the three basic switch modes. The basic assumption is that the lateral motion is small compared to the distance travelled and the speed is constant.

units: $m := 1L \quad s := 1T$

Set up the number of points to plot:

$M := 300 \quad i := 0..M \quad st := 3 \cdot s \quad t_i := \frac{st}{M} \cdot i$

Define velocity, 1g, etc.

$v := 134 \cdot \frac{m}{s} \quad x_i := t_i \cdot v \quad g := 9.81 \cdot \frac{m}{s^2}$

Set values for acceptable g levels, jerk, and roll rates:

parameter	design	min. req.	seat/belt
max bank angle	$mba_d := 24 \cdot \frac{\pi}{180}$	$mba_r := 30 \cdot \frac{\pi}{180}$	$mba_{sb} := 45 \cdot \frac{\pi}{180}$
roll rate	$rr_d := 5 \cdot \frac{\pi}{180 \cdot s}$	$rr_r := 5 \cdot \frac{\pi}{180 \cdot s}$	$rr_{sb} := 10 \cdot \frac{\pi}{180 \cdot s}$
roll acceleration alpha	$\alpha := 15 \cdot \frac{\pi}{180} \cdot \frac{1}{s^2}$	α is the same for all cases	
lateral acceleration	$la_d := .1 \cdot g$	$la_r := .16 \cdot g$	$la_{sb} := .2 \cdot g$
lateral jerk	$lj_d := .07 \cdot \frac{g}{s}$	$lj_r := .25 \cdot \frac{g}{s}$	$lj_{sb} := .25 \cdot \frac{g}{s}$
vertical acceleration (up)	$vau_d := .2 \cdot g$	$vau_r := .1 \cdot g$	$vau_{sb} := .1 \cdot g$
vertical acceleration (down)	$vad_d := .3 \cdot g$	$vad_r := .3 \cdot g$	$vad_{sb} := .4 \cdot g$
vertical jerk	$vj_d := .1 \cdot \frac{g}{s}$	$vj_r := .25 \cdot \frac{g}{s}$	$vj_{sb} := .3 \cdot \frac{g}{s}$

True pure vertical motion without roll with the actual curvature

$N := 100 \quad i := 0..N \quad t_f := 1000 \cdot sec \quad dt := \frac{t_f}{N} \quad t_0 := 0 \cdot sec \quad t_{i+1} := t_i + dt \quad tt_i := dt \cdot i \quad dt = 10 \cdot s$

$j := 0..1 \quad vyzero := 0 \cdot \frac{m}{s} \quad R_{0,0} := 0 \cdot m \quad R_{1,0} := 0 \cdot m$

Parralell guideways calculation for vertical switch. Change J and A to match the lateral values for lateral switch.

$J := vj_d \quad A := vau_d \quad tj_{max} := \frac{A}{J} \quad ta := .0 \cdot sec \quad tj := 1.72 \cdot s$

$J = 0.981 \cdot length \cdot time^{-3} \quad A = 1.962 \cdot length \cdot time^{-2} \quad tj_{max} = 2 \cdot s$

ta is a settable parameter that will give the spacing between guideways.

$tnet := 4 \cdot tj + 2 \cdot ta \quad t_i := \frac{tnet}{N} \cdot i \quad tj = 1.72 \cdot sec$

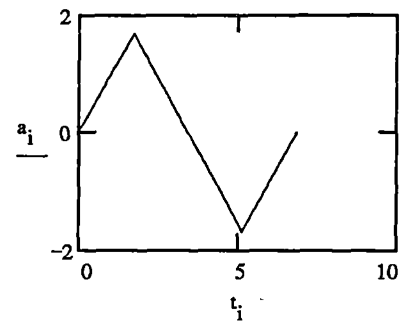
$$AA(tt) := (tt<tj) \cdot J \cdot tt + (tt \ge tj) \cdot (tt<tj+ta) \cdot (J \cdot tj) + (tt \ge tj+ta) \cdot (tt<3 \cdot tj+ta) \cdot (J \cdot tj - J \cdot (tt-(tj+ta))) \; ...$$
$$+ (tt \ge 3 \cdot tj+ta) \cdot (tt<3 \cdot tj+2 \cdot ta) \cdot ((J \cdot tj - J \cdot (3 \cdot tj+ta-(tj+ta)))) \; ...$$
$$+ (tt \ge 3 \cdot tj+2 \cdot ta) \cdot (tt<4 \cdot tj+2 \cdot ta) \cdot ((J \cdot tj - J \cdot (3 \cdot tj+ta-(tj+ta))) + J \cdot (tt-(3 \cdot tj+2 \cdot ta)))$$

$tnet = 6.88 \cdot s \quad dt := \frac{tnet}{N}$

$a_i := AA(t_i)$

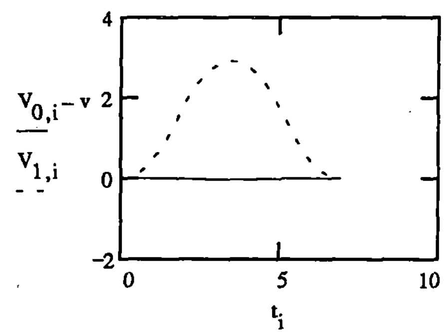
$$vyzero = 0\cdot length\cdot time^{-1}$$

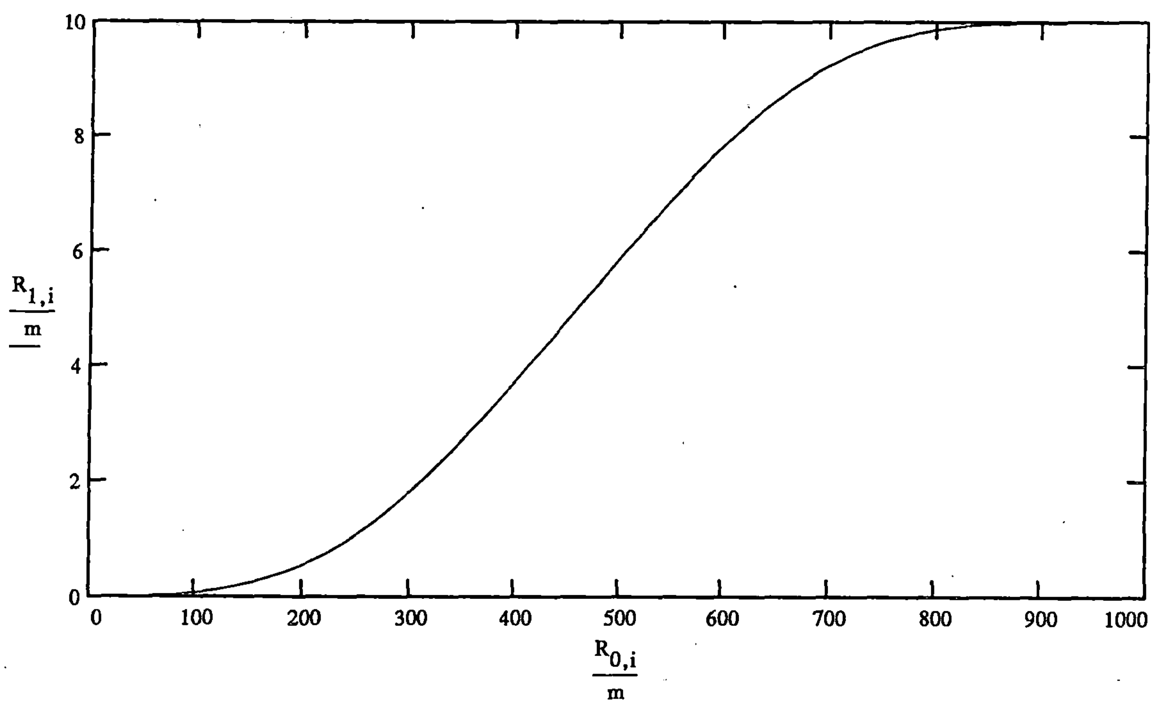
$$V_{0,0} := v \qquad V_{1,0} := vyzero$$



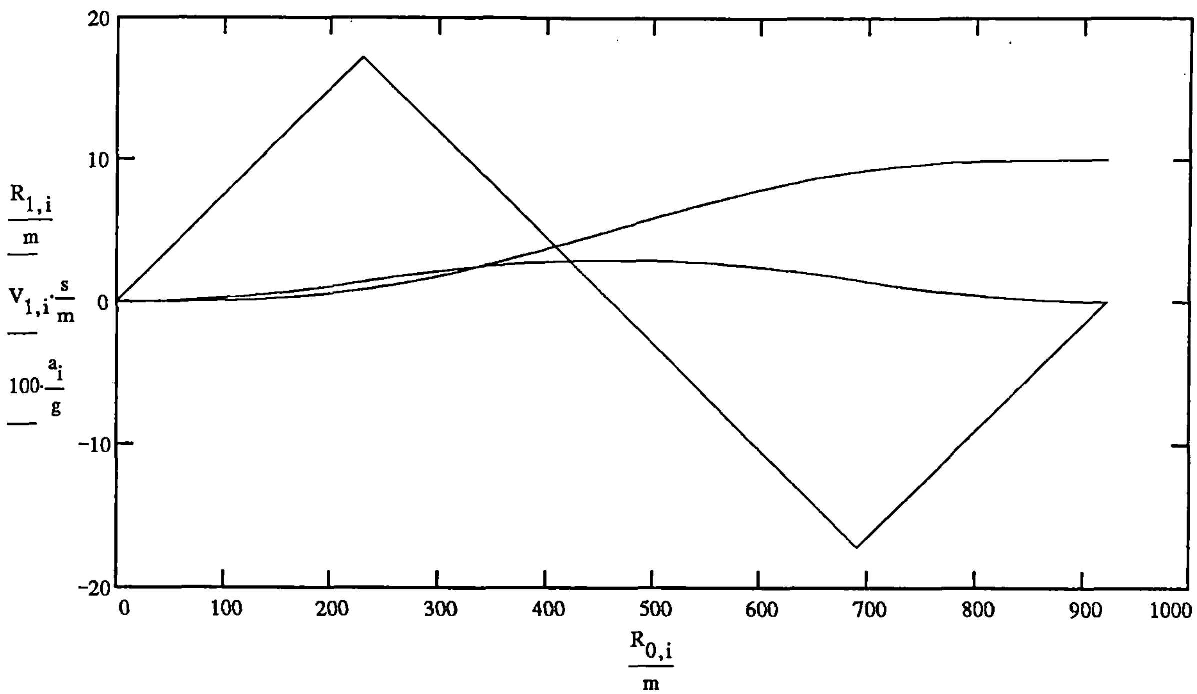
$$\begin{pmatrix} V_{0,i+1} \\ V_{1,i+1} \end{pmatrix} := \begin{pmatrix} V_{0,i} \\ V_{1,i} \end{pmatrix} + \frac{a_i\cdot dt}{\left|\begin{pmatrix} V_{0,i} \\ V_{1,i} \end{pmatrix}\right|}\cdot\begin{pmatrix} -V_{1,i} \\ V_{0,i} \end{pmatrix}$$

$$\begin{pmatrix} R_{0,i+1} \\ R_{1,i+1} \end{pmatrix} := \begin{pmatrix} R_{0,i} \\ R_{1,i} \end{pmatrix} + \left[\begin{pmatrix} V_{0,i} \\ V_{1,i} \end{pmatrix} + \frac{a_i\cdot dt}{\left|\begin{pmatrix} V_{0,i} \\ V_{1,i} \end{pmatrix}\right|}\cdot\begin{pmatrix} -V_{1,i} \\ V_{0,i} \end{pmatrix}\right]\cdot dt$$





$ta = 0\cdot s$ $\qquad tj = 1.72\cdot s$ $\qquad tnet = 6.88\cdot s$ $\qquad R_{1,N} = 9.983\cdot m$ $\qquad R_{0,N} = 921.843\cdot m$



$ta = 0 \cdot s$ $tj = 1.72 \cdot s$ $tmet = 6.88 \cdot s$ $R_{1,N} = 9.983 \cdot m$ $R_{0,N} = 921.843 \cdot m$

APPENDIX B

Analysis of Levitation and Guidance Capabilities for Selected Configurations

B 1 MIT/Bechtel in a Flat Guideway Switched Coil Switch

Levitation and guidance calculations for the MIT/Bechtel system in a flat switched coil guideway switch are done assuming geometric constraints on position using 2-dimensional, frozen flux (very high speed with negligible electrical resistance), assumptions. Calculations are for the forces as a function of position which serves as the basis of determining the capacity and stability of the system. The actual position of levitation is not calculated. The calculated results are based on 2-dimensional analysis and actual capacities are substantially less. The analysis is adequate for determining the feasibility of the approach and the basic quasi-static stability ignoring dynamic instabilities and damping considerations as long as it is realized that actual 3-dimensional analysis is required for a real system design. MathCad documentation of the analysis follows.

THIS FILE CREATED 9-9-93 name HSSLATM1.mcd

The object of this file is to determine the lateral guidance for the hss of a pair of coils including mutual inductance with the MIT system for one side only. But, the results are approximate and are not for accurate values for inductance and mutual inductance. All is 2-d theory assuming relatively large coils and spacing relative to the coil cross-section.

constants

$\mu_0 := 4\cdot\pi\cdot 10^{-7}\cdot\frac{newton}{amp^2}$ henry/m $\qquad N := newton$

super conductor current

$Isc := 1\cdot 10^{6}\cdot amp$ MIT has a very low amp turn system of 400ka Must increase this to 1 M-amp to get levitation.

$WPM := \frac{65\cdot 10^{3}\cdot kg\cdot 9.81\cdot\frac{m}{sec^2}}{36\cdot m}$

coil radius

$a := .05\cdot m$

$WPM = 1.771\cdot 10^{4}\cdot\frac{N}{m}$

Set up the plotting stuff as a function of delta

$n := 100 \quad i := 0..n \quad \delta_{max} := .75\cdot m \quad \delta_i := \left(\frac{i}{n} - \frac{1}{2}\right)\cdot 2\cdot\delta_{max}$

geometry is flat coils with vertical superconductor.

height of superconducting magnet $\qquad z := .5\cdot m$

distance from coil centers to lower superconductor center $\qquad h := .3\cdot m$ $\qquad$ 1 g at about .182

width of left coil $\qquad w := .5\cdot m$

width of right coil $\qquad w_2 := w$

spacing of coils from center to center $\qquad S := .25\cdot m$

mutual inductance for equally spaced
ground conductors per unit length

$$M12 := \frac{\mu_0}{2\cdot\pi}\cdot\left[\ln\left[\frac{S^2 - a^2}{(S - w + a)\cdot(S + w - a)}\right]\right]$$

deflection to the right of the SC coil re ground is δ

general radius equation $\qquad r(\delta, w, S, h) := \sqrt{\left(\frac{S}{2} + \frac{w}{2} + \delta\right)^2 + h^2}$

	bottom SC conductor	middle SC conductor	upper SC conductor
radius inner left	$rilb_i := r(\delta_i, -w, S, h)$	$rilt_i := r(\delta_i, -w, S, h+z)$	$rilu_i := r(\delta_i, -w, S, h + 2\cdot z)$
radius outer left	$rolb_i := r(\delta_i, w, S, h)$	$rolt_i := r(\delta_i, w, S, h+z)$	$rolu_i := r(\delta_i, w, S, h + 2\cdot z)$
radius inner right	$rirb_i := r(-\delta_i, -w, S, h)$	$rirt_i := r(-\delta_i, -w, S, h+z)$	$riru_i := r(-\delta_i, -w, S, h + 2\cdot z)$
radius outer right	$rorb_i := r(-\delta_i, w, S, h)$	$rort_i := r(-\delta_i, w, S, h+z)$	$roru_i := r(-\delta_i, w, S, h + 2\cdot z)$

mutual inductance with SC coils

$$Msc(r1,r2,r3,r4,r5,r6) := \left[\frac{\mu_0}{2\cdot\pi}\cdot\left[\ln\left[\frac{r2}{r1}\cdot\left(\frac{r3}{r4}\right)^2\cdot\frac{r6}{r5}\right]\right]\right]$$

mutual inductances with SC coil

left coil $\quad Msl_i := Msc(rilb_i, rolb_i, rilt_i, rolt_i, rilu_i, rolu_i)$

right coil $\quad Msr_i := Msc(rirb_i, rorb_i, rirt_i, rort_i, riru_i, roru_i)$

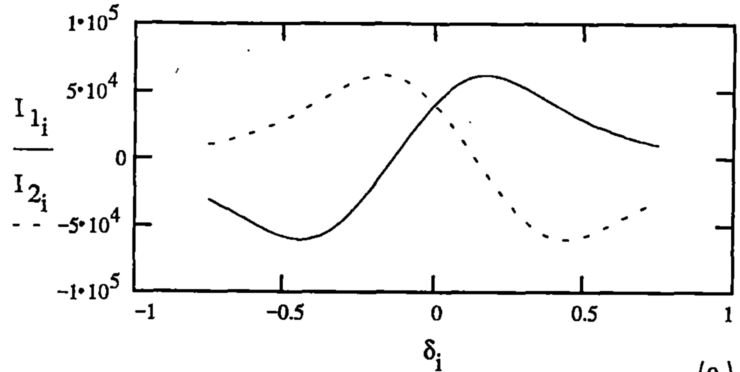
inductance of the ground coil itself (very approximate)

$$L := \frac{\mu_0}{\pi}\cdot\ln\left(\frac{w}{a} - 1\right) \qquad L = 8.789\cdot 10^{-7}\ \cdot\frac{henry}{m}$$

assuming the super conducting coil current is constant gives result with correct sign convention

$$I1_i := Isc\cdot\left[\frac{\frac{Msl_i}{L} - \frac{M12\cdot Msr_i}{L^2}}{1 - \left(\frac{M12}{L}\right)^2}\right]$$

$$I2_i := \frac{Msr_i}{L}\cdot Isc - \frac{M12}{L}\cdot I1_i$$



Now get the forces acting on the SC coil

just for reference the approach is as described below

$$B := \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad Icoil := \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad fourwires := 1..4$$

just for documentation

$$B(r, I) := \frac{\mu_0 \cdot Isc}{2 \cdot \pi \cdot r} \qquad F := \sum_{fourwires} Icoil \times B$$

approach described above is actually done below

force from left coil on SC magnet is a vector and we need the up and lateral force

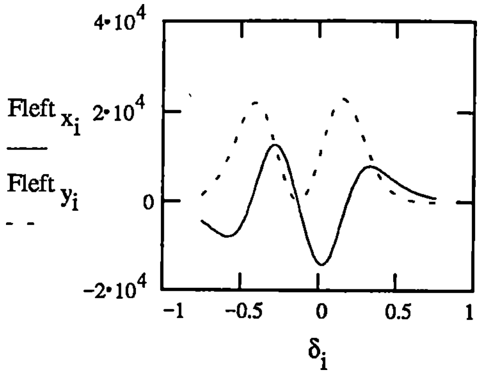
direction function for the left coil in terms of x and y components from coil to SC as positive

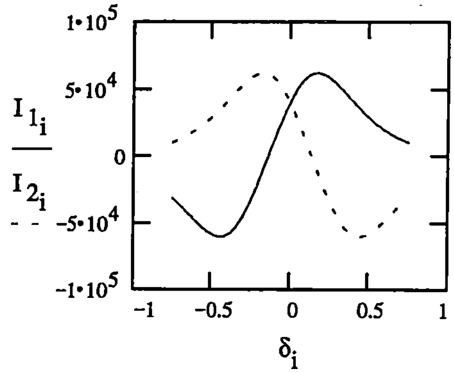
$$r_x(\delta, w, S, h) := \left(\frac{S}{2} + \frac{w}{2} + \delta\right) \quad r_y(\delta, w, S, h) := h$$

positive force is to right and up

$$Fleft_{x_i} := \frac{I_{1_i} \cdot Isc \cdot \mu_0}{2 \cdot \pi} \cdot \left[\frac{r_x(\delta_i, -w, S, h)}{r(\delta_i, -w, S, h)^2} - 2 \cdot \frac{r_x(\delta_i, -w, S, h+z)}{r(\delta_i, -w, S, h+z)^2} + \frac{r_x(\delta_i, -w, S, h+2 \cdot z)}{r(\delta_i, -w, S, h+2 \cdot z)^2} \ldots \right. \\ \left. + - \left(\frac{r_x(\delta_i, w, S, h)}{r(\delta_i, w, S, h)^2} - 2 \cdot \frac{r_x(\delta_i, w, S, h+z)}{r(\delta_i, w, S, h+z)^2} + \frac{r_x(\delta_i, w, S, h+2 \cdot z)}{r(\delta_i, w, S, h+2 \cdot z)^2} \right) \right]$$

$$Fleft_{y_i} := \frac{I_{1_i} \cdot Isc \cdot \mu_0}{2 \cdot \pi} \cdot \left[\left(\frac{r_y(\delta_i, -w, S, h)}{r(\delta_i, -w, S, h)^2} - 2 \cdot \frac{r_y(\delta_i, -w, S, h+z)}{r(\delta_i, -w, S, h+z)^2} + \frac{r_y(\delta_i, -w, S, h+2 \cdot z)}{r(\delta_i, -w, S, h+2 \cdot z)^2} \right) \ldots \right. \\ \left. + - \left(\frac{r_y(\delta_i, w, S, h)}{r(\delta_i, w, S, h)^2} - 2 \cdot \frac{r_y(\delta_i, w, S, h+z)}{r(\delta_i, w, S, h+z)^2} + \frac{r_y(\delta_i, w, S, h+2 \cdot z)}{r(\delta_i, w, S, h+2 \cdot z)^2} \right) \right]$$

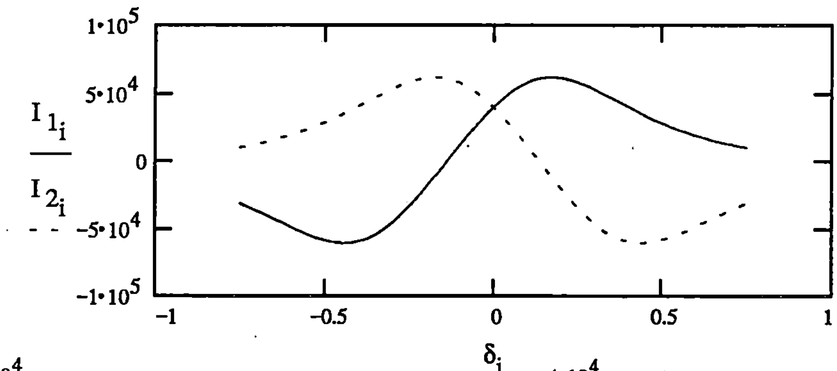


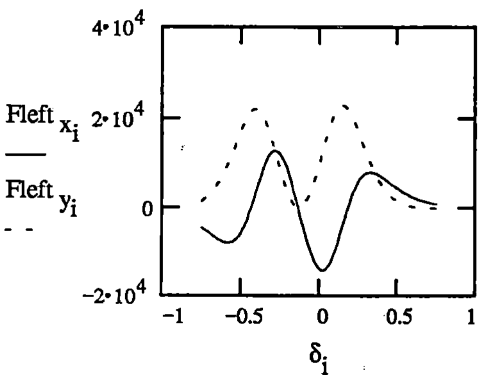


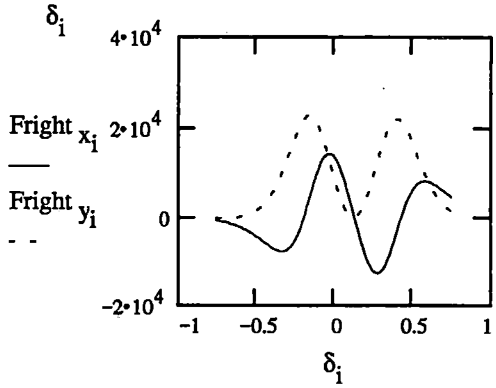
positive force is to right and up   now do for the right coil

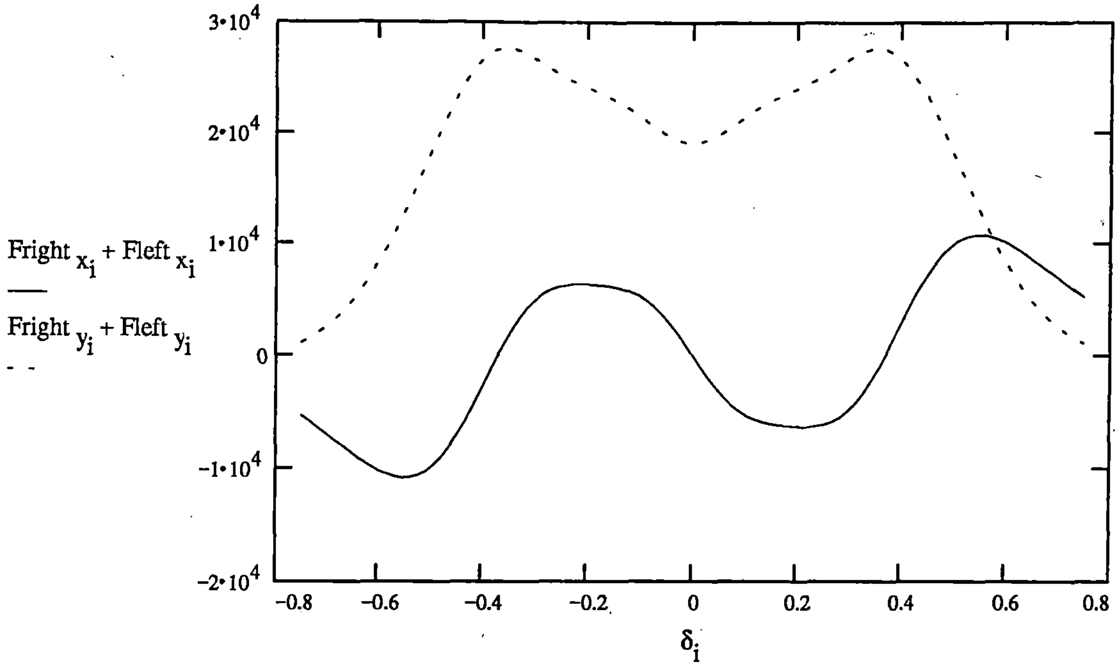
$$\mathrm{Fright}_{x_i} := -\frac{I_{2_i}\cdot Isc\cdot\mu_0}{2\cdot\pi}\cdot\left[\left(\frac{r_x(-\delta_i,-w,S,h)}{r(-\delta_i,-w,S,h)^2}-2\cdot\frac{r_x(-\delta_i,-w,S,h+z)}{r(-\delta_i,-w,S,h+z)^2}+\frac{r_x(-\delta_i,-w,S,h+2\cdot z)}{r(-\delta_i,-w,S,h+2\cdot z)^2}\right)\ldots\right.$$
$$\left.+-\left(\frac{r_x(-\delta_i,w,S,h)}{r(-\delta_i,w,S,h)^2}-2\cdot\frac{r_x(-\delta_i,w,S,h+z)}{r(-\delta_i,w,S,h+z)^2}+\frac{r_x(-\delta_i,w,S,h+2\cdot z)}{r(-\delta_i,w,S,h+2\cdot z)^2}\right)\right]$$

$$\mathrm{Fright}_{y_i} := \frac{I_{2_i}\cdot Isc\cdot\mu_0}{2\cdot\pi}\cdot\left[\left(\frac{r_y(-\delta_i,-w,S,h)}{r(-\delta_i,-w,S,h)^2}-2\cdot\frac{r_y(-\delta_i,-w,S,h+z)}{r(-\delta_i,-w,S,h+z)^2}+\frac{r_y(-\delta_i,-w,S,h+2\cdot z)}{r(-\delta_i,-w,S,h+2\cdot z)^2}\right)\ldots\right.$$
$$\left.+-\left(\frac{r_y(-\delta_i,w,S,h)}{r(-\delta_i,w,S,h)^2}-2\cdot\frac{r_y(-\delta_i,w,S,h+z)}{r(-\delta_i,w,S,h+z)^2}+\frac{r_y(-\delta_i,w,S,h+2\cdot z)}{r(-\delta_i,w,S,h+2\cdot z)^2}\right)\right]$$

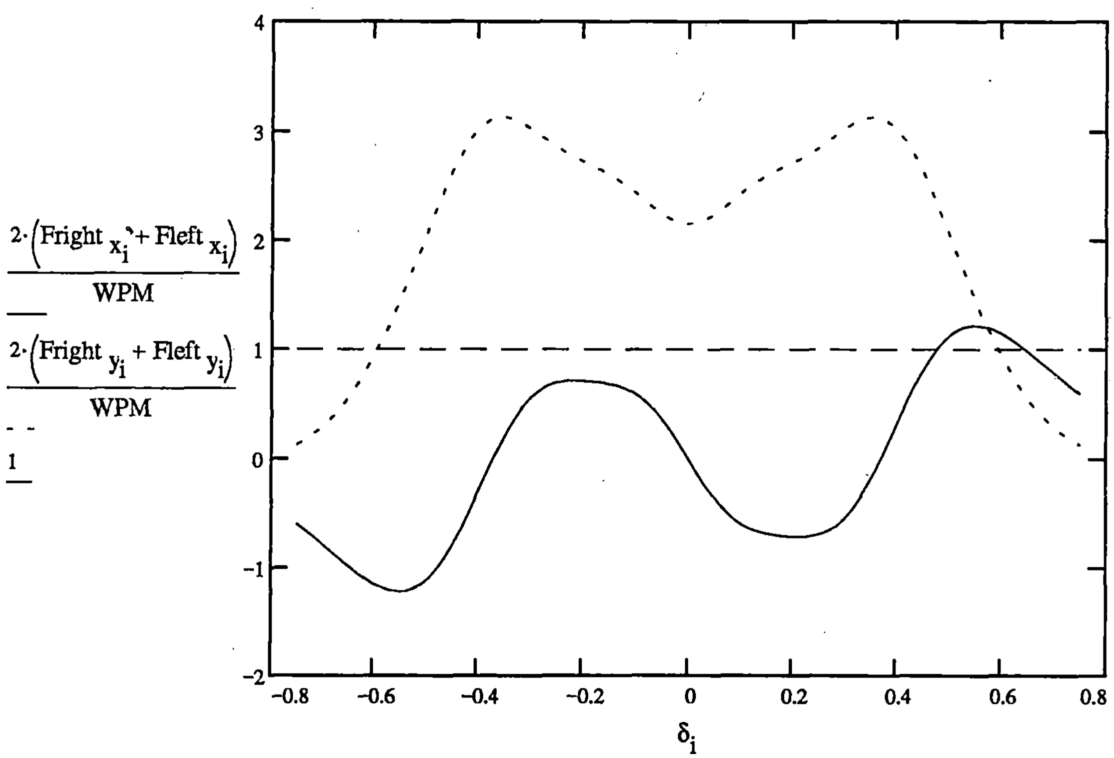








$w = 0.5 \cdot m \quad S = 0.25 \cdot m \quad h = 0.3 \cdot m$



MIT configuration

$w = 0.5 \cdot m$

$S = 0.25 \cdot m$

$h = 0.3 \cdot m$

Amp turns on Superconductor $Isc = 1 \cdot 10^{6} \cdot amp$

Vehicle weight per meter $WPM = 1.771 \cdot 10^{4} \cdot \frac{N}{m}$

B 2 Magneplane In A Vertical Switch

Levitation and guidance calculations for the Magneplane in a null-flux type vertical switch are done assuming similar constraints as for the MIT/Bechtel calculations. MathCad documentation of the analysis follows.

estimate of the lift capacity and guidance of a null type system (without figure 8) based on the single coil beside the Magneplane vehicle. DATE 7-14-93 FILE HSSBFLD2

constants

$$\mu_0 := 4\cdot\pi\cdot10^{-7}\cdot\frac{\text{newton}}{\text{amp}^2}$$ henry/m $\quad N := \text{newton}$

super conductor current

$$WPM := 1.56\cdot10^{4}\cdot\frac{N}{m}$$

$$I_1 := 1\cdot10^{6}\cdot\text{amp}$$

coil radius

$$a := .05\cdot m$$

coil acting on a single (super) conductor closest to outside edge

gap $g := .2\cdot m$

coil height $h := .5\cdot m$

offset $\delta := .01\cdot m$

basic functional relationships

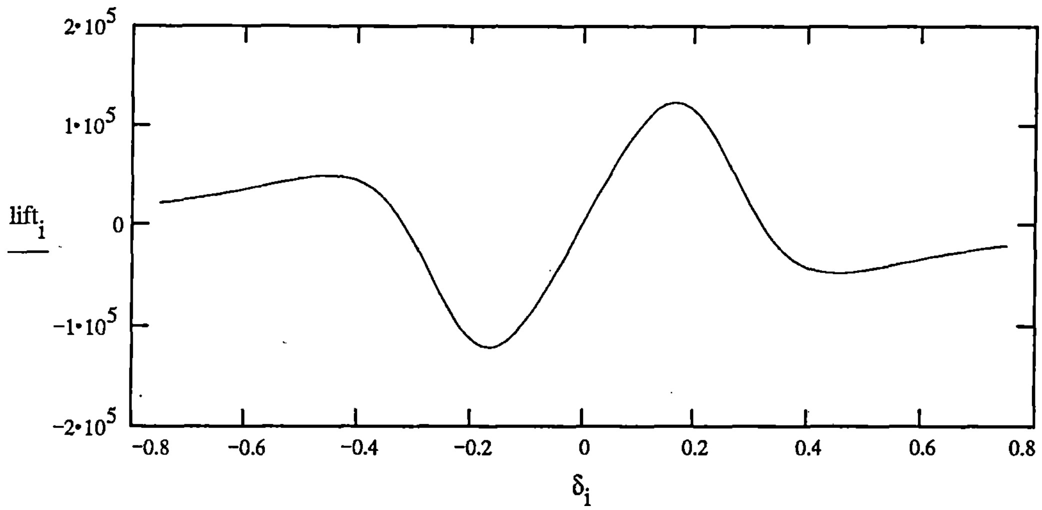
$$I_2(\delta,h,g) := \frac{I_1}{2}\cdot\frac{\ln\left[\frac{\sqrt{g^2+\left(\frac{h}{2}-\delta\right)^2}}{\sqrt{g^2+\left(\frac{h}{2}+\delta\right)^2}}\right]}{\ln\left(\frac{h}{a}\right)}$$

net force calculation (note that this is the ideal zero resistance case)

$$L(\delta,h,g) := -\frac{\mu_0}{4\cdot\pi}\cdot I_1{}^2\cdot\frac{\ln\left[\left[\frac{\sqrt{g^2+\left(\frac{h}{2}-\delta\right)^2}}{\sqrt{g^2+\left(\frac{h}{2}+\delta\right)^2}}\right]^1\right]}{\ln\left(\frac{h}{a}\right)}\cdot\left[\frac{\left(\frac{h}{2}-\delta\right)}{g^2+\left(\frac{h}{2}-\delta\right)^2}+\frac{\left(\frac{h}{2}+\delta\right)}{g^2+\left(\frac{h}{2}+\delta\right)^2}\right]$$

plot as a function of delta

$$n := 100 \quad i := 0..n \quad \delta_{max} := .75 \cdot m \quad \delta_i := \left(\frac{i}{n} - \frac{1}{2}\right) \cdot 2 \cdot \delta_{max} \qquad lift_i := L(\delta_i, h, g)$$



now do a two coil geometry like Magneplane has.
sum the lift from the different coils

locations of superconductors relative to the normal coil centerline

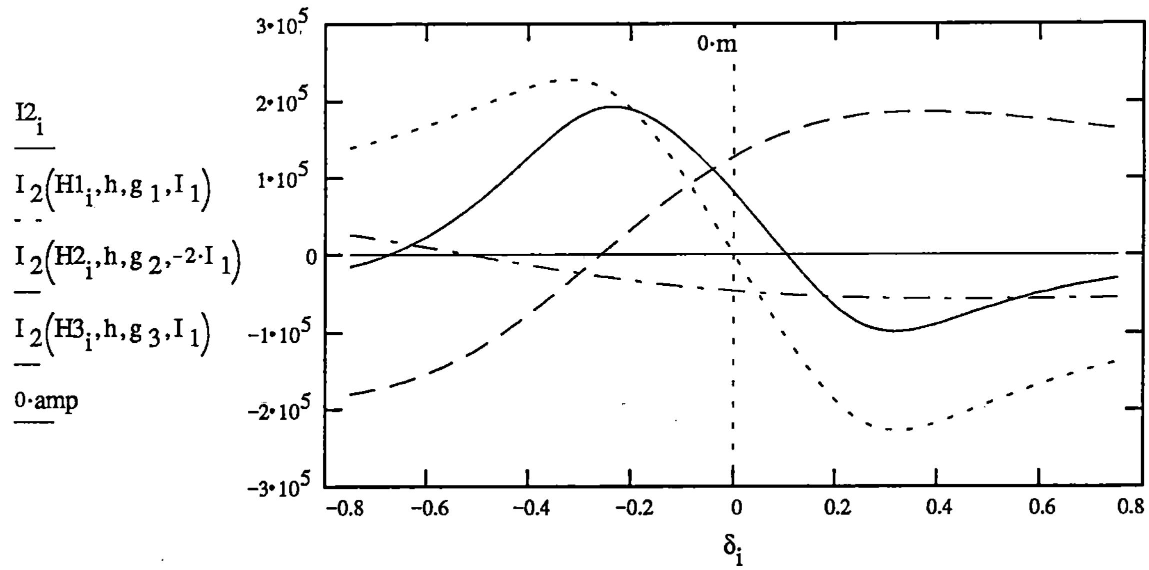
	position re coil 1		gap	height
coil leg 1	baseline origin		$g_1 := .2 \cdot m$	$H1_i := \delta_i$
coil leg 2	$X_2 := .369 \cdot m$	$Y_2 := .258 \cdot m$	$g_2 := g_1 + X_2$	$H2_i := Y_2 + \delta_i$
coil leg 3	$X_3 := X_2 + .369 \cdot m$	$Y_3 := Y_2 + .258 \cdot m$	$g_3 := g_1 + X_3$	$H3_i := Y_3 + \delta_i$

note: coil two has two time the current in the opposite direction from coils 1 and 3.

$$I_2(\delta, h, g, I_1) := \frac{I_1}{2} \cdot \frac{\ln\left[\frac{\sqrt{g^2 + \left(\frac{h}{2} - \delta\right)^2}}{\sqrt{g^2 + \left(\frac{h}{2} + \delta\right)^2}}\right]}{\ln\left(\frac{h}{a}\right)}$$

now get net coil current by superposition

$$I2_i := I_2\left(H1_i, h, g_1, I_1\right) + I_2\left(H2_i, h, g_2, -2\cdot I_1\right) + I_2\left(H3_i, h, g_3, I_1\right)$$



the equations are not correct if delta is replaced with H1,2,3 and g with g1,2,3 and correct signs are used since the current is the one value from all adjacent coils.

new lift equations given the net current from the I2 function

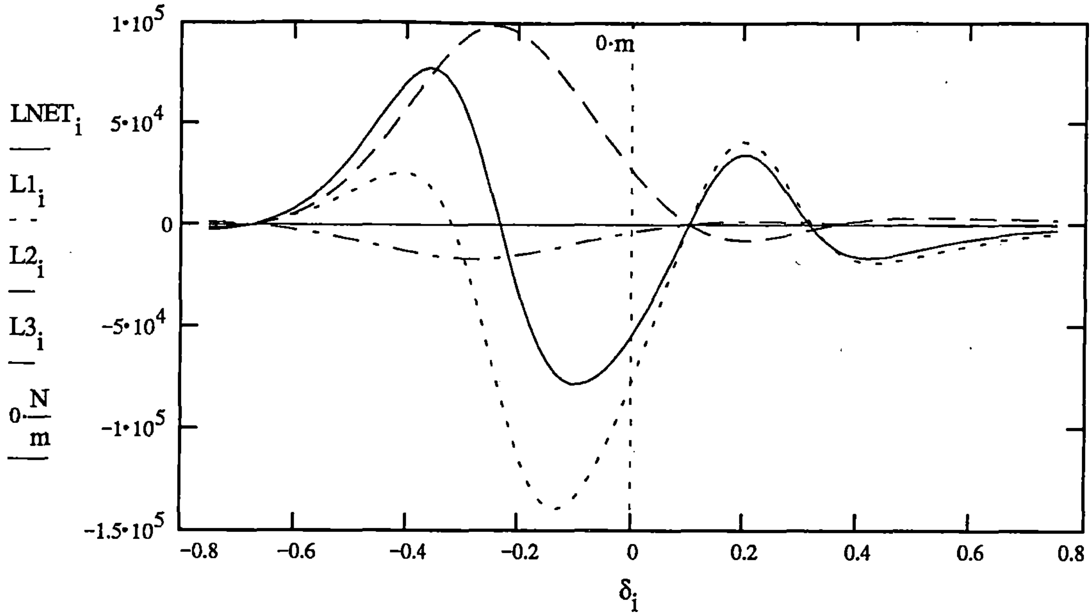
$$\mathrm{LIFT}\left(\delta, h, g, I_1, I_2\right) := -\frac{\mu_0}{2\cdot\pi}\cdot I_1\cdot I_2\cdot\left[\frac{\left(\frac{h}{2}-\delta\right)}{g^2+\left(\frac{h}{2}-\delta\right)^2}+\frac{\left(\frac{h}{2}+\delta\right)}{g^2+\left(\frac{h}{2}+\delta\right)^2}\right]$$

$$L1_i := \mathrm{LIFT}\left(H1_i, h, g_1, I_1, I2_i\right)$$

$$L2_i := \mathrm{LIFT}\left(H2_i, h, g_2, -2\cdot I_1, I2_i\right)$$

$$L3_i := \mathrm{LIFT}\left(H3_i, h, g_3, I_1, I2_i\right)$$

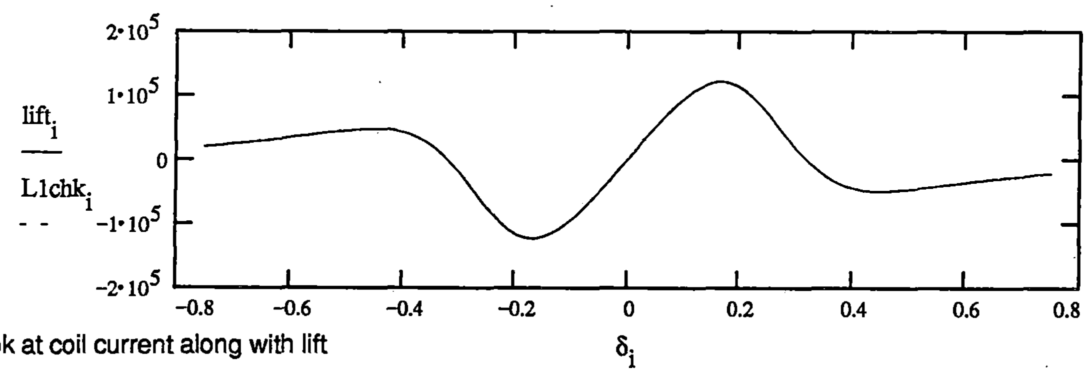
$$LNET_i := L1_i + L2_i + L3_i$$



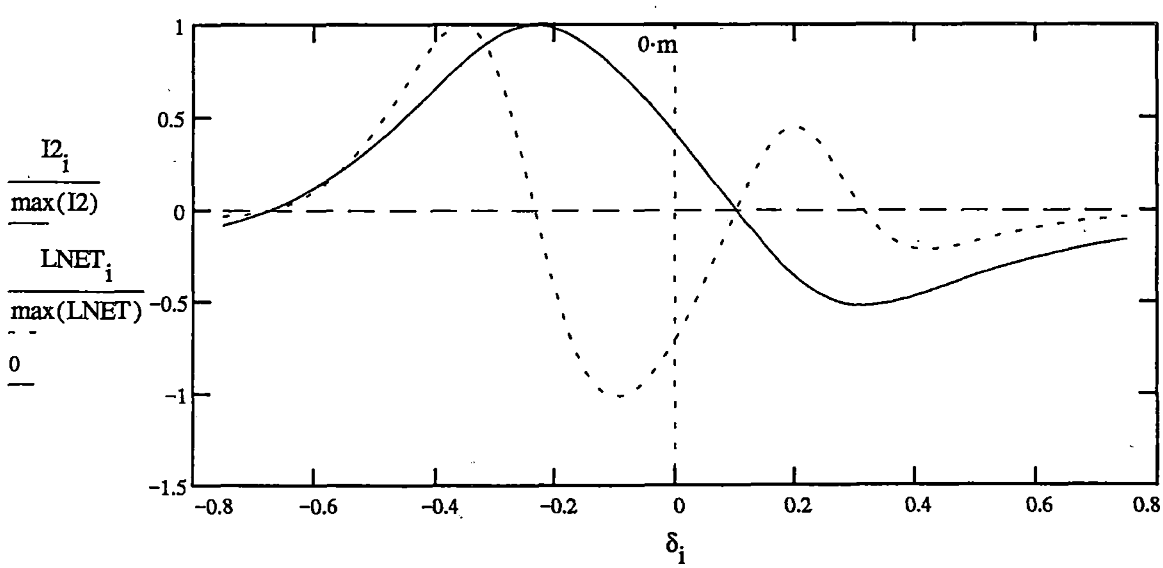
note that the best positive levitation occurs with the coil very low!!!

check the results of the split calculation with that of the original single calculation by doing the same case for both.

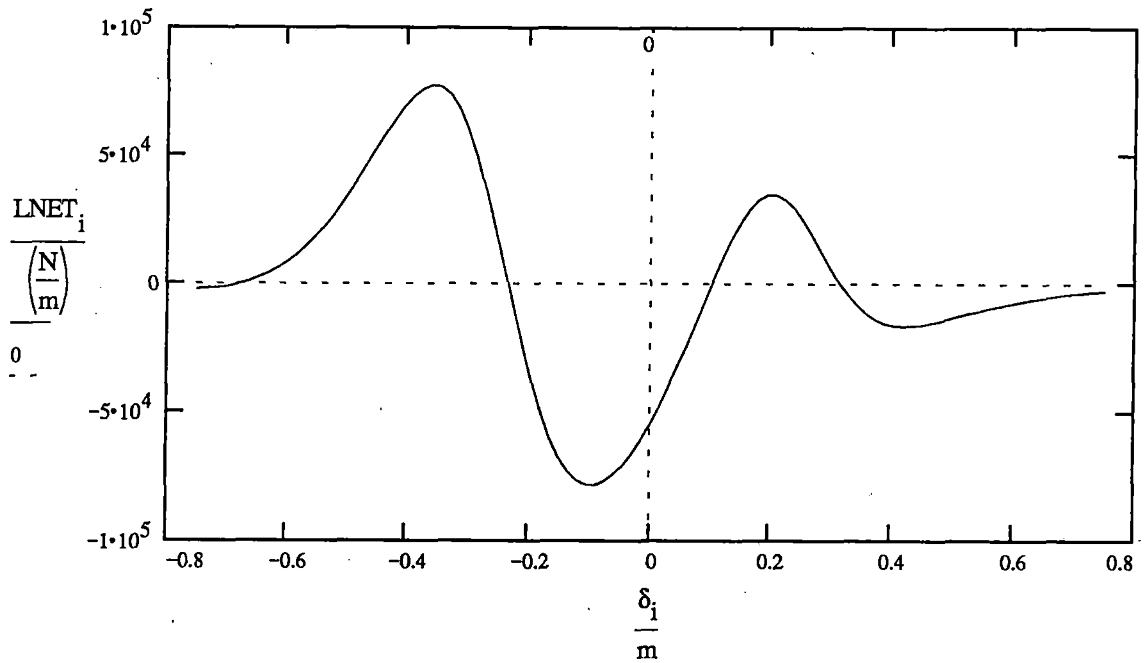
$I21chk_i := I_2(H1_i, h, g_1, I_1)$ $\quad L1chk_i := LIFT(H1_i, h, g_1, I_1, I21chk_i)$ checks!!!

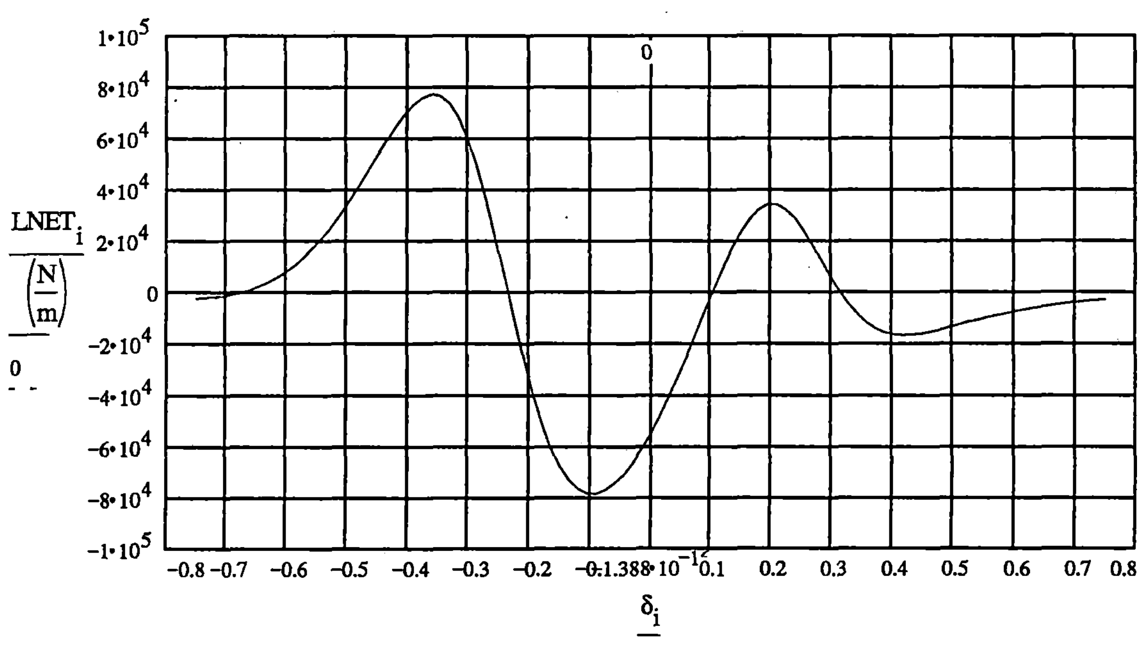


look at coil current along with lift



Note that the best lift is with the coil at .5 m down (never want to be near the top of the curve).
The coil is .5 m high for this case so the coil is about .25 meters below the outer conductor and that doesn't fits well with the lateral switch since the bottom of the vehicle is about .6 meters down from the edge conductor. Maybe a different coil arrangement could get the extra distance though.
Might should look at the stability. Roll and lateral stability in particular.



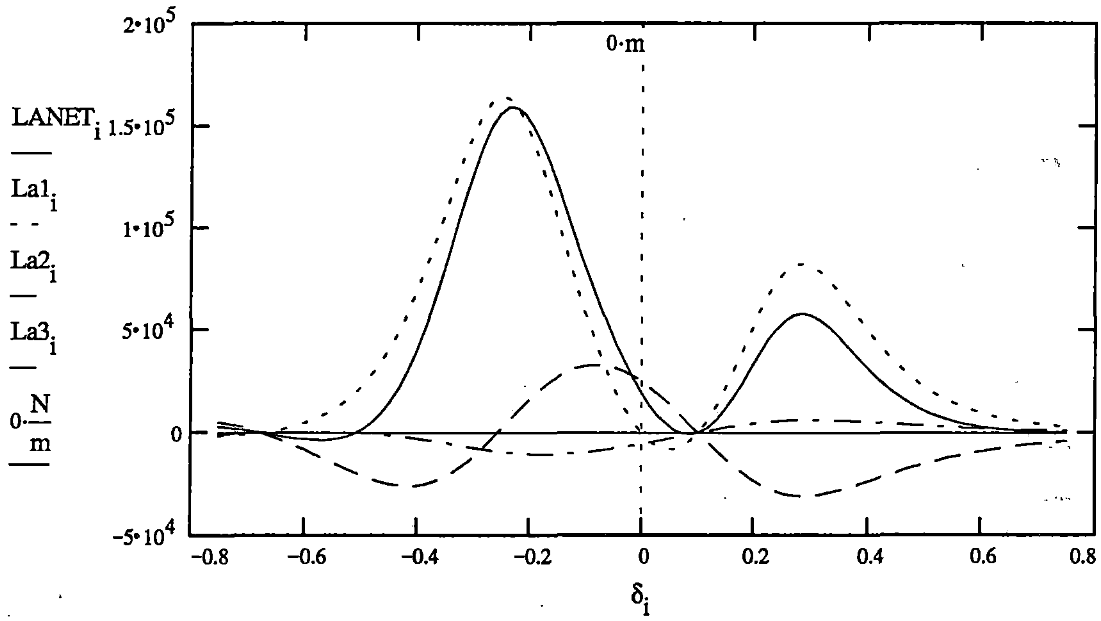


now look at the lateral forces generated

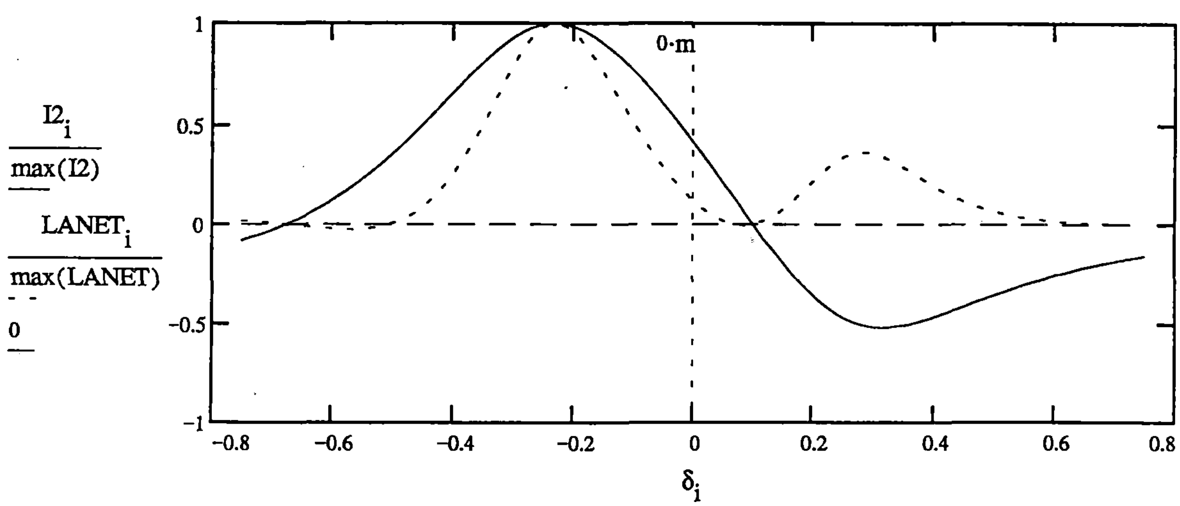
centering force is positive

$$LAT(\delta, h, g, I_1, I_2) := -\frac{\mu_0}{2\cdot\pi}\cdot I_1 \cdot I_2 \cdot \left[\frac{g}{g^2 + \left(\frac{h}{2} - \delta\right)^2} - \frac{g}{g^2 + \left(\frac{h}{2} + \delta\right)^2}\right]$$

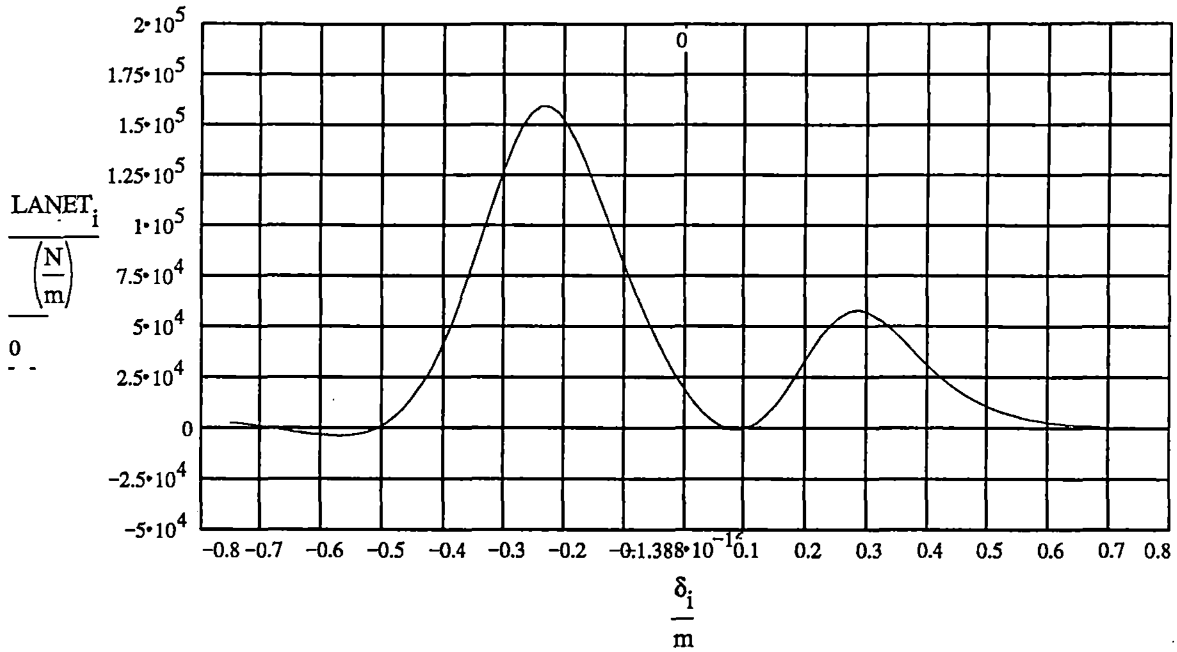
$$La1_i := LAT(H1_i, h, g_1, I_1, I2_i)$$
$$La2_i := LAT(H2_i, h, g_2, -2\cdot I_1, I2_i)$$
$$La3_i := LAT(H3_i, h, g_3, I_1, I2_i)$$
$$LANET_i := La1_i + La2_i + La3_i$$



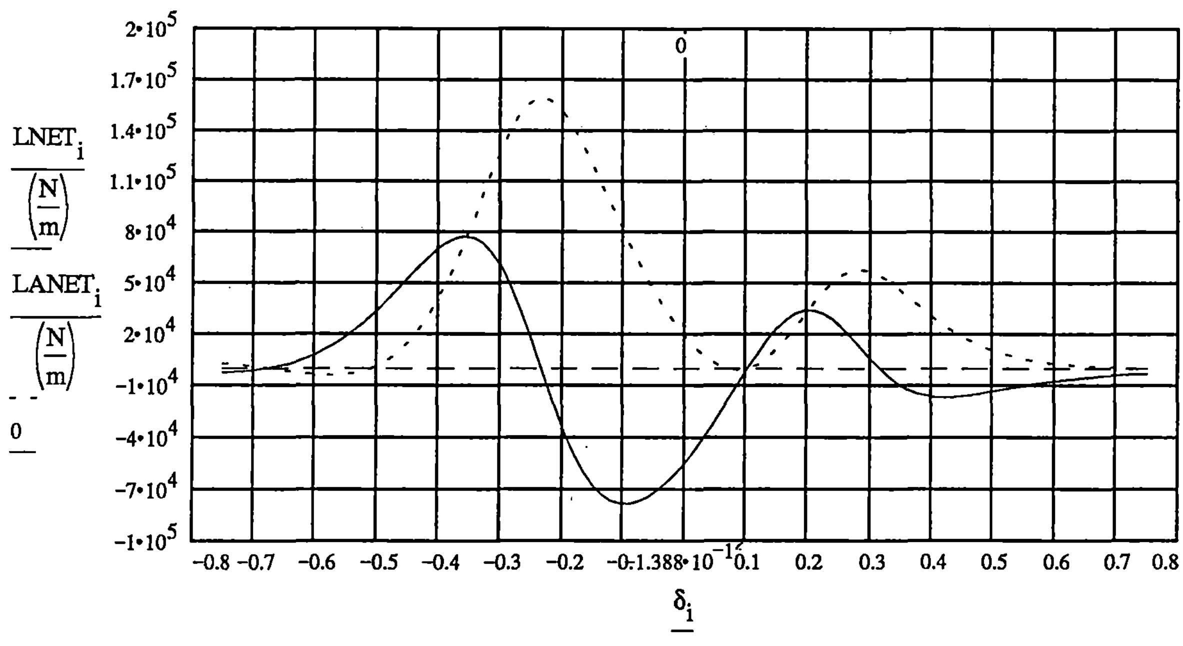
look at the normalized current and centering force on the same plot



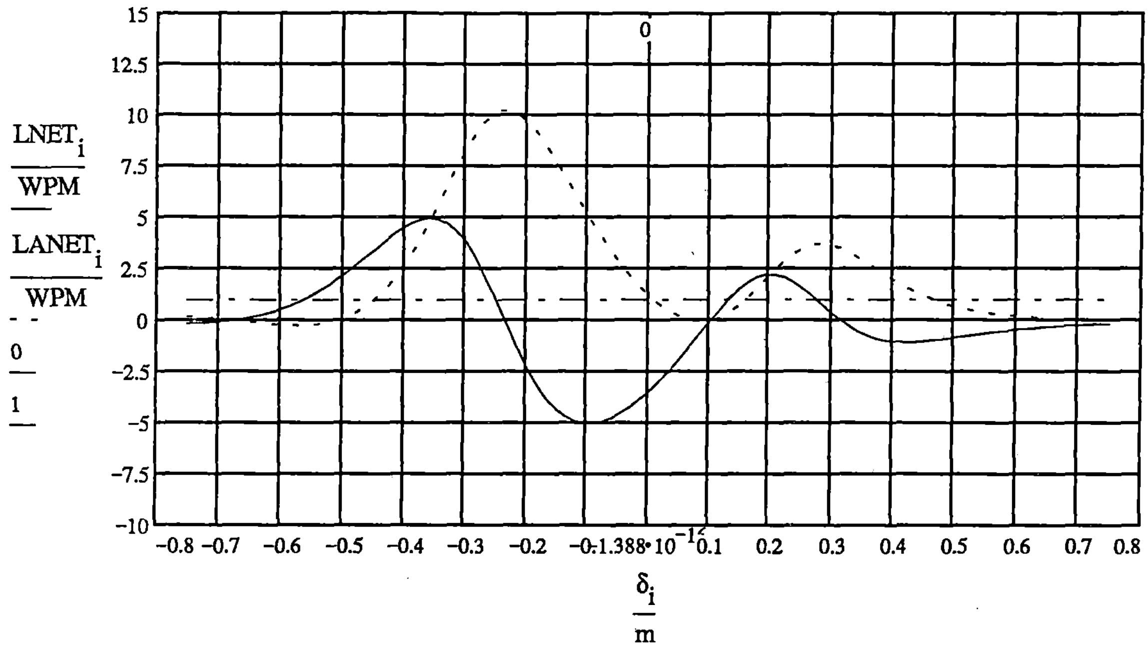
look at just the lateral centering force



look at the lift and the centering force at the same time to see what happens when



Normalize the reulsts by the weight of the magnet per meter of the vehicle magnet.



now look at the centering forces for lateral motions at a given displacement delta.

FIRST FOR ONE SIDE ONLY !!! (WILL ADD OPPOSITE SIDES EFFECT LATER)

centering force is positive and same equation holds for one side:

$$LAT(\delta, h, g, I_1, I_2) := -\frac{\mu_0}{2\cdot\pi}\cdot I_1\cdot I_2\cdot\left[\frac{g}{g^2+\left(\frac{h}{2}-\delta\right)^2}-\frac{g}{g^2+\left(\frac{h}{2}+\delta\right)^2}\right]$$

now the gap g changes and delta can be held constant. (Would like to do for several delta values).

first just look at the centering force for a controllable delta
Let the gap vary now

$n := 100$ $\quad j := 0..n$ $\quad g_{max} := .1\cdot m$ $\quad g0 := .2\cdot m$ $\quad \varepsilon_j := \left(\frac{j}{n}-\frac{1}{2}\right)\cdot 2\cdot g_{max}$

Gap goes bigger when g is bigger $\quad g_j := g0 + \varepsilon_j$

Set the different displacements up now

$k := 0..3$

$\delta d_0 := .1\cdot m$

$\delta d_1 := .175\cdot m$

$\delta d_2 := .225\cdot m$

$\delta d_3 := .3\cdot m$

Get the current for each gap   same current equation holds

$$I_2(\delta, h, g, I_1) := \frac{I_1}{2} \cdot \frac{\ln\left[\frac{\sqrt{g^2 + \left(\frac{h}{2} - \delta\right)^2}}{\sqrt{g^2 + \left(\frac{h}{2} + \delta\right)^2}}\right]}{\ln\left(\frac{h}{a}\right)}$$

now get net coil current by superposition

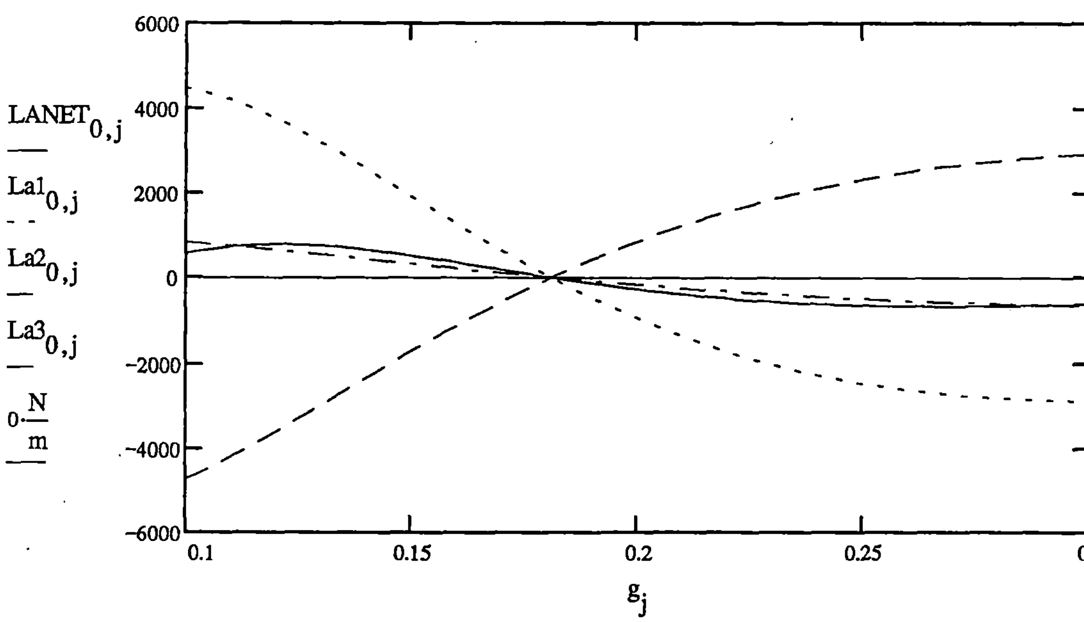
$$I2_{k,j} := I_2(\delta d_k, h, g_j, I_1) + I_2(\delta d_k + Y_2, h, g_j + X_2, -2 \cdot I_1) + I_2(\delta d_k + Y_3, h, g_j + X_3, I_1)$$

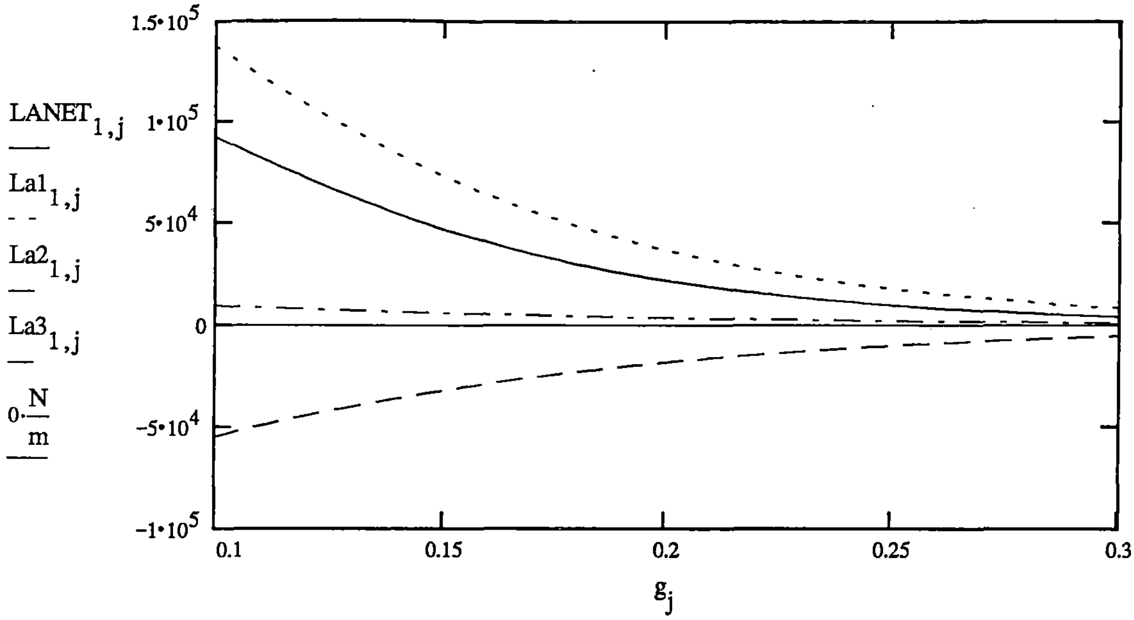
$$La1_{k,j} := LAT(\delta d_k, h, g_j, I_1, I2_{k,j})$$

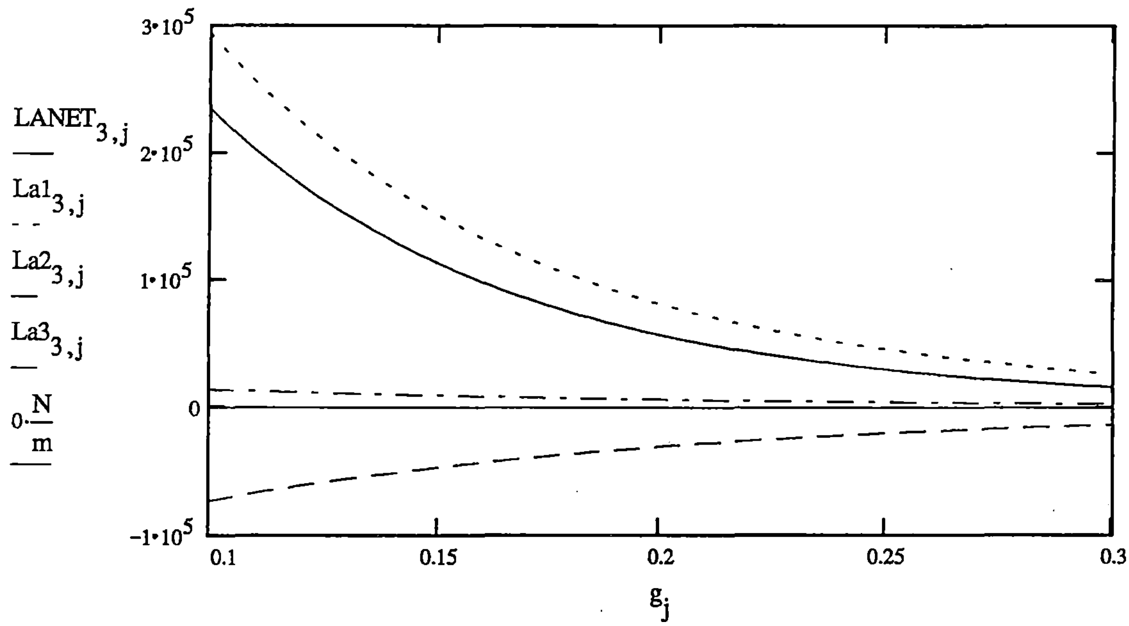
$$La2_{k,j} := LAT(\delta d_k + Y_2, h, g_j + X_2, -2 \cdot I_1, I2_{k,j})$$

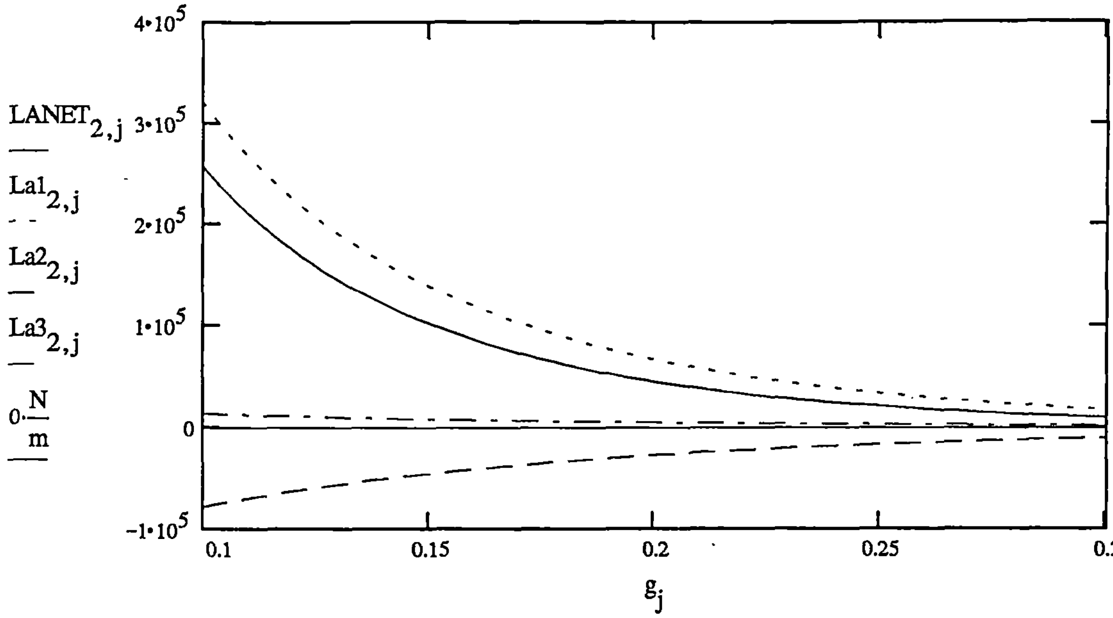
$$La3_{k,j} := LAT(\delta d_k + Y_3, h, g_j + X_3, I_1, I2_{k,j})$$

$$LANET_{k,j} := La1_{k,j} + La2_{k,j} + La3_{k,j}$$



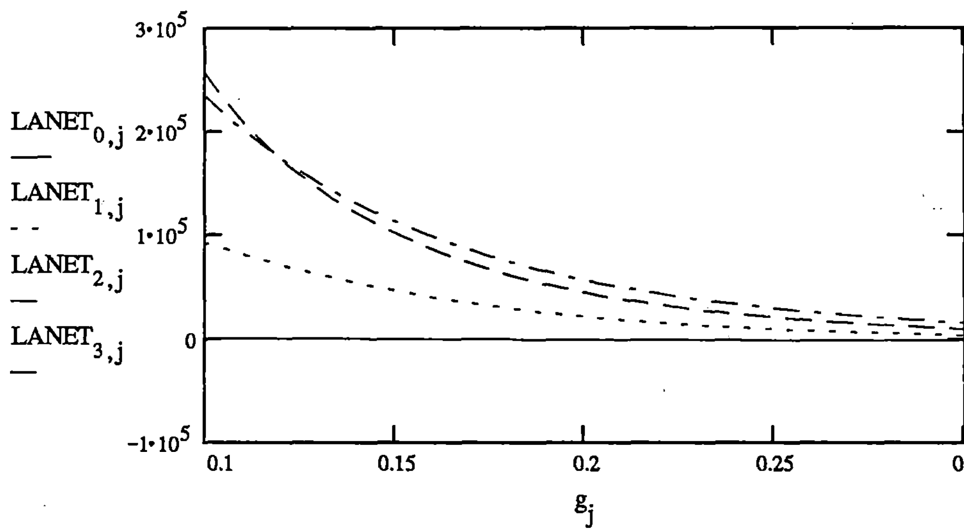

LANETf1,j
La1 1,j
La2 1,j
La3 1,j
0·N/m
1.5·10^5
1·10^5
5·10^4
0
-5·10^4
-1·10^5
0.1
0.15
0.2
0.25
0.3
g j


LANET 3,j
La1 3,j
La2 3,j
La3 3,j
0·N/m
3·10^5
2·10^5
1·10^5
0
-1·10^5
0.1
0.15
0.2
0.25
0.3
g j



plot only the net lateral force (centering is positive)

note that an increasing gap should produce less force and a deceasing gap should produce more force



NOW DO BOTH SIDES TO GET NET CENTERING FORCE

The force as calculated above must be added to the negative of the force produced by the other side to get the answer in the form of the net force. If the gap is increasing (more positive) on the right side then the force should be to the right positive to provide centering. But, now if the gap is being reduced (g<.2) then the force should be negative to push it back.

I would like a better sign convention. So I have introduced epslon (e) to be the displacement from the center. The displacement can be right or left. For this situation the sides are symetrical and only the displacement matters, but for the case where the two sides are not equally levitated this might not be so. I am not doing the unequal levitation case yet but I will still allow a right or left deviation. This allows a check since the results should be symetric

Now do the "left" side where increasing g on the right side is reducing the gap gl on the "left" side.

gl is the left side gap.

now get net coil current one the left side by superposition $gl_j := g0 - \varepsilon_j$

$$I2l_{k,j} := I_2(\delta d_k, h, gl_j, I_1) + I_2(\delta d_k + Y_2, h, gl_j + X_2, -2\cdot I_1) + I_2(\delta d_k + Y_3, h, gl_j + X_3, I_1)$$

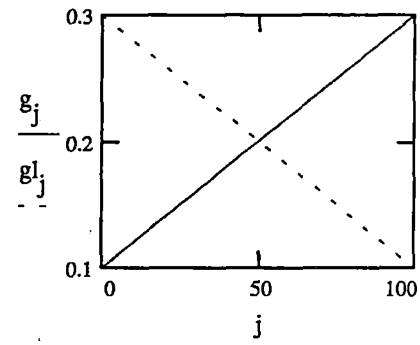
$$Lal1_{k,j} := LAT(\delta d_k, h, gl_j, I_1, I2l_{k,j})$$

$$Lal2_{k,j} := LAT(\delta d_k + Y_2, h, gl_j + X_2, -2\cdot I_1, I2l_{k,j})$$

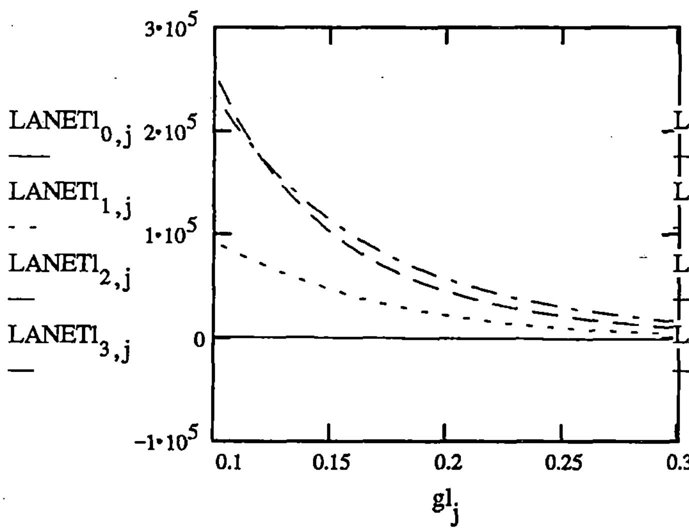
$$Lal3_{k,j} := LAT(\delta d_k + Y_3, h, gl_j + X_3, I_1, I2l_{k,j})$$

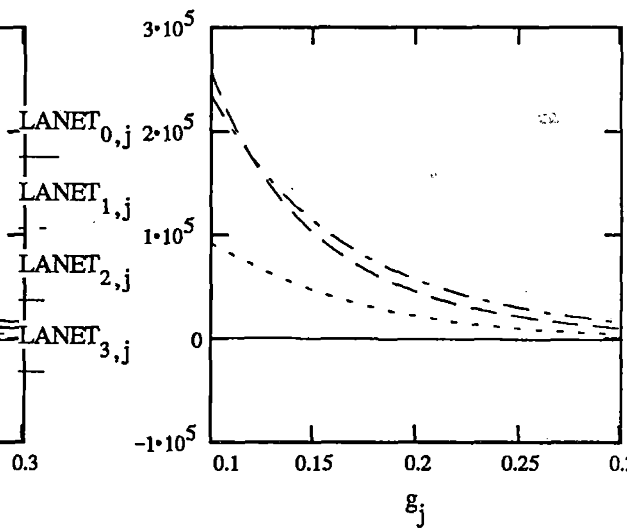
$$LANETl_{k,j} := Lal1_{k,j} + Lal2_{k,j} + Lal3_{k,j}$$

$$CNET_{k,j} := LANET_{k,j} - LANETl_{k,j}$$

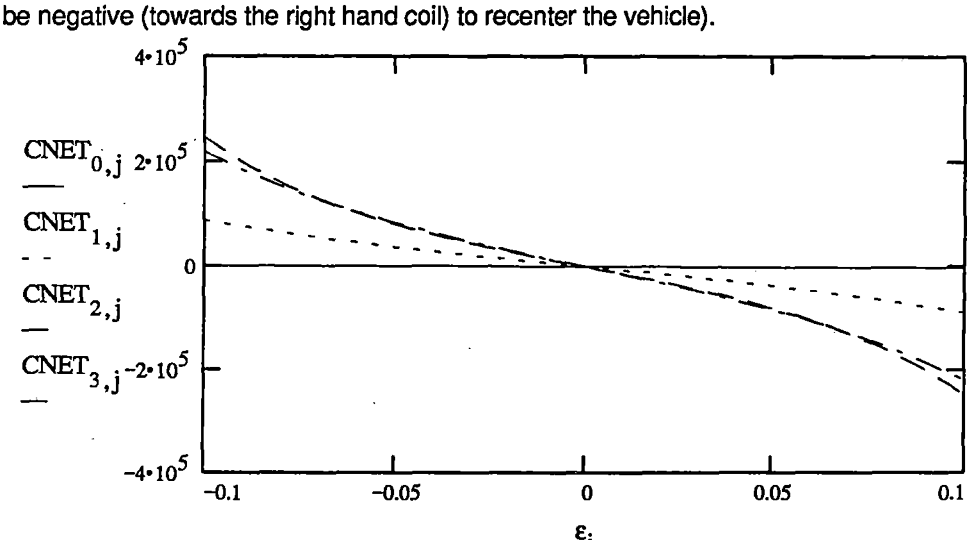


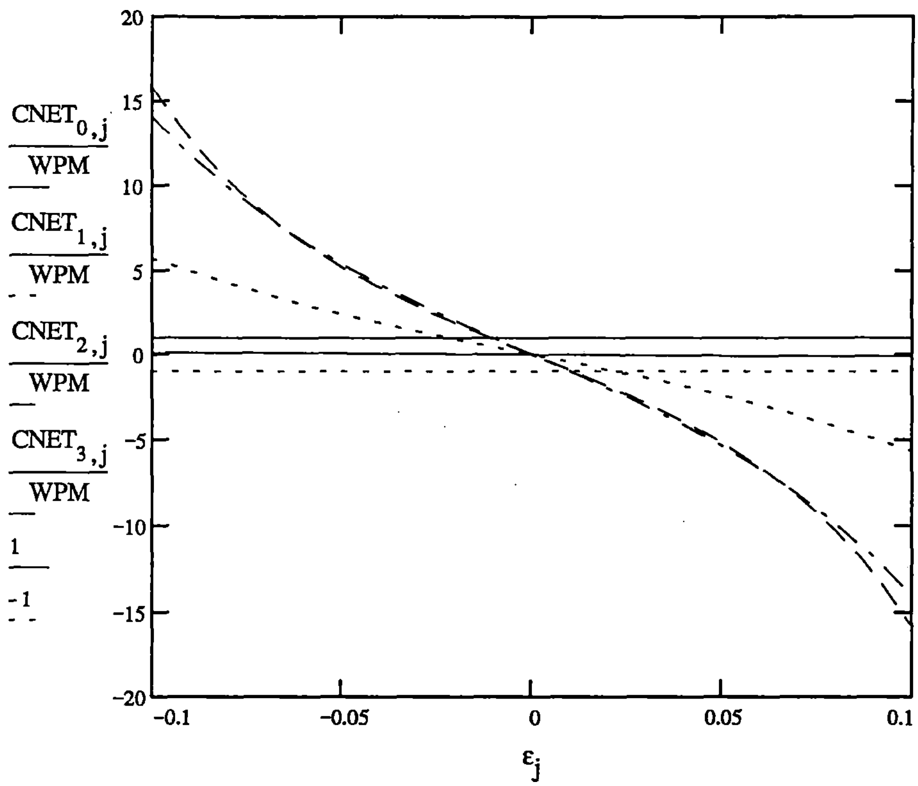
check to see that both give the same answer. They should look the same but note that the gaps are mapped to g and gl by j oppositly so that they can be added based on j to get the net result. CHECKS BELOW OK.





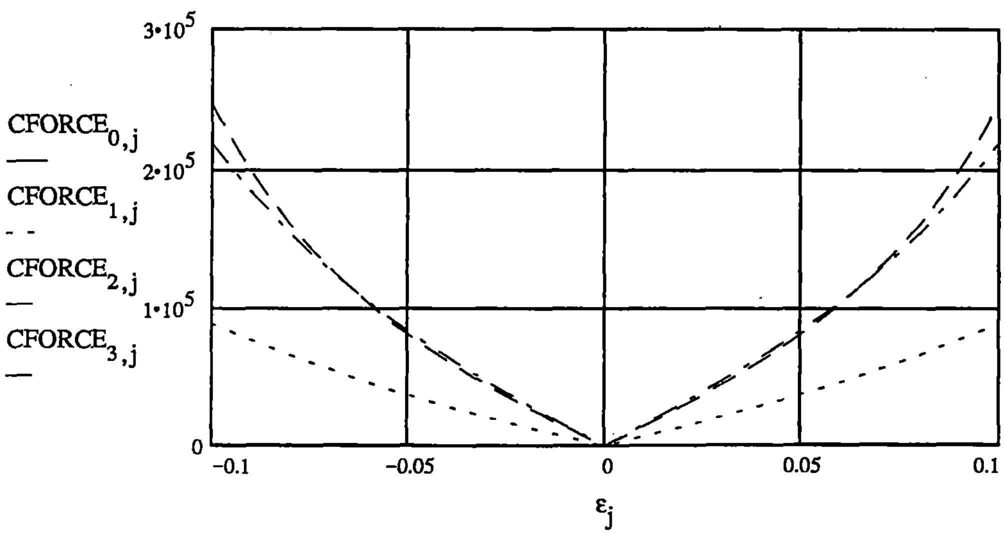
note that an increasing epslon increases the gap on the right and the sign convention was that a positive force pushed the vehicle to the left (away from the right coil) so as shown below the net force in the right hand quadrant should be negative (towards the right hand coil) to recenter the vehicle).





NOW FIX THE SITUATION SO THAT THE CURVES ARE MORE EASILY UNDERSTOOD IN TERMS OF A TROUGH

$$CFORCE_{k,j} := -CNET_{k,j} \cdot \frac{\varepsilon_j}{\left|\varepsilon_j\right|}$$



$$\delta d = \begin{bmatrix} 0.1 \\ 0.175 \\ 0.225 \\ 0.3 \end{bmatrix} \cdot m$$

APPENDIX C

Additional Switch Concepts

Additional switch concepts not included in the text follow, generally without comment. An air bearing switch based on early air cushion vehicle configurations, except that the roles of the guideway and vehicle are reversed since the vehicle does not have adequate onboard power, indicates that the power requirements for air jets in the guideway to levitate the vehicle are on the order of 6 Mw or more (16 kW/m) if the entire switch length is energized at once. This provides no power advantage relative to electromagnetic switches. Reliability and maintenance of this air bearing switch is considerably worse than electromagnetic switches.

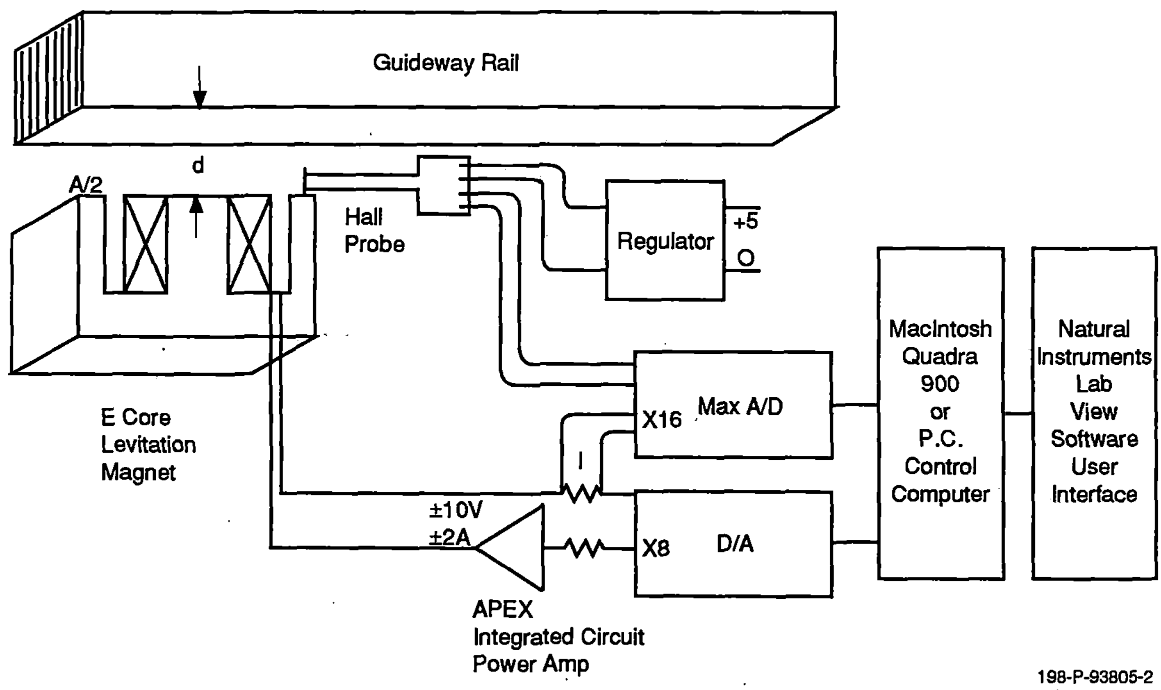


Figure C-2. Demonstration System Concept Schematic. The EMS Switch Concept (Shown in Figures 21 & 22) Demonstrated Using an Arrangement Similar to this with More Magnets

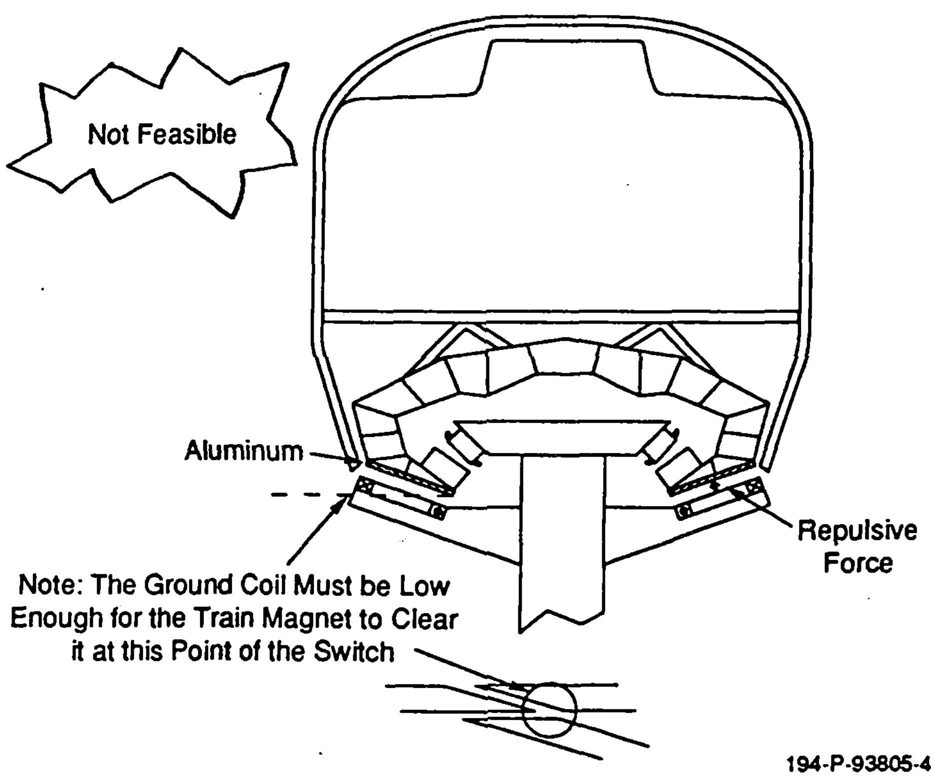
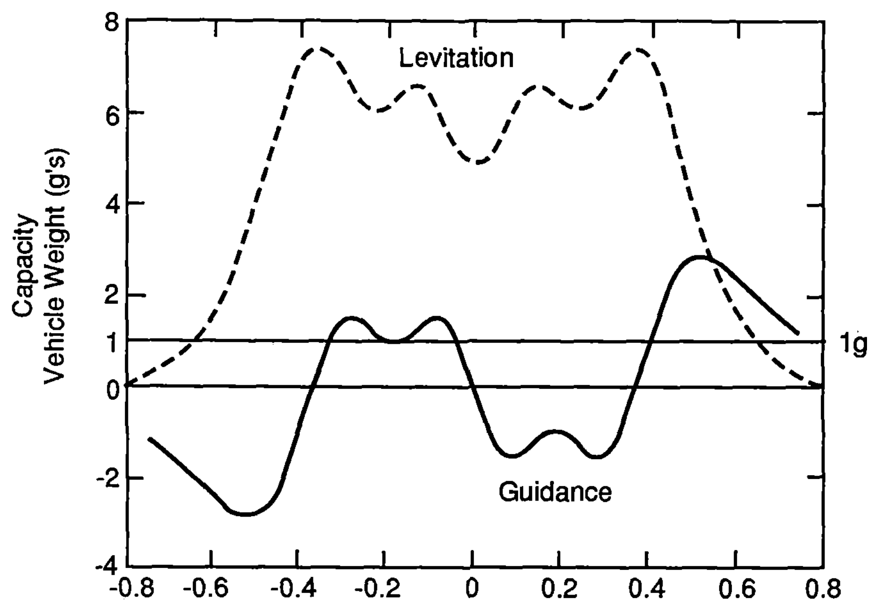


Figure C-3. The Slotted Guideway Concept for the Grumman System (the Steep Angles of the Pole Faces Lead to Interference Problems)



Amp turns on Superconductor Isc = $1 \cdot 10^6 \cdot$ amp

Vehicle Weight per meter WPM = $2.747 \cdot 10^4 \cdot \frac{N}{m}$

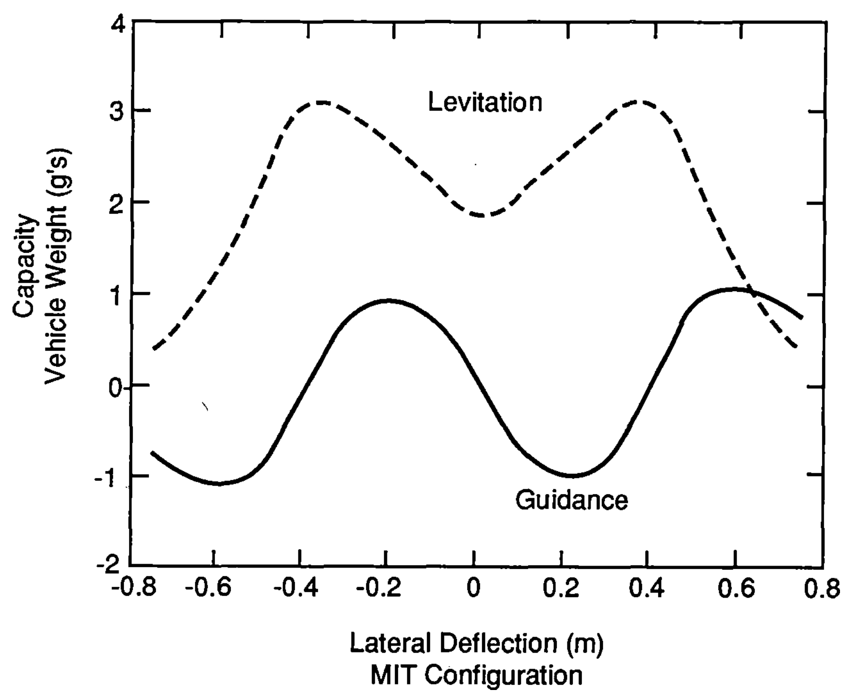
Levitation height h = 0.2m

Coils: 0.5m wide
0.25 m Center to Center Spacing

FMI Configuration Demonstrates Ample Stiffness -
Forces shown at Contact Spacing of 20cm
Spacing between SC and Ground Coil Centereline Heights

213-DOT-9711-6

Figure C-4a. Levitation and Guidance for the Foster-Miller Vehicle on a Flat Overlapping Coil Guideway Similar to Figure 31.



Amp turns on Superconductor $Isc = 1 \cdot 10^6 \cdot amp$

Vehicle Weight per meter $WPM = 2.747 \cdot 10^4 \cdot \frac{N}{m}$

Levitation height $h = 0.3m$

Coils: 0.5m wide
0.25 m Center to Center Spacing

FMI Configuration has Ample Capacity and Levitation at over 30 cm Center to Center Gap

213-DOT-9711-7

Figure C-4b. Levitation and Guidance for the Foster-Miller Vehicle on a Flat Overlapping Coil Guideway with a Large Gap

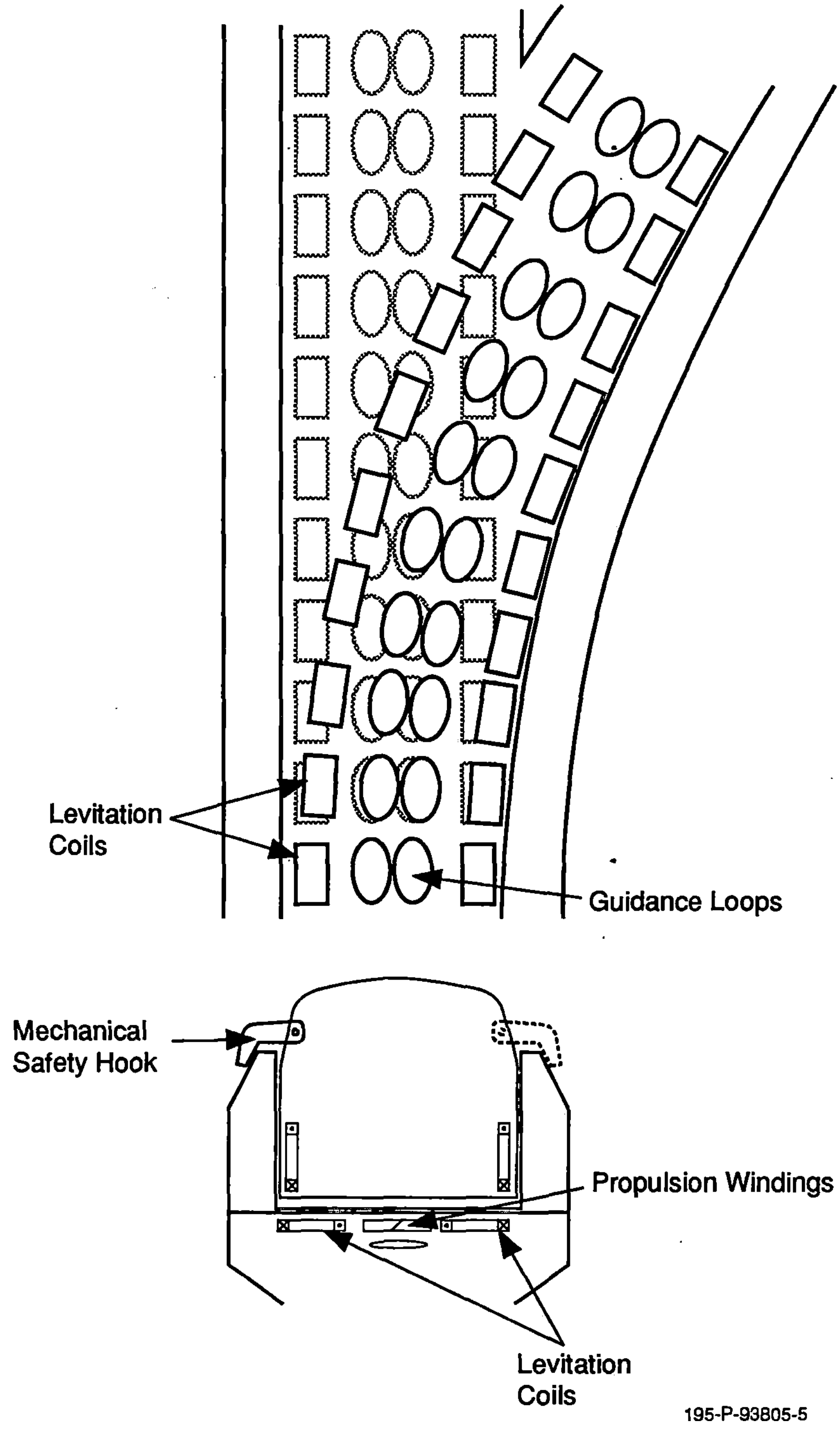


Figure C-5. Switched Ground Coil Lateral Switch for Magnaplane, Bechtel, or Foster-Miller Configurations

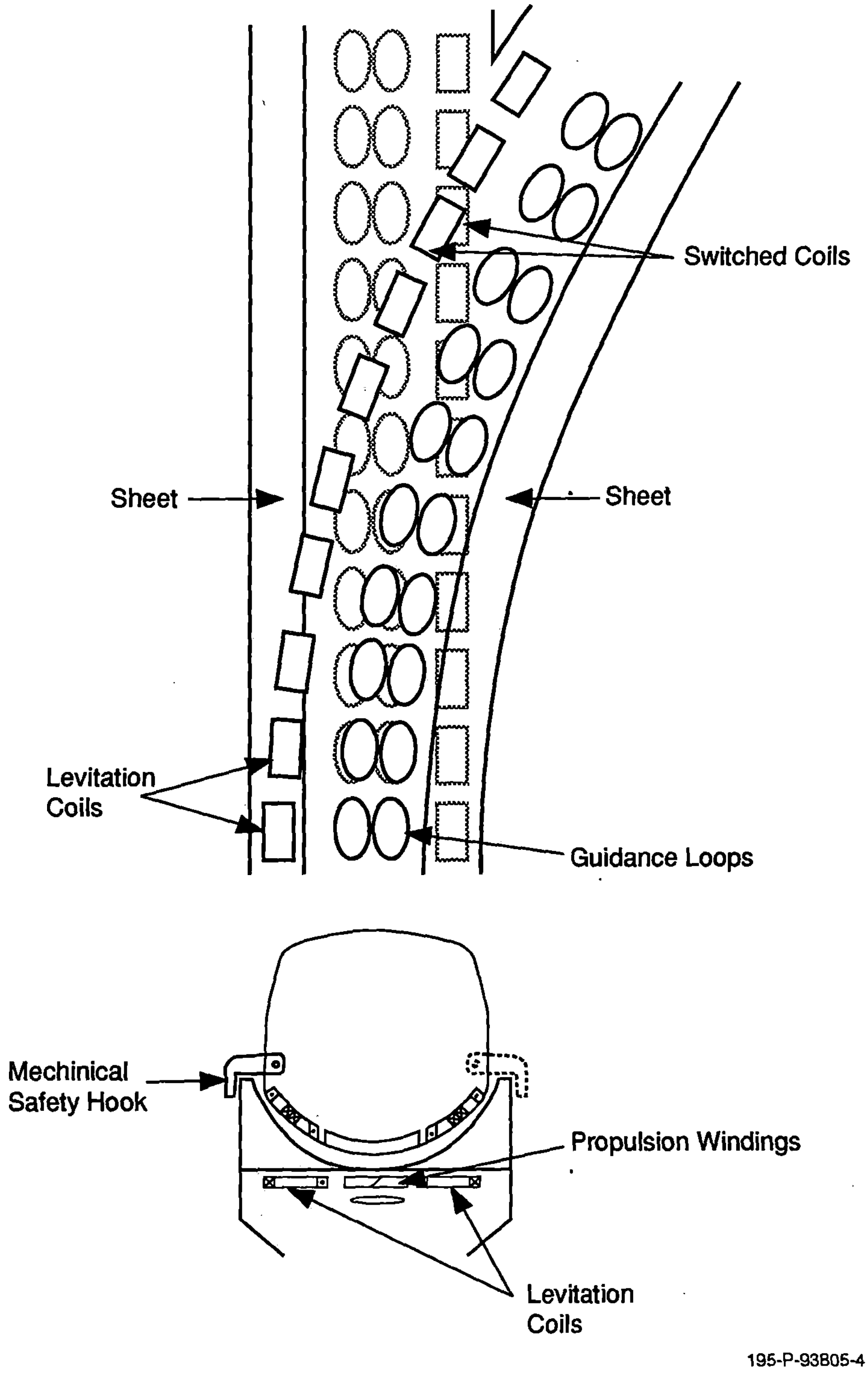


Figure C-6. Switched Coil and Sheet System for Magnaplane, Bechtel, or Foster-Miller Configurations

APPENDIX D

Comparison of Switch Performance Using Pugh Charts

The complete Pugh charts including all of the criteria follow for reference.

	For the Bechtel MIT Syste	DATUM =	flat	arched	roof	switched	switched	vertical	powered	powered
		roof mounted	sheet	sheet	mounted	guideway	guideway	switch	guideway	guideway
		switch			switch	flat	slotted		flat ac	slotted ac
	Criteria		MOD	MOD	powered r	MOD	MOD	MOD	STOCK	STOCK
			comp	comp	comp	comp	comp	comp	comp	comp
	Speed	max	s	s	datum	s	s	s	s	s
		min	-	-	to zero	-	-	-	s	s
	Susceptability interference	snow /ice	-	-	vehicle	-	-	+	-	-
		debris	-	-	surface	-	-	+	-	-
	Cost	guideway	+	+	reasonabl	+	+	+	s	s
#		land	s	s	lateral	s	s	+	s	s
#		vehicle	+	+	moderate	+	+	+	+	+
		power	+	+	low	+	+	+	-	-
		electronics	+	+	high	+	+	+	s	s
	Ride Comfort	Coordinated turns	s	+	slightly	s	s	+	s	s
#		stiffness, suspen.	-	-	controllabl	-	-	+	-	-
#		uses secondary	+	+	no	+	+	+	+	+
#		Propulsion	s	s	syncreluct	s	s	+	s	s
		Propulsion type	1/2lsm	1/2lsm	reluct,LSM	1/2lsm	1/2lsm	lsm	lim?	1/2lsm
	Transitions	entry	-	-	good	-	-	+	-	-
		swich	-	-	good	-	-	+	-	-
		exit	-	-	good	-	-	+	-	-
	Related performance factors									
	VEHICLE impact	Frontal area (drg)	s	s	small	s	s	s	s	s
		max width	s	s	small	s	s	s	s	s
#		Weight	+	+	moderate	+	+	+	+	+
					5%&struct					
		space used (INT)	+	+	structure	+	+	+	+	+
		extra power used	s	s	small	+	+	+	+	+
#		complexity	+	+	od to hig	+	+	+	+	+
		ease of maintanc	+	+	easy	+	+	+	+	+
		vehicle cost	+	+	moderate	+	+	+	+	+
		noise	s	s	little	s	s	+	s	s
	SYSTEM impact	Right of way	-	-	vertical	-	-	s	-	-
		switch speed	s	s	any	s	s	+	-	-
#		reliability	+	+	moderate	+	+	+	s	s
		maintanence	+	+	moderate	+	+	+	s	s
		spacing of next s	s	s	close	s	s	+	-	-
		branch number	-	-	2	s	-	+	s	-
#		cost	+	+	moderate	+	+	+	-	-
	SAFETY									
	normal operation	wind	-	s	moderate	+	+	+	s	s
		high speed	+	+	good	+	+	+	s	s
		low speed	-	-	good	-	-	-	-	-
	emergencies	p power loss	+	+	eed backu	+	+	+	-	-
		levitation capacity	s	s		s	s	s	s	s
#		braking surfaces	-	-	backups	-	s	+	-	-
	failure modes									
	restarting after a problem		-	-	ok	-	-	-	s	s
	MECHANICAL BACKUP									
	COMMENTS									
	comp	plusses	15	16	0	17	17	31	8	8
	+	minusses	13	12	0	11	11	3	14	14
	comp	sames	11	11	7	11	11	5	17	17

	For the Magnaplane Syste	DATUM =	flat	arched	roof	switched	switched	vertical	powered	powered
		roof mounted	sheet	sheet	mounted	guideway	guideway	switch	guideway	guideway
		switch			switch	flat	slotted		flat ac	slotted ac
	Criteria				powered r					
			comp	comp	comp	comp	comp	comp	comp	comp
	Speed	max	s	s	datum	s	s	s	s	s
		min	-	-	to zero	-	-	-	s	s
	Susceptability interference	snow /ice	-	-	vehicle	-	-	+	-	-
		debris	-	-	surface	-	-	+	-	-
	Cost	guideway	+	+	reasonabl	+	+	+	s	s
#		land	s	s	lateral	s	s	+	s	s
#		vehicle	+	+	moderate	+	+	+	+	+
		power	+	+	low	+	+	+	-	-
		electronics	+	+	high	+	+	+	s	s
	Ride Comfort	Coordinated turns	s	+	slightly	s	s	+	s	s
#		stiffness, suspen.	-	-	controllabl	-	-	+	s	s
#		uses secondary	+	+	no	+	+	+	+	+
#		Propulsion	s	s	syncreluct	s	s	+	s	s
		Propulsion type	1/2lm	1/2lm	reluct,LSM	1/2lm	1/2lm	lm	lim?	1/2lm
	Transitions	entry	-	-	good	-	-	+	-	-
		swich	-	-	good	-	-	+	-	-
		exit	-	-	good	-	-	+	-	-
	Related performance factors									
	VEHICLE impact	Frontal area (drg)	s	s	small	s	s	s	s	s
		max width	s	s	small	s	s	s	s	s
#		Weight	+	+	moderate	+	+	+	+	+
					5%&struct					
		space used (INT)	+	+	structure	+	+	+	+	+
		extra power used	s	s	small	+	+	+	+	+
#		complexity	+	+	od to hig	+	+	+	+	+
		ease of maintanc	+	+	easy	+	+	+	+	+
		vehicle cost	+	+	moderate	+	+	+	+	+
		noise	s	s	little	s	s	+	s	s
	SYSTEM impact	Right of way	-	-	vertical	-	-	s	-	-
		switch speed	s	s	any	s	s	+	-	-
#		reliability	+	+	moderate	+	+	+	s	s
		maintanence	+	+	moderate	+	+	+	s	s
		spacing of next s	s	s	close	s	s	+	-	-
		branch number	-	-	2	s	-	+	s	-
#		cost	+	+	moderate	+	+	+	-	-
	SAFETY									
	normal operation	wind	-	s	moderate	+	+	+	s	s
		high speed	+	+	good	+	+	+	s	s
		low speed	-	-	good	-	-	-	-	-
	emergencies	p power loss	+	+	eed backu	+	+	+	-	-
		levitation capacity	+	+		+	+	+	+	+
#		braking surfaces	+	+	backups	-	-	+	-	-
	failure modes									
	restarting after a problem		-	-	ok	-	-	-	s	s
	MECHANICAL BACKUP									
	COMMENTS									
	comp	plusses	17	18	0	18	18	32	9	9
	+	minusses	12	11	0	11	12	3	13	13
	comp	sames	10	10	7	10	9	4	17	17

	For the modified Grumma or the Transrapid	DATUM roof mounted switch	powered guideway flat AC	powered guideway flat DC	powered guidewa slotted	roof mounted switch	modified double levitation	modified track levitation	repulsive keel	powered flat iron core	powered slotted iron core
	Criteria		G	G	G	G	MG	G	G	G	G
			comp	comp	comp	comp	comp	comp	comp	comp	comp
	Speed	max	s	s	s	datum	s	s	s	s	s
		min	s	-	-	to zero	s	s	-	-	-
	Susceptability interference	snow /ice	-	-	-	vehicle	+	+	-	-	-
		debris	-	-	-	surface	+	+	-	-	-
	Cost	guideway	-	-	-	reasonabl	s	s	-	-	-
#		land	s	s	s	lateral	s	s	s	s	s
#		vehicle	+	+	+	moderate	s	-	-	-	+
		power	to 12 M	to 12 M	4 to 6 M	low	s	s	to 12 M	?	?
		electronics	s	s	s	high	s	s	s	s	s
	Ride Comfort	Coordinated turns	s	s	s	slightly	s	s	s	s	s
#		stiffness, suspen.	-	-	-	controllabl	+	s	-	-	-
#		uses secondary	+	+	+	no	+	+	+	+	+
#		Propulsion	-	-	-	syncreluct	+	s	-	-	-
		Propulsion type	LIM	LIM	LIM	reluct,LSM	LSM	LSM	LIM	LIM	LIM
	Transitions	entry	-	-	-	good	+	s	-	-	-
		swich	-	-	-	good	+	s	-	-	-
		exit	-	-	-	good	+	s	-	-	-
	Related performance factors										
	VEHICLE impact	Frontal area (drg)	s	s	s	small	-	-	s	s	s
		max width	s	s	s	small	-	-	s	s	s
#		Weight	+	+	+	moderate	s	+	+	+	+
						5%&struct					
		space used (INT)	+	+	+	structure	+	+	+	+	+
		extra power used	-	-	-	small	+	s	-	-	-
#		complexity	+	+	+	od to hig	+	+	+	+	+
		ease of maintanc	s	s	s	easy	-	-	s	s	s
		vehicle cost	+	+	+	moderate					
		noise	s	s	s	little	-	-	s	s	s
	SYSTEM impact	Right of way	s	s	s	lateral	s	s	s	s	s
		switch speed	-	-	-	any	+	s	-	-	-
#		reliability/redunda	-	-	-	moderate	+	s	-	-	-
		maintanence	s	s	-	moderate	-	-	s	s	-
		spacing of next s	-	-	-	close	+	s	-	-	-
		branch number	s	s	-	2	-	-	s	s	-
#		cost	-	-	-	moderate	+	+	-	-	-
	SAFETY										
	normal operation	wind	s	s	s	moderate	+	+	-	s	s
		high speed	s	s	s	good	+	+	-	s	s
		low speed	-	-	-	good	+	+	-	-	-
	emergencies	p power loss	-	-	-	eed backu	+	s	-	-	-
		levitation capacity	s	s	s		+	s	s	s	s
#		braking surfaces	-	-	-	backups	+	+	-	-	-
	failure modes										
	restarting after a problem		-	-	-	ok	+	+	-	-	-
	MECHANICAL BACKUP										
	COMMENTS										
	comp	plusses	6	6	6	0	22	12	4	4	4
	+	minusses	17	18	20	0	6	7	21	19	19
	comp	sames	15	14	12	7	10	19	12	14	14