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System Concept Definition of the Grumman Superconducting Electromagnetic Suspension (EMS) Maglev Design

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SUMMARY

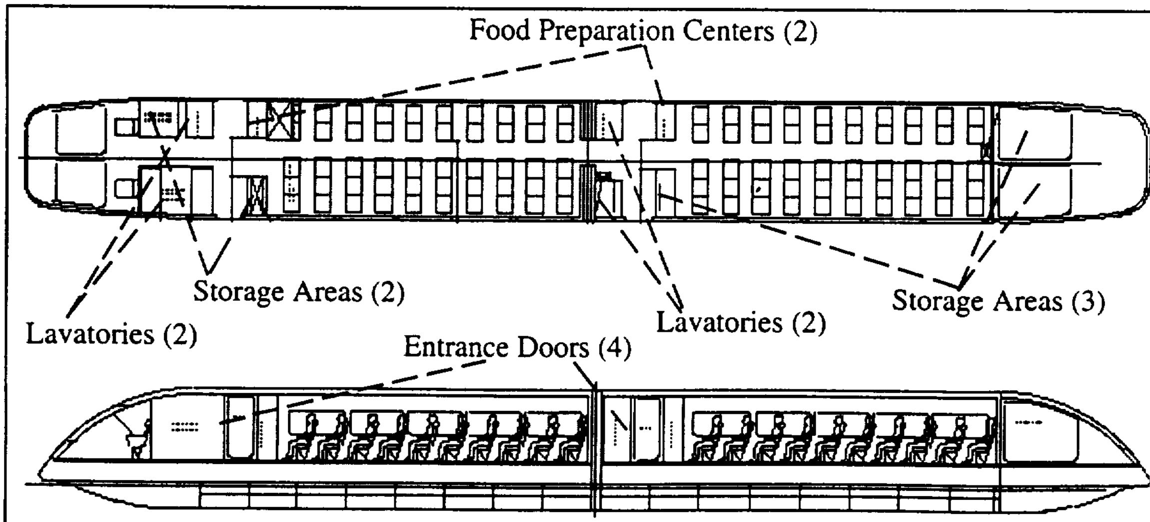
Grumman, under contract to the Army Corps of Engineers, completed a System Concept Definition (SCD) study to design a high-speed 134 m/s (300 m.p.h.) magnetically levitated (Maglev) transportation system. The primary development goals were to design a Maglev that is safe, reliable, environmentally acceptable, and low-cost. The cost issue was a predominant one, since previous studies [1] have shown that an economically viable Maglev system (one that is attractive to investors for future modes of passenger and/or freight transportation) requires a cost that is about $12.4M/km ($20 Million per mile).

The design (Fig. 1) is based on the electromagnetic suspension (EMS) system using superconducting iron-core magnets mounted along both sides of the vehicle. The EMS system has several advantages compared to the electrodynamic suspension (EDS) Maglev systems such as low stray magnetic fields in the passenger cabin and the surrounding areas, uniform load distribution along the full length of the vehicle, and small pole pitch for smoother propulsion and ride comfort. It is also levitated at all speeds and incorporates a wrap-around design for safer operation. The Grumman design has all the advantages of an EMS system identified above, while eliminating (or significantly improving) drawbacks associated with normal magnet powered EMS systems. Improvements include larger gap clearance, lighter weight, lower number of control servos, and higher off line switching speeds. The design also incorporates vehicle tilt ($\pm 9^{o}$) for higher coordinated turn and turn out speed capability.

INTRODUCTION

The Grumman Corporation assembled a team of six corporations and one university that were exceptionally qualified to perform the identified SCD study. The Grumman team members and associated responsibilities were:

- *Grumman Corporation* - system analysis and vehicle design
- *Parsons Brinckerhoff* - guideway structure design
- *Intermagnetics General Corp. (IGC)* - superconducting magnet design
- *PSM Technologies* - linear synchronous motor (LSM) propulsion system design
- *Honeywell* - communication, command, and control (C^3) design
- *Battelle* - safety and environmental impact analysis
- *NYSIS* - high temperature superconductor (HTSC) and magnetic shielding analysis.



The "Baseline Configuration" is 100 passengers with 5 across seating. The seats have a 0.96 meter spacing.

Fig. 1 . Grumman baseline Maglev vehicle configuration

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As a result of the team's efforts, a unique high-speed Maglev system concept (Fig. 1), was identified. If implemented, this design would meet all the goals specified in the abstract and would satisfy U.S. transportation needs well into the 21st century. The design is based on the electromagnetic suspension (EMS or Attractive) system concept using superconducting (SC) iron core magnets mounted along both sides of the vehicle.

The Grumman team selected an EMS design instead of an electrodynamic suspension (EDS or Repulsive) design because of the following significant advantages that the EMS offers over the EDS system:

- Low magnetic fields in the cabin and surrounding areas (this eliminates or minimizes the need for magnetic shielding and non-metallic rebar in concrete guideways)
- Uniform load distribution along the full length of vehicle (minimizing guideway loads and vibrations in the cabin and contributes to the elinination of a secondary suspension system)
- Small pole pitch (results in smoother propulsion)
- Magnetically levitated at all speeds (needs no supplemental wheel support)
- Wrap-around configuration (safer operation).

EMS systems exist. However, the German Transrapid TR-07 and the Japanese High Speed Surface Transportation (HSST) systems, which use copper wire iron cored magnets instead of SC coils, have a number of basic disadvantages:

- Small gap clearance (1 cm (0.4 in.)), which results in tighter guideway tolerance requirements
- Heavier weight with limited or no tilt capability to perform coordinated turns and maximize average route speed
- Limited off-line switch speed capability (56 m/s maximum)
- Large number of magnets and control servos (≈100 total).

The Grumman team design has retained all of the advantages of an EMS system. At the same time it has succeeded in eliminating, or significantly improving, every aspect of the identified EMS disadvantages. A brief description of our baseline system and how it has accomplished this goal follows.

LEVITATION, GUIDANCE & PROPULSION SYSTEM DESIGN

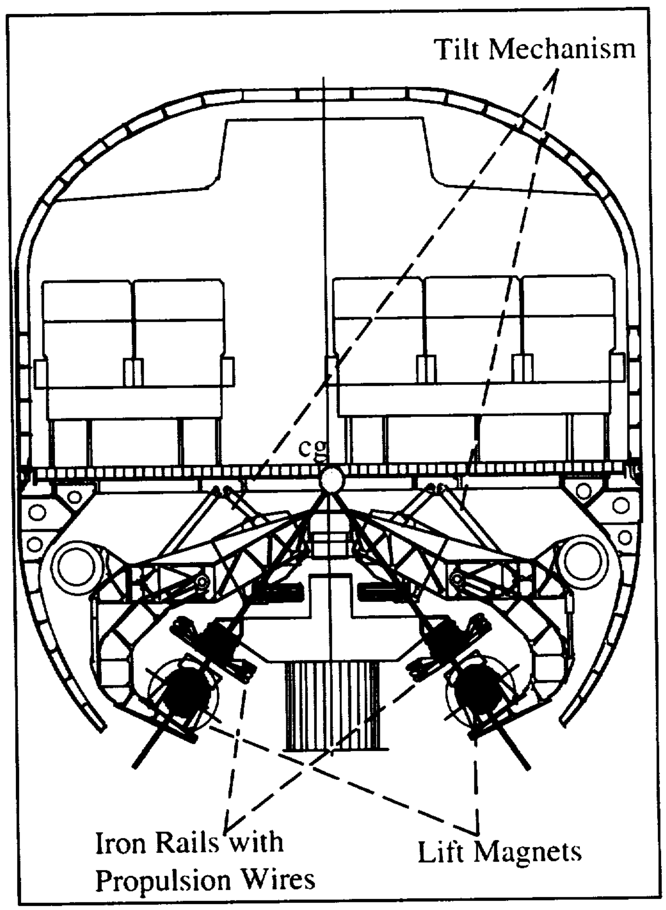

Fig. 2. Cross section of vehicle showing lift magnets, iron rail, guideway and tilt mechanism.

Fig. 2 shows a cross section of the vehicle with the iron core magnets and guideway rail identified in black. The laminated iron core magnets and iron rail are oriented in an inverted "V" configuration with the attractive forces between the magnets and rail acting through the vehicle's center of gravity (cg). Vertical control forces are generated by sensing the gap clearance on the left and right side of the vehicle and adjusting the currents in the control coils to maintain a relatively large 4 cm (1.6 in.) gap between the iron rail and the magnet face. Lateral control is achieved by differential measurements of the gap clearance between the left and right sides of the vehicle magnets. The corresponding magnet control coil currents are differentially driven for lateral guidance control. There are 48 magnets, 24 on each side of a 100 passenger vehicle. In this manner control of the vehicle relative to the rail can be achieved in the vertical, lateral, pitch, and yaw directions. Vehicle speed and roll attitude control are discussed below.

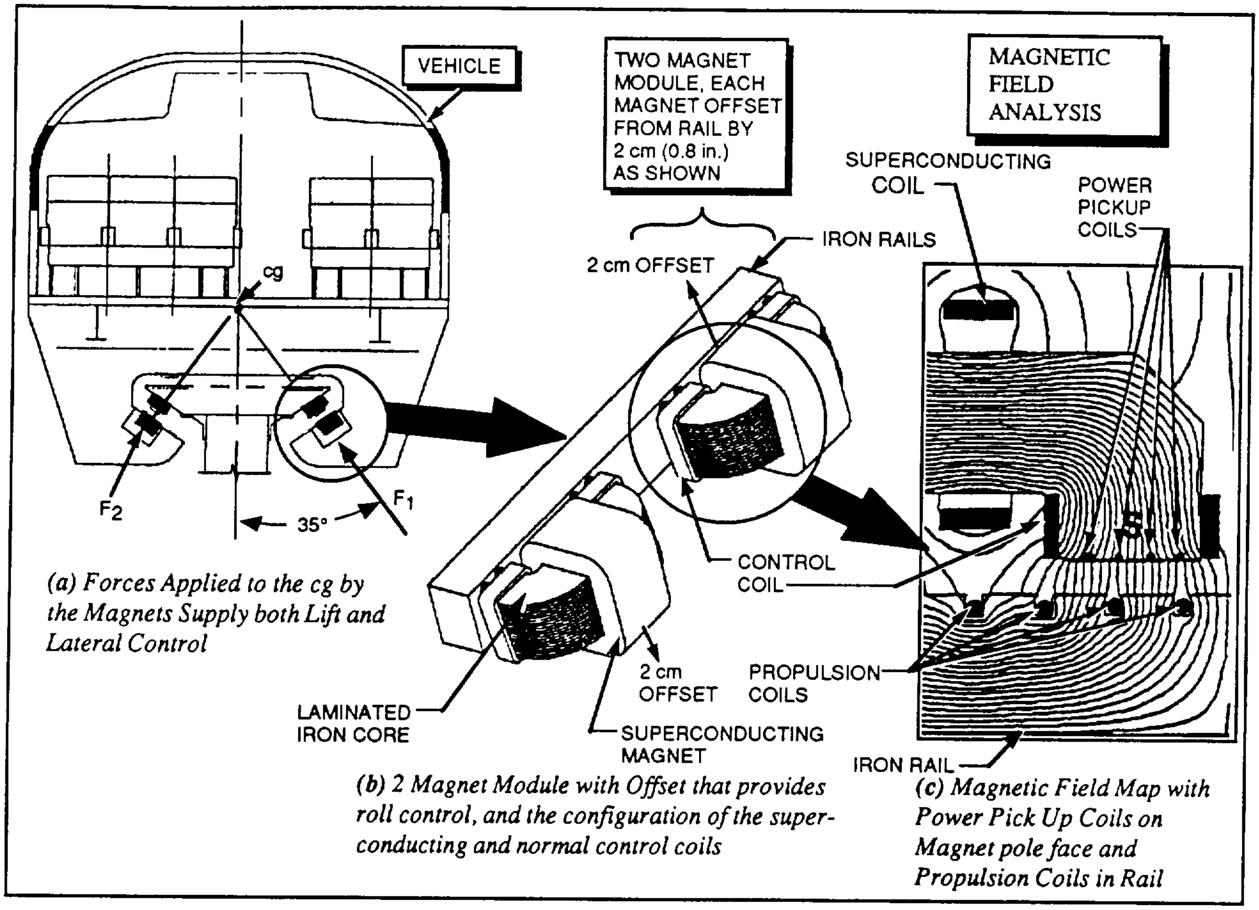

Fig. 3. Configuration of magnets and the control, propulsion and power pick-up coils

Two magnets combined as shown in Fig. 3 make up a "magnet module." Each magnet in a magnet module is a "C" shaped, laminated iron core with a SC coil wrapped around the center body of the magnet, and two copper control coils wrapped around each leg. Vehicle roll control is achieved by offsetting the magnets by 2 cm (0.8 in.) in a module to the left and right side of a 20 cm (8 in.) wide rail. Control is achieved by sensing the vehicle's roll position relative to the rail and differentially driving the offset control coils to correct for roll errors. The total number of independent control loops required for a complete 100 passenger vehicle control is 26 (1 for each of the 24 modules and 2 for roll control).

The iron rail shown in Fig. 3 (b) also is laminated and contains slots for the installation of a set of 3-phased alternating current (ac) Linear Synchronous Motor (LSM) propulsion coils. The coils are powered with a variable-frequency variable-amplitude current that is synchronized to the vehicle's speed. Speed variations are achieved by increasing or decreasing the frequency of the ac current.

Comprehensive two and three dimensional magnetic analyses [2] have been performed to assure that the magnetic design will simultaneously meet all levitation, guidance and propulsion control requirements identified above, and do it without magnetically saturating the iron core. An example of this analysis is shown in Fig. 3 (c).

Power pickup coils are located on each magnet pole face designed to operate at all speed, including standing still, using a unique inductive approach described in [3].

Low magnetic fields in the passenger compartment and surrounding areas represent an important aspect of this design. Fig. 4 identifies constant flux densities in the cabin and station platform that can be expected for the baseline design. Flux density levels above the seat are less than 1 gauss, which is very close to the earth's 0.5 gauss field level. On the platform, magnetic levels, when the vehicle is in the station, do not exceed 5 gauss, which is considered acceptable in hospitals using magnetic resonant imaging (MRI) equipment. The data in Fig. 4 is based on a three-dimensional magnetic analysis program and assumes no shielding. With a modest amount of shielding, these levels could be further reduced should future studies (now under way) indicate a need for lower values. Similarly, ac magnetic fields are anticipated to be within acceptable levels.

Another important aspect of the magnet design is the use of SC wire in place of copper coils used in existing EMS systems. This allows us to operate with a large 4 cm (1.6 in.) gap clearance without paying the heavy weight penalty required if copper coils were used for the same purpose.

The use of an iron core with the SC coil provides an added advantage. The magnetic flux is primarily concentrated in the iron core, not the SC coils as is the case of an EDS system. This reduces the flux density and loads in the SC wire to very low values (<0.35 Tesla and 17.5 kPa, respectively). In addition we have implemented a patented constant current loop controller [4] on the SC coil that diminishes rapid current variations on the coil, minimizes the potential of SC coil quenching and allows for the use of state-of-the-art SC wire.

The use of iron-cored SC magnets with their associated low flux density and load levels identified above affords an added advantage of our design over EDS concepts. High temperature SC technology has progressed to the point that the field levels these magnets require are achievable with existing High temperature SC wire. It is now reasonable to consider the application of this new emerging technology to this concept. Although we are not baselining the use of high temperature SC for this application (except for its use as lead-in wire to the low temperature SC coil), we are pursuing a development program at this time to manufacture samples of high temperature SC coils of sufficient length and with adequate current carrying density to satisfy our requirements.

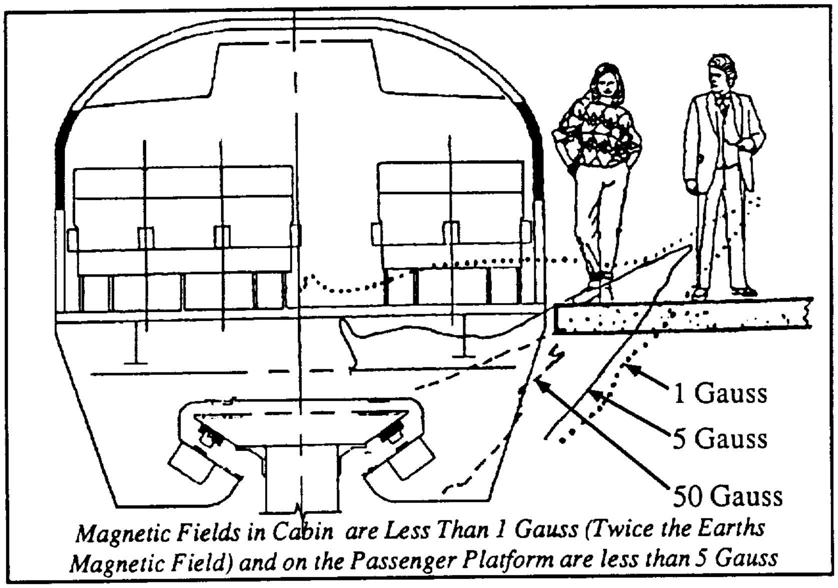

Fig. 4. Magnetic fields in cabin and surrounding area

In summary, the use of SC iron-core magnets resulted in significant advantages for this concept:

- Large gap size - 4 cm (1.6 in.)
- Low magnetic fields in SC coil - <0.35 T
- Low fields in passenger cabin - <1.0 gauss dc
- Low load forces in SC coil- 17.5 kP a

VEHICLE DESIGN

A number of important system trade studies were performed to arrive at the baseline vehicle configuration shown in Fig. 1. An example is given in Fig. 5 which identifies how the total system cost,

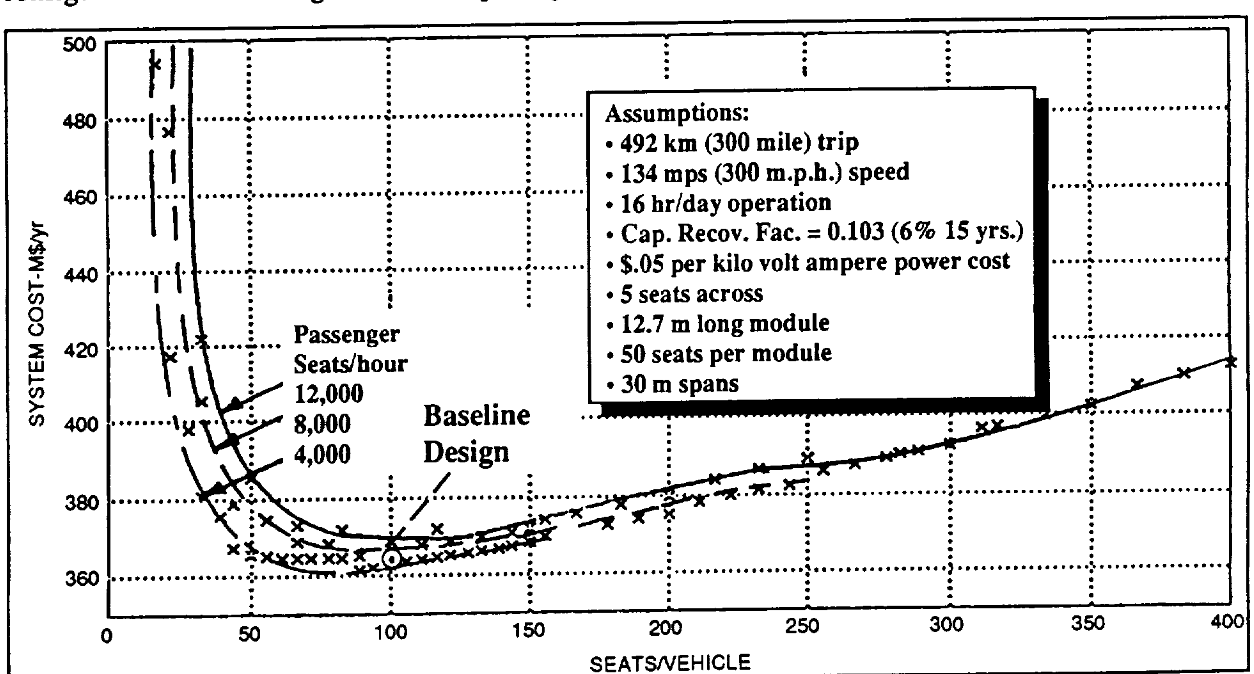

Fig. 5. System cost trade study

which includes the guideway, vehicles, levitation, propulsion, and operating cost, is affected by the number of passenger seats in the vehicle and the number of passengers per hour utilizing the system. Note that minimum cost results are between 50 and 150 seats per vehicle. We have chosen 100 passenger seats per vehicle for our baseline configuration.

The 100 passenger baseline system shown in Fig. 1 lends itself to other single and multi-vehicle (train) configurations that can be developed based on two basic building block modules. The main module consists of a 12.7 m (41.7 ft) long section, which seats 50 passengers with 2 entrance doors (one on each side of the vehicle), 2 lavatories (one designed to accommodate handicapped passengers), multiple overhead and closet storage facilities and a galley area. The forward and aft sections of the vehicle utilize the second module, which consists of a 4.9 m (16 ft) long section that is externally identical, but internally different, depending on its forward or rear location on the vehicle. We have adopted one-way vehicle operation to minimize the impact of weight for reverse facing seat mechanisms and cost duplicating all the electrical controls and displays on both sides of the vehicle. We also chose to include business-type aircraft seats with an ample 0.96 m (38 in.) spacing between seats to assure a comfortable seating arrangement for all passengers. Additional detailed vehicle characteristics are given in [5].

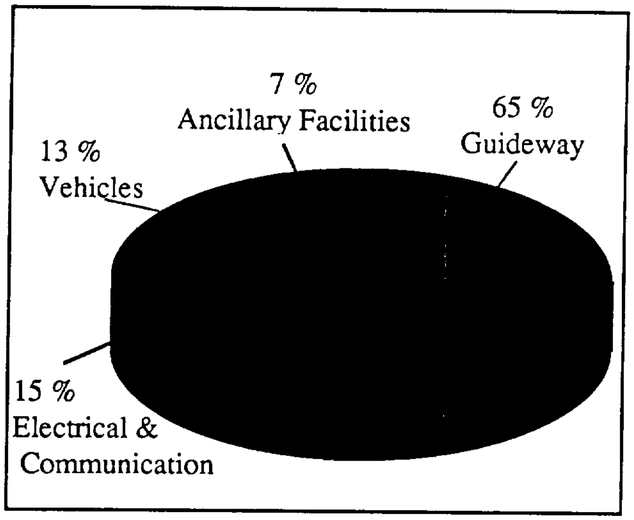

Fig. 6. Distribution of costs across the four major components of the Maglev system

Comprehensive two and three-dimensional Navier Stokes computational aerodynamic analyses [6] were also performed on the baseline design to estimate drag and other disturbances acting on the vehicle. Vehicle speeds up to 134 m/s (300 m.p.h.) with 22.3 m/s (50 m.p.h.) crosswinds where investigated.

GUIDEWAY DESIGN

The guideway is an important aspect of our system design because it represents the largest percentage of the total system cost. Fig. 6 shows how system cost distributes between the four major components, i.e., guideway (64.4%); electrical and communication (14.8%); vehicles (13.3%); and the ancillary facilities such as stations, buildings and vehicle parking (7.46%). Details of our system costing procedures are given in [7].

A number of different guideway designs were investigated. Four are shown in Fig. 7 and are identified in terms of increasing cost.

In each case our design mandated that a center platform exist along the full length of the guideway to provide a safe exit for the passengers, in case of an emergency such as a fire or smoke in the cabin.

Analysis of the four guideway configurations identified in Fig. 7 showed that the "spine girder" guideway design is not only lowest in cost, but also is relatively insensitive to span length [8]. This has important implications when the guideway must be installed in areas such as the U.S. Interstate Highway system, which will require wide ranges in span length depending on local road conditions. In summary, based on this and other considerations, the "spline girder" configuration shown in Fig. 8 was chosen as our baseline for the following reasons:

- Lowest cost dual- guideway ($7.99M/km, for spread footing including iron rail cost)
- Smaller footprint
- Can be more closely designed to suit span variations
- Visually less intrusive with single column
- Creates less shadow
- Esthetically pleasant.

Detailed descriptions of the baseline guideway and associated cost estimates are given in [9] and [8] respectively. The total system cost, which includes guideway, electrical and communication, vehicles, station buildings etc. was estimated at $12.4M/km ($20M/mile) [7].

A 5 degree-of-freedom analysis of the interactive effects of the vehicle traveling over a flexible guideway was undertaken [10]. Guideway irregularities resulting from random step changes, camber variations, span misalignment and rail roughness where included in the simulation. Also included where linearized versions of the vehicle levitation and lateral control loops. The results indicated that passenger comfort levels could be maintained without the need for a secondary suspension system.

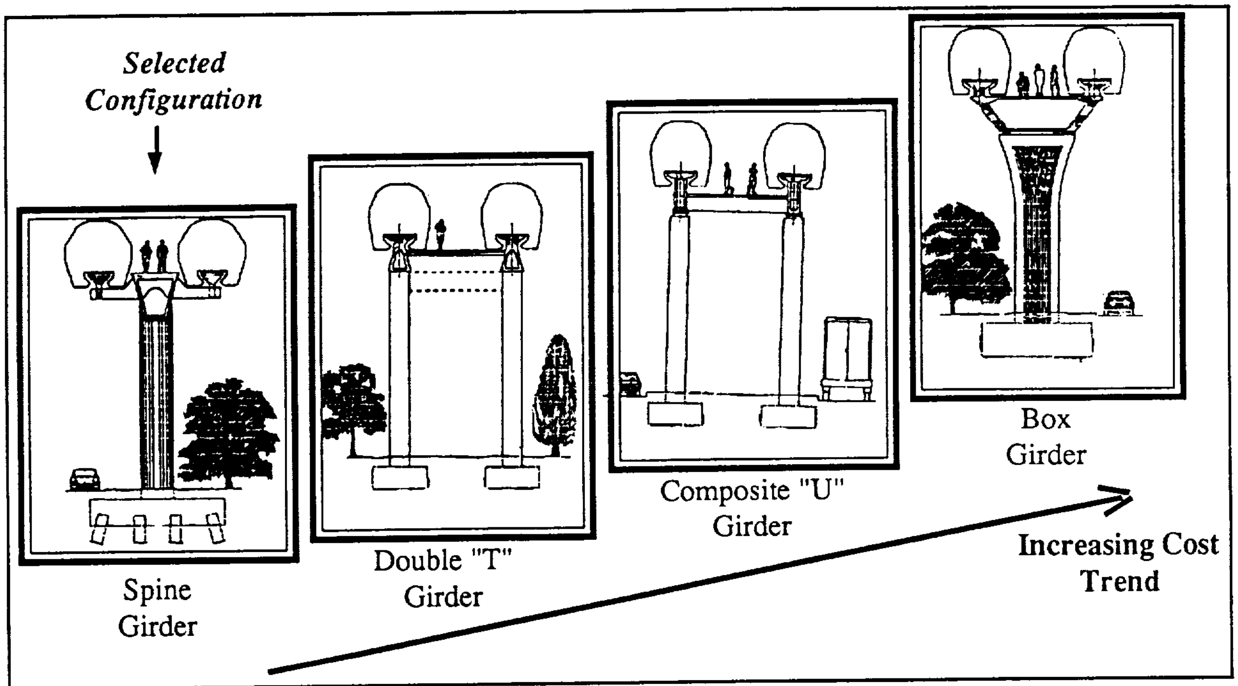

Fig. 7. Alternate guideway structures considered

HIGH SPEED OFF-LINE SWITCHING

Another important aspect of our design is the capability of providing high-speed off-line switching. Unlike the German Transrapid design, which moves one 150 m (492 ft) section of the track laterally 3.61 m (12 ft), we move two sections laterally 3.0 m (10.0 ft) with one actuator motion. The track switching concept is shown in Fig. 9. It identifies the two sections of the track that are moved to accomplish this function. The lower figure shows the through traffic condition for the track switch. The upper figure identifies how the 60 m long switch, A, is flexed to a curved section, while the right hand 60 m long switch, B, is pivoted about the fixed switch points. This combined motion of the two sections (120 m total length) provides a turnout speed of 65 m/s (143 m.p.h.). A 182 m switch length will allow off-line switching at 100 m/s (220 m.p.h.). Transrapid turnout is limited to 56 m/s (123 m.p.h.) with a section length of 150 m.

VEHICLE CABIN TILT DESIGN

Unlike any of the other existing high-speed Maglev designs, such as, the Transrapid TR07 or the Japanese MLU002, we are providing the capability of tilting the vehicle passenger compartment by ±9 degrees relative to the guideway. In this manner, the

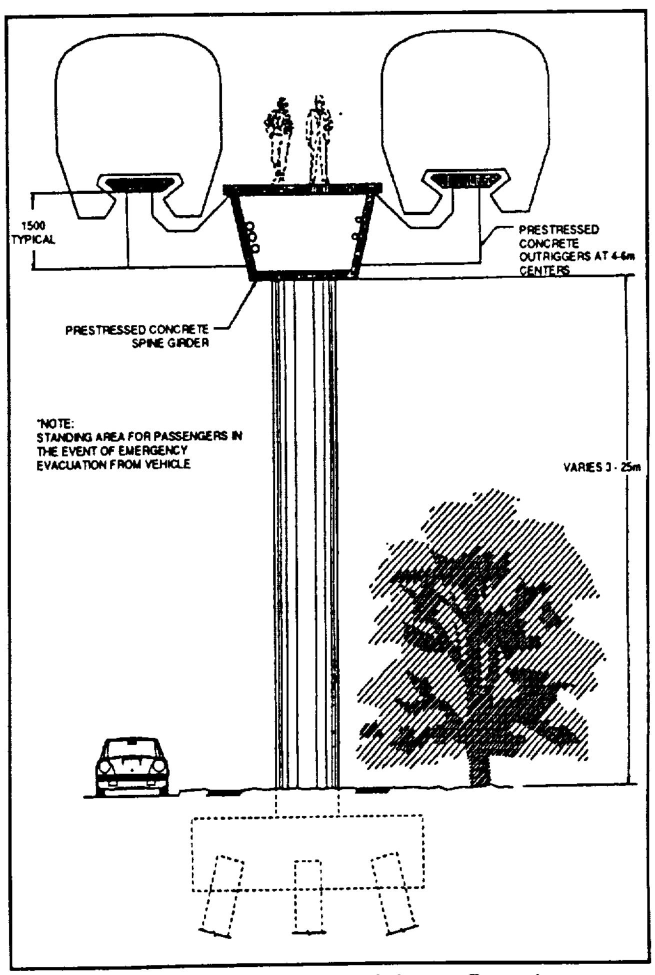

Fig. 8. Baseline spine girder configuration

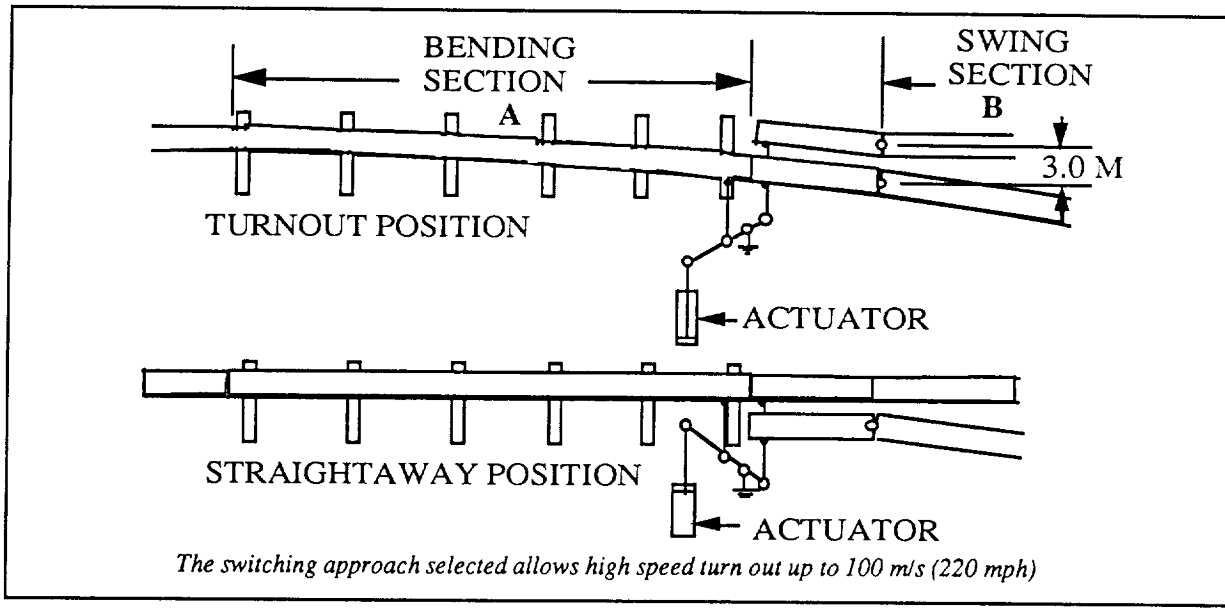

Fig. 9. Off-line switching concept

design, as shown in Fig. 10, will allow for coordinated turns up to ±24 degrees banking (±15 degrees in the guideway and ±9 degrees in the vehicle). This capability will assure that all coordinated turns can be performed at the appropriate tilt angle independent of the speed with which the vehicle is traversing the turn, as well as allowing for high-speed off-line switching.

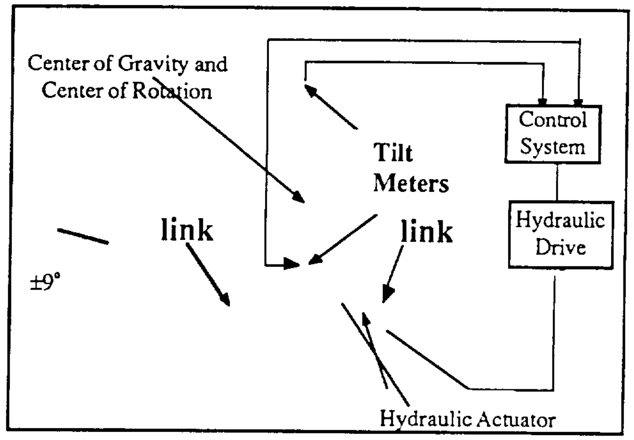

Fig. 10. Tilting mechanism and control system

ECONOMIC ANALYSIS

An economic forecast analysis for a Maglev system was performed as a function of two primary cost drivers: total cost of the major Maglev elements identified in Fig 6, and the passengers per hour utilizing the system. The results of this analysis are presented in Fig. 11 with the as-

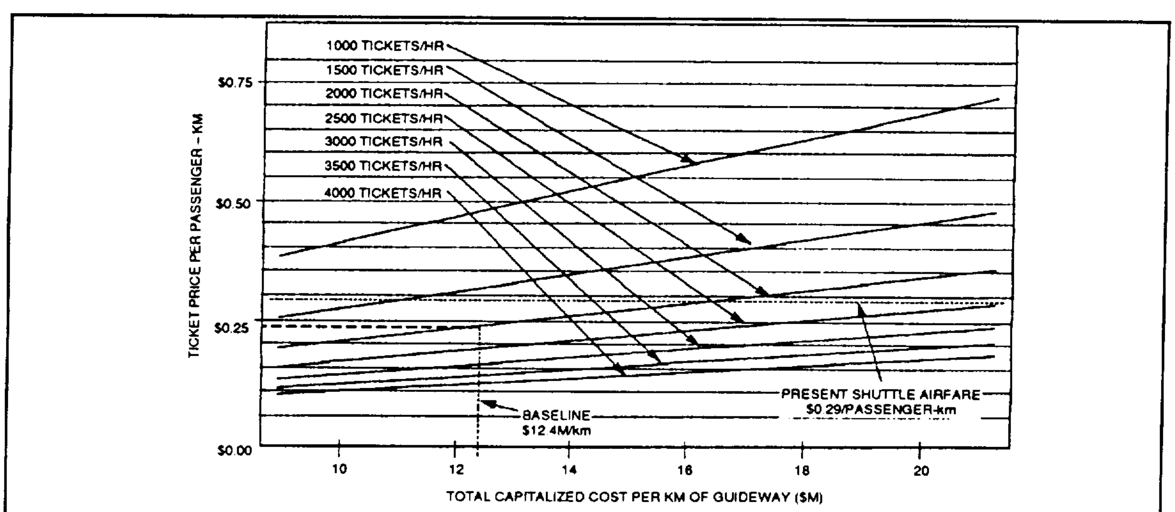

Fig. 11. Economic analysis

sumptions listed below:

- 493 km (300 mile) corridor
- Development and demonstration cost of the Maglev system is not included
- Federal, state and local governments supply right-of-way at no cost
- Ridership is based on 260 days/year, 16 hours/day, 60% capacity
- 20% pre-tax margin on ticket price based on 5 year build, 15 year operation
- Future interest (8%) & inflation rate (5.4%)

If we assume a 2,000 passenger per hour usage (typical of high volume routes like Boston/New York/Washington DC) with the previously identified $12.4M/km ($20M/mile) for the baseline system cost the ticket price that would have to be levied is $0.23/km ($0.38/mile); this would still provide a 20% profit margin on the ticket cost for the system operator. Also shown on the figure is the $0.29/km ($0.47/mile) present charge for the New York/Washington, DC/Boston corridor. The results indicate that a Maglev system of the type being recommended in this paper can pay for itself during its first 15 years of operation. The implication is that after 15 years, when the capital investments have been fully paid, the proceeds from the high volume traveled routes could be used to support the building and operation of Maglev routes that are located in less densely populated areas. This means that system route miles can double every fifteen years, implying that by the mid twentieth century there could be over 4000 miles of maglev lines in the U.S.

CONCLUSION

It is our opinion that the Grumman Team superconducting EMS Maglev concept as described in this paper will provide an effective low cost U. S. Maglev transportation system that can meet all of the goals identified in the abstract and at the same time minimize the negative issues previously discussed. We believe that the Grumman team has performed sufficient analyses in the areas of guideway design, levitation, propulsion and guidance, vehicle structural design, aerodynamics, controllability, dynamic interaction, environmental, safety, and reliability to warrant this optimism.

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