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FTA Low-Speed Urban Maglev Research Program

Lessons Learned

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16. Abstract

In 1999, the Federal Transit Administration initiated the Low-Speed Urban Magnetic Levitation (UML) Program to develop magnetic levitation technology that offers a cost effective, reliable, and environmentally sound transit option for urban mass transportation in the United States. Maglev is an innovative approach for transportation in which trains are supported by magnetic forces without any wheels contacting the rail surfaces. Maglev promises several attractive benefits including the ability to operate in challenging terrain with steep grades, tight turns, all weather operation, low maintenance, rapid acceleration, quiet operation, and superior ride quality, among others. This UML program is nearing completion and government program executives and managers desire a program review with an emphasis on lessons learned. The lessons learned in this report have been captured through a multi-faceted assessment of general project impressions, project execution, project conclusions and deliverables, project team performance, stakeholder participation, risk management, and project communications. The assessments are drawn from project documentation, discussions with the performing teams, and direct experience with the five UML projects

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FTA LOW-SPEED URBAN MAGLEV RESEARCH PROGRAM LESSONS LEARNED

March 2009

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FOREWORD

In 1999, the Federal Transit Administration initiated the Low-Speed Urban Magnetic Levitation (UML) Program to develop magnetic levitation technology that offers a cost effective, reliable, and environmentally sound transit option for urban mass transportation in the United States. Maglev is an innovative approach for transportation in which trains are supported by magnetic forces without any wheels contacting the rail surfaces. Maglev promises several attractive benefits including the ability to operate in challenging terrain with steep grades, tight turns, all weather operation, low maintenance, rapid acceleration, quiet operation, and superior ride quality, among others. For urban alignments, maglev potentially could eliminate the need for tunnels and noise abatement, resulting in significant cost savings. Five projects were selected for funding under the UML program— General Atomics Urban Maglev Project; Maglev 2000 of Florida Corporation; Colorado Department of Transportation; Maglev Urban System Associates of Baltimore, MD; and MagneMotion, Inc.

The UML program is nearing completion and government program executives and managers desire a program review with emphasis on lessons learned. This final report presents a summary of the lessons learned from each of the five projects and the program in general. The lessons learned have been captured through a multi-faceted assessment of general project impressions, project execution, project conclusions and deliverables, project team performance, stakeholder participation, risk management, and project communications.

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ACKNOWLEDGMENT

This report, *FTA Low-Speed Urban Maglev Research Program – Lessons Learned*, represents the final report submitted to the Federal Transit Administration under this contract DTFH61-98-C-00074, SAIC Subcontract 4400052215.

The authors wish to thank Ms. Mary Louise Anderson, FTA Program Manager, and Mr. Walter Kulyk, Director, Office of Mobility Innovation at FTA for their support on this work.

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Executive Summary

In January 1999, the Federal Transit Administration (FTA) published a notice in the Federal Register announcing the creation of the low-speed Urban Magnetic Levitation (UML) Transit Technology Development Program. This program is nearing completion and government program executives and managers desire a program review with an emphasis on lessons learned. The lessons learned are captured through a multi-faceted assessment of the following categories: general project impressions, project execution, project conclusions and deliverables, project team performance, stakeholder participation, risk management, and project communications. The assessments are drawn from project documentation, discussions with the performing teams, and direct experience with the UML projects. Direct and indirect contributors include: Dr. Marc Thomson, Mr. Frank Raposa, Mr. George Anagnostopoulos, Dr. Gopal Samavedam, Mr. Roger Hoopengardner, and Dr. David Keever.

The overall objective of FTA Low-Speed Urban Magnetic Levitation Program is to develop magnetic levitation technology that offers a cost effective, reliable, and environmentally sound transit option for urban mass transportation in the United States. Maglev is an innovative approach for transportation in which trains are supported by magnetic forces without any wheels contacting the rail surfaces. Maglev promises several attractive benefits including the ability to operate in challenging terrain with steep grades, tight turns, all weather operation, low maintenance, rapid acceleration, quiet operation, and superior ride quality, among others. Maglev is typically unmanned and operates on elevated guideway. For urban alignments, maglev potentially could eliminate the need for tunnels for noise abatement, resulting in significant cost savings. The FTA UML projects selected for funding are:

- The General Atomics Urban Maglev Project (General Atomics, San Diego, CA as the lead company) is developing a system based on permanent magnets.
- Maglev 2000 of Florida Corporation is establishing the feasibility of a super conducting electrodynamics suspension (repulsive force) technology based on concepts from renowned magnetism scientists Drs. Gordon Danby and James Powell.
- The Colorado Department of Transportation partnered with Sandia National Laboratories, Colorado Intermountain Fixed Guideway Authority, and Maglev Technology Group, LLC for the development of a low-speed maglev to link Denver International airport with Vail, about 140 miles away.
- Maglev Urban System Associates of Baltimore, MD is exploring the viability of bringing to the United States a Japanese-developed low-speed maglev technology that has undergone over 100,000 kilometers of testing.
- MagneMotion, Inc. is leading the development of a key Maglev technology for implementation in transportation systems serving traffic-congested urban areas. A principal element of the MagneMotion urban maglev system is the use of the company’s linear synchronous motor technology to propel bus-sized vehicles that can operate with short headway under automatic control.

The major findings from the lessons learned assessment are:

- The FTA urban maglev program has demonstrated that low-speed magnetic levitation systems are advanced enough to merit consideration as system alternatives in the United States, but the initial infrastructure costs and availability of safety and operationally certified maglev technologies are intimidating. The efforts taken under this program have shown that low-speed maglev is feasible, but the results of multiple projects have indicated that substantial up-front costs exist.
- Most large urban areas in the United States have already invested in some type of mass transit system (subway or light rail) and urban maglev poses a fundamental change in technology that is viewed as being both a major risk and cost-prohibitive by transit agencies and investors.
- The lack of an actual system in place to demonstrate the projected savings in maintenance and operation costs contributes to a reluctance to embrace the technology.

The principal lesson learned from the perspective of the overall project execution was that, as with most research efforts, there will be unexpected challenges and obstacles during the course of the projects. Each project team identified different challenges, such as gaining cooperation with State, city, and local stakeholders for alignment issues; obtaining details on already operating systems that were not considered proprietary; and underestimating the technical challenges of super cooling magnets.

In addition, while the very nature of this research program draws creative individuals who are interested in solving complex problems, but very often are not as concerned about following sound project management principles, let alone Federal guidelines for submitting required reports on time. The lesson learned from the program in this regard was the value of requiring someone on the project team to provide a project plan with enough detail that FTA could determine when the project had drifted and enough detailed updates to determine whether progress has been achieved. Eventually all of the programs were able to provide interim milestone reports and deliverables in the context of a longer-term research program based on their individual strategies and concepts. As a result of these program plans, the researchers were able to better focus their resources and results, which allowed FTA program managers to assess progress and promulgate findings to the research and transit agency community.

1. Introduction

In January 1999, the Federal Transit Administration (FTA) published a notice in the *Federal Register* announcing the creation of the Urban Magnetic Levitation (UML) Transit Technology Development Program. The Transportation Equity Act for the 21st Century ("TEA-21") authorized "the FTA to support further development of magnetic levitation technologies for potential application in the U.S. mass transit industry."[1] This authorization provided funds for FTA to oversee a research and development (R&D) program for low-speed magnetic levitation (maglev) technology, while the Federal Railroad Administration (FRA) continued to examine the application of magnetic levitation to a high-speed application between cities, an effort that had been under way in that agency for a number of years. The overall objective of FTA's program was "to develop magnetic levitation technology that is a cost effective, reliable, and environmentally sound transit option for urban mass transportation in the United States."[2] FTA organized its program to be conducted in three progressive phases: evaluation of proposed system concept, prototype subsystems development, and system integration and deployment planning. Based on the performance of researchers in each phase, FTA would authorize work to continue to the next phase. This program structure encouraged a competitive environment for participants in each phase of the UML, but also required performance-based independent assessments for the participants to advance.

For this program, the FTA selected 5 project teams (out of 10 submissions) to work in Phase I of its Urban Low Speed Maglev Program. A team led by General Atomics (GA) began its work in July 2000 and is still working on a proposed system that would be deployed at California University, Pennsylvania. A team from Sandia National Laboratory and the Colorado Department of Transportation (DOT) looked at a new propulsion technology that could be applied to urban, or low-speed, maglev in the Denver, CO area. Maglev 2000, Inc. evaluated the possibility of utilizing superconducting quadrupole magnets as a modification to the original ideas for propulsion and levitation put forth by renowned magnetism scientists Drs. Gordon Danby and James Powell. The fourth team, Magnetic Urban Systems Associates, a consortium of Japanese and U.S. experts, examined the possibility of modifying the current Japanese low-speed maglev system for operation in the United States. A fifth Team, MagneMotion, examined a prototype system using linear synchronous motor propulsion and is now teamed with Old Dominion University for possible deployment of a prototype system at that campus. All of these projects focused their efforts in four main areas:

- **Systems Studies** – The main effort of this task was to develop a system concept definition for a preferred urban maglev technical approach.
- **Base Technology Development** – This effort was to use state-of-the-art design and computational tools to identify and resolve technical risks associated with the selected technical approach.
- **Route Specific Requirements** – This task evaluated key technical issues with respect to topographically varied alignments, if specific alignments have been identified.

[1] *Federal Register,* Friday, January 29, 1999, Vol. 64, No. 19, Notices, page 4772.
[2] Ibid.

- **Preliminary Design for a Full-Scale System Concept** – This effort focused on the development of a full-scale maglev system concept that includes a vehicle, guideway, and alignment based on the system concept definition. System performance was also to be estimated during this task, and would include the development of some system prototype elements.

1.1 Challenges in Low Speed Urban Transit

While magnetic levitation trains are in use throughout the world, those systems are primarily high-speed test environment systems where speeds reach in excess of 250 miles per hour. Of those high-speed magnetic levitation systems, Germany and Japan have been considered to be most successful in the use of the maglev concept. Recent operation of the Shanghai airport-to-Pudong magnetic levitation system can be classified as a variant of the German Transrapid production system.

Urban maglev faces a much different set of operating circumstances than high-speed magnetic levitation systems, and the successful introduction of such a system to an urban environment presents different challenges. Some of the challenges faced by urban maglev include:

- Speeds in an urban environment will normally be much slower than those required for the high-speed systems due to the short distances between stops. Urban maglev should only need to achieve a maximum speed of about 100 mph.
- Obtaining rights of way in an urban area will be very challenging. Some of the planned high-speed systems will run near already cleared train track rights of way, but in an urban environment such already cleared areas may not be available.
- U.S. safety standards are in many instances much more demanding than standards in other countries. Adapting a foreign system to run in the United States will require careful scrutiny of all safety requirements to determine if it is economically feasible to actually adapt the system.

1.2 Magnetic Levitation Opportunities and Lessons Learned from High-Speed Maglev Programs

As noted earlier, high-speed systems are in operation in several other countries, and the United States has been pursuing its own high-speed maglev options through a program administered by the FRA. That program has focused on higher speeds (> 200 mph) over much longer distances than envisioned for urban maglev. The FRA has down-selected from its original list of proposals to two proposed systems in PA and MD, and those two systems are now waiting for FRA review of their draft environmental impact plans. Some lessons learned from that FRA program include that:

- The American public seems inclined to like the concept, as long as the system is not in their area.
- Finding segments of line on which it is possible to attain speeds of more than 200 mph has proven to be a challenge. That may be because the high cost per mile (estimates range from $75 million to $125 million per mile) of these systems makes it difficult to propose really long stretches of guideway.

- Tolerances on the guideway are extremely tight and drive the cost per mile up. Large levitation gaps may help reduce that cost as the same level of precision in construction and manufacture that is required for smaller gaps are not necessary.

1.3 FTA Research Program Interests

In their original announcement of the Low-Speed Urban Maglev Program, FTA articulated the following technical objectives:

> *(1) Develop a base of knowledge on urban maglev low-speed technology supportive of eventual deployment, including a full system design and advanced technology hardware development and demonstration;*
>
> *(2) Enhance one or more of the…critical maglev subsystems using advanced technologies…;*
>
> *(3) Integration of a Maglev system design, including fleet operations, safety, inter-vehicle communications and control systems, and subsystems integration;*
>
> *(4) Evaluate and optimize a full scale demonstration system; and*
>
> (5) *Demonstrate low speed magnetic levitation technologies...*[3]

A by-product of the work conducted under this program would also provide valuable lessons learned that could not only be applied to other maglev system ideas, but also be of benefit to all transit agencies, regardless of an agency's configuration.

[3] Ibid.

2. FTA Urban Magnetic Levitation Transit Technology Development Program

2.1 Three-Phase FTA Research Program

The FTA development program was designed to provide a flexible approach that would accommodate various concepts for designing, developing, or demonstrating maglev systems that would be appropriate for urban environments. As such, the program was created with a three-phased structure:[4]

- **Phase I – Evaluation of Proposed System Concept**. In this phase, the FTA expected participants to prepare: a) a projection of overall system performance and a preliminary design for the proposed full-scale demonstration system, b) documentation of all assumptions and methodology used to project and estimate the system performance, c) identification and analysis of key risk elements, and d) a "letter of interest" from a potential end-user.
- **Phase II – Prototype Subsystem(s) Development**. In this phase, participants were expected to complete the development of proposed advanced technology portions of their overall maglev system design. Anticipated activities in this phase included: a) completion of a functional specification of the prototype advanced technology subsystem(s), b) completion of advanced technology hardware subsystems where improvements are proposed and warrant prototypes for testing and verification, c) demonstration of advanced technology hardware subsystems, and d) a commercialization plan with potential end-user involvement.
- **Phase III – System Integration and Deployment Planning**. In this phase, funding recipients were expected to integrate the completed advanced technology portions of their proposed design to create an overall urban maglev system. Expected activities for this phase were: a) completion of functional specifications for a full-scale demonstration system, b) full-scale computer modeling and simulation to demonstrate and verify system operations, c) identification of a specific deployment site, and d) an Environmental Assessment for that site.

FTA allowed each participant team to propose its own schedule and milestones. Each team was also required to develop a project implementation plan with specific milestone dates that coincided with billing dates from the recipients. This allowed FTA to monitor progress of the efforts and provide a basis for the funding payments. When requested, FTA provided assistance in the development of these plans.

As programs reached logical milestones that would signal the transition point from one phase to the next, FTA required an independent review of the program and a formal decision on whether the recipient would be allowed to move to the next phase. Given the nature of research and development work, it was fully anticipated that some programs would not be allowed to continue on into the next logical phase because the recipient had not completed all of the expected steps. This allowed the FTA to focus funds on teams that were making logical progress and to ensure that the available funds were allocated as effectively as possible.

[4] Elements of this program are paraphrased from the *Federal Register* announcement.

2.2 FTA Strategy for Implementing the Program

In selecting awardees for this program, FTA attempted to select a wide variety of approaches and ideas to ensure that all feasible approaches were considered. One of the teams selected (Maglev 2000, Inc.) was a non-selected team from the FRA high-speed program, and this allowed the team to explore its ability to adapt and leverage the work it had already begun in the high-speed program. Two other teams (CDOT and MUSA) explored the idea of exploiting and adapting foreign technologies for use in the United States. Two teams proposing the use of superconducting technology (General Atomics and Maglev 2000) were selected to ensure that superconducting technology was evaluated and considered (a directive in the SAFE TEA legislation). And finally, teams proposing novel integration of key components (GA and MagneMotion) were selected to ensure that all unique ideas were considered. It was expected that some of these recipients would not move forward in the process, but the work they did complete would advance the state of knowledge in the maglev arena.

2.2.1 Independent Review Process and Periodic Performance Milestones

For all of the selected programs, FTA initiated an independent review process with quarterly or milestone reviews. FTA used FTA staff members and contracted subject matter experts to assist in these reviews and to assist FTA in monitoring the progress of each program. These reviewers were also used to assist teams in the development of their project implementation plans and helped FTA ensure that these plans were being followed.

3. Major Contributions from the Individual Urban Maglev Projects[5]

Major contributions from each of the projects can be assessed by a number of factors, including:

- Technical insights (as described in technical memoranda).
- Technical demonstrations/prototypes.
- Patents or patent pending.
- Publications (referred technical journals, journals, others).
- Conference presentations (other than specific FTA-sponsored conferences).
- Stakeholder involvement.

These criteria form the basis for the following summaries of the major contributions by project.

3.1 MUSA (CHSST)

Earthtech in Baltimore, MD assembled a team called MUSA with Chubu High-Speed Surface Transport (CHSST) as one of the subcontractors. MUSA adopted CHSST technology as the basis for its Maglev system. The CHSST maglev system has been in development in Japan for more than 25 years and has evolved through several progressively more practical forms. Fundamentally, the CHSST maglev utilizes electromagnetic attractive forces between simple dual-pole magnets (analogous to two facing horseshoe magnets) to provide both levitation and guidance. Consequently, there are substantial technical documents which highlight the findings and modifications proposed by MUSA.

The CHSST technology is a matured technology currently deployed in revenue service in Japan. It seems to be the "best" available low-speed urban maglev technology in the world. MUSA focused more on the application of the CHSST vehicle than on improvements in performance and cost reduction, redesigning the vehicle interior to accommodate Americans with Disabilities Act requirements. Potential fire and smoke issues were also adequately addressed, as were egress and crashworthiness issues. By and large, the MUSA report presents a straight summary of the technical work developed by the Chubu HSST.

MUSA did not specify any specific route, nor generate sufficient interest among transit authorities. No deployment plans were developed. While the CHSST technology for low-speed maglev has many positive attributes and a proven record of operation under deployment in Japan, MUSA has not exploited this technology for potential introduction in the United States. Nor did MUSA add any significant improvements or innovation to the CHSST technology.

MUSA was not able to demonstrate its technology; conducting only comparative, analytic studies instead. These comparative studies were hampered by the substantial difference in regulatory and safety requirements, among others, between U.S.- and Japan-based urban transit systems.

[5] This section draws from the report Comparative Analyses of FTA Urban Maglev Project, FTA report dated March 2004.

3.2 Colorado CDOT

This project focused on the application of Maglev technology along the I-70 route in Colorado, which connects Denver International Airport to Eagle County, covering a distance of about 140 miles. This particular alignment was appealing to the project team since it combined urban, steep terrain, and all-weather operating conditions. This project was jointly performed by the following major subcontractors:

- Colorado Department of Transportation.
- Maglev Technology Group (MTG).
- Sandia National Laboratories (SNL).
- T. Y. Lin.

The interstate I-70 alignment being considered by the CDOT team members is shown in Figure 1. This route has steep gradients and is challenging for any mode of transportation.

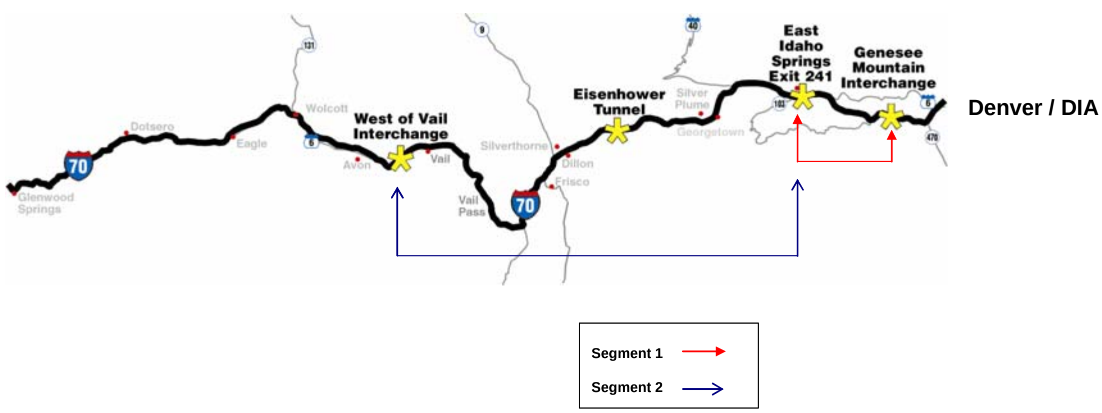


Figure 1. Interstate 70 Route Alignment

The CDOT team made useful contributions to the technology. The linear induction motor's design was improved to achieve higher propulsion power, providing improved grade climbing capability and a peak speed of >160 kph. A large number of technical reports, produced by the team partner at Sandia (SNL), documented much of the design, testing, and development of this motor. A subscale testing facility was developed at SNL to confirm design concepts and calibrate initial performance, although a full-scale motor model was never developed. Several patentable concepts were developed; however, it is uncertain if any formal patent applications were made.

Another significant improvement proposed by the CDOT team was in the guideway design. The proposed guideway looks better aesthetically and is also significantly less expensive. This could result in a comparatively economical maglev system, but further evaluation via testing a full-scale guideway will be required to verify the benefits of the guideway concept.

The CDOT team made several presentations of their project to the research community. In the area of the motor design, several internal SNL seminars and discussions were offered. Professional (symposium) publications were produced as well.

Although CDOT is a very progressive organization for public participation, no public meetings of the urban maglev concept were held due to the immaturity of the concept and the fact the project was not on the metropolitan planning organization's (MPO) long-range plan.

3.3 Maglev 2000

Maglev 2000 is a company incorporated in Titusville, Florida. Drs. James Powell and Gordon Danby, the early inventors of superconducting maglev systems based on null flux levitation, are part of the technical team of Maglev 2000. The Maglev 2000 system was designed for high-speed operations (~ 300 mph) and has been adapted to operate between 30 to 120 mph for low speed urban transportation.

The Maglev 2000 initially conceptualized its system for high-speed, long-distance application using a system similar to one that was developed (but has not yet been deployed due to costs and other reasons) in Japan over the last three decades. When it was not selected for FRA funding, Maglev 2000 altered its concept and proposed a similar system for low-speed Maglev. It appears no specific innovations have been made by Maglev 2000 under the FTA project, nor has a reasonable design been produced for low speed test and applications.

3.4 MagneMotion

The MagneMotion system is being developed by a group of people in Acton, MA, focused on levitation and propulsion with subcontract support from Earthtech and others for guideway structures. The MagneMotion maglev vehicles are small and are to be operated in platoons to achieve a high capacity of ~ 12,000 passengers per hour (pph).

MagneMotion made an important innovation when it increased the magnetic and mechanical gap of the electromagnetic suspension EMS by using permanent magnets and controlling the gap by using coils. The magnetic and mechanical gaps are almost twice those achieved by the German Transrapid and the Japanese HSST, which should have a significant impact on the cost of the system. MagneMotion has demonstrated the levitation and propulsion of its system using a 1/7 scale model in the laboratory, which is pictured in Figure 2.

Figure 2. Photograph of the Low Speed Prototype Showing Vehicle, Guideway, and Propulsion Coils

3.5 General Atomics

San Diego-based General Atomics, along with their subcontractors in Pittsburgh and elsewhere, has been actively developing a low-speed maglev system initially with the idea of demonstrating the system at California University in Pennsylvania, and later introducing the system as a circulator in downtown Pittsburgh. This alignment, however, would require substantial revisions and revisiting given the age of the alignment data. GA had identified the maglev requirements systematically, based on the route in Pittsburgh, resulting in a system requirement document that was the basis for a more generic document applicable to all urban maglev systems.

This program represents the world's first full-scale application of permanent magnet maglev technology for use in urban transportation systems. The technology adopted by General Atomics uses permanent magnets on the vehicle arranged in a Halbach array for "passive" EDS levitation. The permanent magnets on the vehicle interact with three-phase linear synchronous motor (LSM) windings on the guideway for propulsion. The overall benefit of this technology is its inherent simplicity and robustness. There are no high power components on the vehicle, resulting in relatively light vehicles compared to other maglev approaches; however, power pick-up designs have yet to be revealed.

There were other "lessons learned," ranging from maglev-specific findings resulting from the completion of the dynamic testing of the single test chassis on the GA test track in San Diego to potential benefits from this R&D program to the transportation field in general. The benefits are a result of the new technologies that were developed and matured under this program. Some specific technical innovations include:

- Modular guideway construction techniques to enable low-cost, rapid construction of the guideway. The GA guideway girder piers and foundation design and details are well documented in technical memoranda and presentations given at selected world-wide conference on urban transportation systems.

- Low-cost, high-strength guideway construction materials including fiber-reinforced concrete.
- An Automatic Train Protection (ATP) system that is safety certified and is fully compatible with a levitated maglev system under all operational conditions.
- A vehicle propulsion control system capable of automated operation of multiple vehicles under challenging dynamic loading conditions (resulting from the program imposed 10% grade and 1.6 m/s^2 acceleration requirements).
- A vehicle positioning system that is very accurate in its ability to position the vehicle on the track and accurately monitor its speed. Current position accuracy is 18mm; future planned system will be even more accurate, resulting in further efficiency improvements.

Of all the projects, the GA project is the most comprehensive and well-documented. Numerous technical documents, technical memoranda, summary briefs, referred journal articles, and periodic peer-review sessions were conducted. As part of the environmental assessment process, public hearings were held in California, Pennsylvania to describe the proposed first-phase alignment (top of the hill) and the associated environment impact. As a result of this process and attention to public comments, a Finding of No Significant Impact (FONSI)was issued by the environment reviewing agencies.

4. Summary of Lessons Learned

4.1 General Project Impressions

Overall, the urban maglev program has demonstrated that low-speed magnetic levitation systems are advanced enough to merit consideration as system alternatives in the United States, but the initial infrastructure costs are intimidating. In addition, most large urban areas in the United States have already invested in some type of mass transit system (subway or light rail) and urban maglev poses a fundamental change in technology that is viewed as being both a major risk and cost-prohibitive. The efforts made under this program have shown that low-speed maglev is feasible, but has substantial up-front costs. The lack of an actual system in place to demonstrate the projected savings in maintenance and operation costs also contributes to a reluctance to embrace the technology.

Given this context, the contributions and lessons learned would need to point to risk reduction and cost mitigation findings which would encourage investors and transit agencies to consider urban maglev. The discussion of each of the projects highlight those lessons learned which help to make such advances.

4.1.1 MUSA

The project from MUSA examined the conversion challenges of foreign technology to U.S. standards and regulations and concluded that, with a number of suggested changes and recommendations, the Japanese “Chubu-HSST 100-L transportation system has the originality and technical competency to fulfill a need for [a] low-speed (60 mph max.) intra-urban area transportation system in the 21st Century.” The costs associated with an urban maglev project and the fact that a heavy rail system is already in place made it difficult for MUSA to find a suitable location for creating a prototype. Moreover, there were substantial differences between Japanese and U.S. safety and operational design standards. These differences would necessitate substantial redesign of subsystems, in essence rendering the MUSA strategy of quick adaptation of a Japanese-based system to U.S.-based standards substantially more difficult than initially perceived.

4.1.2 CDOT

The project overseen by the Colorado Department of Transportation originally looked at utilizing propulsion technology that was under development at Sandia National Labs, but ended up focusing its efforts on the development of the alignment for a potential urban maglev system in which terrain and weather conditions would favor the maglev technology. The project described the conceptual components of a steep terrain, all-weather system originating in the Denver area and stretching along the I-70 corridor towards Eagle, Colorado. The initial phase was to be tested in a segment of approximately 30 miles. The project concluded with some focused insights based on the Sandia-derived technology and preliminary engineering plans for lower cost guideway designs.

4.1.3 Maglev 2000

The project run by Maglev 2000 of Florida attempted to demonstrate the feasibility of using super conducting magnets for its system. While this program had been initiated under the FRA

High-Speed Maglev Program, it still struggled to create a prototype suspension system that would demonstrate the viability of using superconductivity. The project was never able to successfully levitate its chassis due to production difficulty with the cooling systems necessary for superconducting magnets.

4.1.4 MagneMotion

The MagneMotion, Inc. project features permanent magnets and LSM propulsion. The program focused on the development of a 1/7 scale system to demonstrate its concepts and is still showing promise for possible deployment at a test site. The permanent magnet concept allows for a 20mm gap, which should reduce tolerances in guideway construction, thereby making them cheaper to construct. The program has been awarded additional funding for further work in creating a possible demonstration site at Old Dominion University in Virginia.

4.1.5 General Atomics

The system proposed by General Atomics also uses permanent magnets, but they are configured in what is called a Halbach array, and are used in conjunction with LIM propulsion. This program is coordinating with the California University of Pennsylvania to use the campus as a potential test site for the system. A full-scale chassis and limited test track were constructed for testing at the GA facilities in California, with the hope of moving directly to a full-scale operating system in Pennsylvania.

4.2 Project Execution

The principal lesson learned in the overall project execution was that, as with most research efforts, there will be unexpected challenges and obstacles during the course of the projects. Each project team identified different challenges, such as gaining cooperation with State, city, and local stakeholders for alignment issues, obtaining details on already operating systems that were not considered proprietary, and underestimating the technical challenges of super cooling magnets.

In addition, while the very nature of research programs draws people who are interested in solving complex problems, very often these people are not as concerned about following Federal guidelines and submitting required reports on time. The lesson learned from the program in this regard was the value of requiring someone on the project team to provide a project plan with enough detail that FTA could determine when the project had veered off-course, and to provide them with enough details on project progress to determine whether a payment of funds was warranted. Eventually all of the programs were able to provide interim milestone reports and deliverables in the context of a longer-term research program based on their individual strategies and concepts. As a result of these program plans, the researchers were able to better focus their resources and results, which allowed FTA program managers to assess progress and the need for continued investment.

4.3 Project Conclusions and Deliverables

At the time of this report, only two of the five research teams are still engaged in urban maglev search efforts: General Atomics and MagneMotion. All teams have provided reports and briefings of their work. Some of the team members have made presentations at professional conferences or workshops associated with technology research (magnetic levitation) or with transportation system research (conceptual plans for Urban Maglev systems). No major patents or patent pending applications have been reported. These contributions have been highlighted in Section 3.

While individual teams have presented reports and briefings, there is no comprehensive summary to-date of the research program. When the program is concluded, a summary, short report should be produced which highlights the major contributions and outcomes. These would include not only the individual team contributions, but also the major findings, such as the general systems requirements, technological advances, programmatic innovations, and contributions to the literature.

4.4 Project Team Performance

Two of the five teams, Maglev 2000 and MagneMotion, were organized and operated as small research teams, usually headed by one or two senior scientists with up to three or four associates. The remaining three teams used large-scale, system integration team models to assemble and operate their teams. These project team configurations were appropriately aligned to the type of research that each team was pursuing. Recall that the original solicitation allowed the responders to propose any type of project team configuration they wished to use.

The Maglev 2000 strategy was focused on extending technical insights from the high-speed rail program to the urban maglev environment. Consequently, the two scientists who had conducted the high-speed rail work constituted the major team members for this project. MagneMotion employs a “professor-graduate student” project model which is appropriate for the scale and scope of this research endeavor, namely an extension of known technologies to the urban maglev environment. These project team configurations allowed for relatively easy assessment of performance and more direct understanding of the advances and challenges. It also reduced the expenses for project management, allowed for an easier project execution/control/reporting structure, and enabled more funds to be applied to the technology-focused research goals.

The large-scale, systems integration project team configurations were directed at planning for and implementing full-scale experiments or demonstrations. Each team had a prime contractor with associated specialty subcontractors. On average, each team had 6 subcontractors in areas such as structures and guideways, urban transportation system design, control systems, environmental impact assessments, vehicle and chassis design, cost estimation, etc. While such a project team configuration does allow for improved coordination and integrated design, a larger portion of the research funding is necessarily spent on project management and project reviews.

Future FTA research projects of this type would benefit from either the small team project model (expert scientists with small staff support or “professor-student” model) or a phased implementation of the system integrator model. In the phased implementation project team model, specialty subcontractors are identified in the initial work plan, but are only engaged during the project at critical design reviews. This approach minimizes expenditures for those subcontractors whose expertise may not be needed until substantial maturation of the conceptual design and advanced technologies. This approach balances fixed costs with technical risk by keeping all key functional areas informed at critical design reviews to ensure there are no major design flaws or defects pertinent to their area of expertise.

4.5 Stakeholder Participation

Three sets of major stakeholders exist for this research project: FTA, urban maglev users and operators, and the magnetic levitation research community. The general public would be represented and involved through the urban maglev user group, i.e., the transit agency, organization, or MPO involved in assessing and possibly employing the proposed system.

The relationship between the FTA and the research team is twofold. The first is the traditional sponsor-performer relationship in which a contracted work plan is established, progress reports are provided, corrections implemented, and administration of the contract is managed. The second is the oversight of the research and technological innovations as proposed and updated by the project team. In this program, FTA benefitted from the availability of technical experts to periodically review and assess the technical performance of the teams. An enhancement of this approach would be to engage more technical experts in magnetic levitation and control system technologies earlier in the program to ensure the fundamental technologies and advanced innovations were evolving constructively. While these reviews did take place eventually, approximately 16 months was allowed to pass before the first substantial technical review occurred, primarily due to multiple changes in project leadership at FTA early in the program. Moreover, this technical expertise need not be secured through a large support contract, but could be implemented through specific service agreements with known experts.

The systematic nature of the urban maglev technologies is address through the engagement of the users or operators of a candidate system. Recall that Phase I of the program was to demonstrate sufficient promise in the technology to warrant advancement to Phase II, in which more interaction with and influence from users and operators would be required for prototyping. Approximately 1 year passed on the program before a general systems requirements document was produced and made available to all teams. The requirements document covered all of the major areas of service characteristics, operations, safety, passenger comfort, and other critical factors. The effect of this document was to provide a benchmark for the FTA stakeholders to assess the technical performance of the research teams. It also provided a common vernacular and perspective for the user and operator community by which they could make initial assessments of the value of the advanced magnetic levitation technology. Three of the five research teams used this requirements document to engage, at various levels, potential users and operators. The CDOT project involved CDOT engaging the Denver MPO in preliminary discussions about the potential application of urban maglev. MagneMotion has worked with Old Dominion University and others to explore potential applications of their technologies. General Atomics has worked with California University of Pennsylvania and others to assess potential alignments and phased implementation of its technical solution. In future programs of this type, a general systems requirement document, not overly constraining of the technology, should be made available early and updated, as appropriate, to guide researchers, provide benchmarks for the FTA review process, and to engage potential users and operators.

The third stakeholder group is the general magnetic levitation research community. FTA brokered three team meetings in which all research teams presented their interim findings and conclusions. These were helpful sessions, but did not yield much inter-team cooperation or coordination. More generally, several team members presented papers or status reports at professional conferences. At the conclusion of the program, a more comprehensive summary of all team accomplishments should be developed so that future research directors would understand the challenges of urban maglev and the accomplishments achieved through this program.

4.6 Risk Management

Risk management is most appropriately applied when assembling component subsystems into a larger transportation system. Consequently, not much effort was devoted during Phase I when the basic magnetic levitation technologies were being explored and tested. During Phase I, risk management was developed and managed by individual researchers in the course of their studies and analysis, with little or no formal documentation other than in quarterly progress reports. In Phase II, more formal risk management practices were employed to ensure that interface controls and design risks were openly addressed.

After the benchmark system requirements were made available to all teams, FTA required risk management plans, allowing for monitoring of key technologies and critical path items. For example, in the case of General Atomics, the position sensor is a critical technology for the operation of the entire levitation and propulsion system and chassis. This risk component was identified by the GA team early in the program, but they have yet to offer a credible, tested technical solution, despite inquires by FTA and various technical review teams. This example illustrates the benefits to FTA in having such a process in place to ensure that critical path risk items are resolved before embarking on other technical activities.

4.7 Project Communications

Communications during projects of this nature are extremely critical to allow FTA to ensure that its funds are being used in the best way possible. Because of the extremely technical nature of the work, FTA wisely found subject matter experts (SME) to assist in monitoring progress and asking the hard questions of the project team. The FTA also insisted on conducting (as much as feasible) quarterly reviews with the various teams to allow for direct interaction between the research team and the FTA team. The complex nature of the activities that some of the teams were engaged in made written communication difficult to understand at times. The quarterly reviews allowed that face-to-face interaction that is so necessary to understanding just what was being accomplished. As the time period for this work came to a close, FTA also gathered all of the teams for a two-day workshop that allowed everyone to share their work and hear what other teams had been working on.

4.8 Project Summaries

4.8.1 MUSA

The primary lesson learned from the MUSA project was that conversion of a foreign system to meet U.S. safety and ADA (Americans with Disabilities Act) requirements would be a very difficult task. The Japanese system studied did not meet the speed criteria set by FTA (100 mph), and it appeared that modifying the system to meet this requirement would be a major change that would drive already very high system costs even higher. Egress and emergency exiting requirements would also cause fundamental design changes that would also impact costs. The estimated cost for this system is approximately $50 million per mile.

4.8.2 CDOT

After initially focusing on adapting a linear motor developed at Sandia National Labs, the CDOT project ultimately looked at how it could change the Japanese HSST system to meet its alignment requirements. CDOT's main contributions, or lessons learned, were its concept designs for the elevated guideway and their LIM design, which would allow the system to reach top end speeds of approximately 100 mph. The team examined both a light-weight concrete guideway design and a tubular steel design. Both designs helped reduce estimated guideway costs down to approximately $33 million per mile. Both concepts would appear to have possible applications in other transit systems that use elevated tracks. The modified LIM would not only allow the system to reach the desired top-end speeds, but would also allow the system to operated on the challenging 7 percent grade that this alignment required. The LIM design is based on experimental tests, but has not been manufactured and tested for actual performance measurements.

4.8.3 Maglev 2000

One of the initial goals of the FTA program was to have a team examine the possibility of using super-conducting magnets for a maglev application. The Maglev 2000 team was the only grantee to examine this concept and try to bring it to a successful demonstration phase. While the FRA had provided initial funding for this team to begin its work, the FTA grant allowed them to continue with their magnet design in the hope of at least levitating the chassis that had already been designed. This demonstration was never accomplished and this program drove home the difficulty of designing magnets that would be mounted on a guideway to provide the levitation for such a system. The team experienced one failure after another in its attempts to design and build a system that would cool the magnets to the required temperatures. These failures in a controlled laboratory environment indicated that the use of super-conducting magnets for a moving, outdoor environment is still not a viable concept.

4.8.4 MagneMotion

The MagneMotion team has worked with a permanent magnet design that allows them to operate with a 20 mm air gap, which is more than twice the gap achieved by systems that are operating in Germany and Japan. By increasing the gap between the vehicle and the guideway, the ultimate contraction of the guideway will not have to be as precise as on other systems, which should drive the cost of construction down. MagneMotion's other main contribution is in the design of its LSM propulsion system. The LSM design is one that is already is use in an industrial manufacturing facility and provides very precise position sensing capability, greatly reduced power consumption, and is simpler to manufacture. This has applications to anything that uses linear motors.

4.8.5 General Atomics

General Atomics originally considered the use of super-conducting magnets for its levitation system, but ended up designing a permanent magnet system in what is known as a Halbach array. This concept, like MagneMotion's permanent magnet design, allows the General Atomics system to achieve a much larger gap (20mm – 30mm) than current maglev designs. Again, one of the main advantages of the larger air gap is that the design and construction tolerances are not as rigid and precise. General Atomics also uses an LSM for propulsion and has built a full-scale chassis that is being tested on a test track.

Appendix A. Brief Overview of Magnetic Levitation Technologies for Low-Speed Urban Transportation

Magnetic levitation (maglev) is a relatively new transportation technology in which non-contacting vehicles travel safely at speeds of a few miles-per-hour to several hundred miles-per-hour while suspended, guided, and propelled above a guideway by magnetic fields. The operating speed is determined by the system application; i.e., city-to-city passenger transportation, urban passenger use, or non-passenger applications such as freight transportation. The guideway is the physical structure along which maglev vehicles are levitated.

The primary functions basic to maglev technology include:

- Levitation or suspension of the transit vehicle from the guideway.
- Forward or reverse propulsion.
- Vehicle guidance.

In most current concepts and designs, magnetic technologies are used for all three functions, although a nonmagnetic source of propulsion could be used. No consensus exists on an optimum design to perform each of the primary functions.

A.1. Magnetic Levitation Technologies

Suspension

The two principal means of levitation are electromagnetic suspension (EMS) and electrodynamic suspension (EDS). EMS is an attractive force levitation system whereby electromagnets on the vehicle interact with and are attracted to magnetic-attractive components on the guideway. EMS is made especially practical by continuing advances in electronic control systems that precisely maintain the air gap between vehicle and guideway, preventing contact and optimizing power usage. An attractive feature of EDS is its inherent ability to compensate for variations in payload weight, dynamic loads, and guideway irregularities through rapid changes in the magnetic field (via the control system) resulting in the maintenance of the proper vehicle-guideway air gaps.

Electrodynamic suspension (EDS) employs magnets on the moving vehicle to induce currents in the guideway. A key technical property of EDS is that the repulsive forces produced are inherently stable because the magnetic repulsion increases as the vehicle-guideway gap decreases. Usually the vehicle must be equipped with wheels or other forms of support for "takeoff" and "landing" because an EDS levitation design will not operate at speeds below approximately 20 mph. EDS performance has progressed with advances in materials research, cryogenics, and the potential application of superconducting magnet technology.

Propulsion Systems

Two types of propulsions systems are employed using magnetic technologies. Both rely on the principle of stator motor design and magnetic induction to create propulsive physical forces.

- "Long-stator" propulsion uses an electrically powered linear motor winding in the guideway. This configuration is the more expensive of the two because of higher total guideway construction costs.
- "Short-stator" propulsion uses a linear induction motor (LIM) winding onboard the vehicle and a passive guideway with a magnetically "receptive" material (e.g., ferromagnetic aluminum, copper, etc.) installed along the rail surface. The LIM is heavy and reduces vehicle payload capacity, typically resulting in higher operating costs and lower revenue potential compared to the long-stator propulsion. However, the guideway costs are less.

Guidance Systems

Guidance systems are required in all degrees of freedom (i.e., forward and backward, left and right, pitch, yaw, etc.) in order to steer or guide the vehicle safely along the guideway under all operating speeds and conditions. The guidance system can be the result of direct application of the magnetic forces necessary to meet ride requirements and can be used in either an attractive or repulsive manner. Similarly, certain design concepts allow for the same magnets on board the vehicle which supply levitation to be used concurrently for guidance. This approach is more complicated, but if successful can reduce vehicle weight.

Appendix B. FTA UML Maglev Project Descriptions

MUSA Project

Earthtech in Baltimore, MD assembled a team called MUSA with Chubu High-Speed Surface Transport (CHSST) as one of the subcontractors. MUSA adopted CHSST technology as the basis for its Maglev system. A brief description of the technology is presented here.

Principles of Levitation and Propulsion

The high-speed surface transport (HSST) maglev system has been in development in Japan for more than 25 years, and has evolved through several progressively more practical forms. Fundamentally, the Chubu high speed surface transport (CHSST) maglev utilizes electromagnetic attractive forces between simple dual-pole magnets (analogous to two facing horseshoe magnets) to provide both levitation and guidance. The simplified diagram is shown in Figure 3. The upper, or fixed, rail side is a simple steel (iron) section with two downward facing poles mounted on the guideway structure. The lower, upward-facing magnet is mounted on the vehicle and is an electromagnet whose intensity is varied continuously by a gap sensor to maintain a constant magnetic gap in the 8 mm range. This active control is required since otherwise the gap is unstable with the two magnets attracting each other. Lateral guidance is provided by the tendency of the two opposing magnet pole pairs to maintain their lateral alignment. Propulsion and braking is provided by a separate linear induction motor (LIM) system, with the active (energized) side being vehicle-mounted above the same steel rail used for levitation and guidance. There is an additional aluminum plate fastened to the rail top to provide an optimum mix of materials for the LIM function. Finally, there are mechanical brakes and landing skids provided on the vehicle which also act on the outer flange and top, respectively, of the basic steel rail section.

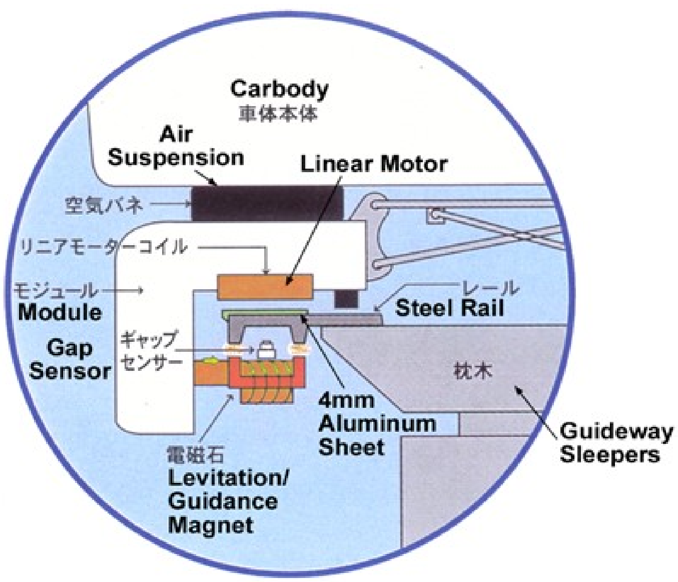


Figure 3. CHSST Maglev Rail and Module Cross-Section

Guideway

The baseline guideway in both the test track and in planned applications is elevated and comprises a simple box girder for each travel direction topped with transverse steel sleepers, which in turn support the maglev rails described above. Two-way elevated guideways comprise the two parallel guideway beams, supported on traditional cross-beams, pylons, and footings, designed for local conditions and long-term stability (Figure 4). All services, such as power transmission, signal and communication, etc., are located on the guideway. Rights of way of existing major streets can thus be utilized. Beam stiffnesses are claimed to be sufficiently high with spans in the 20 m range so that dynamic behavior under operating, off-design, and varied environmental conditions is adequately controlled. Also, ride quality requirements (G-spectra) are claimed to be met, and operations on the test track so far confirm this.

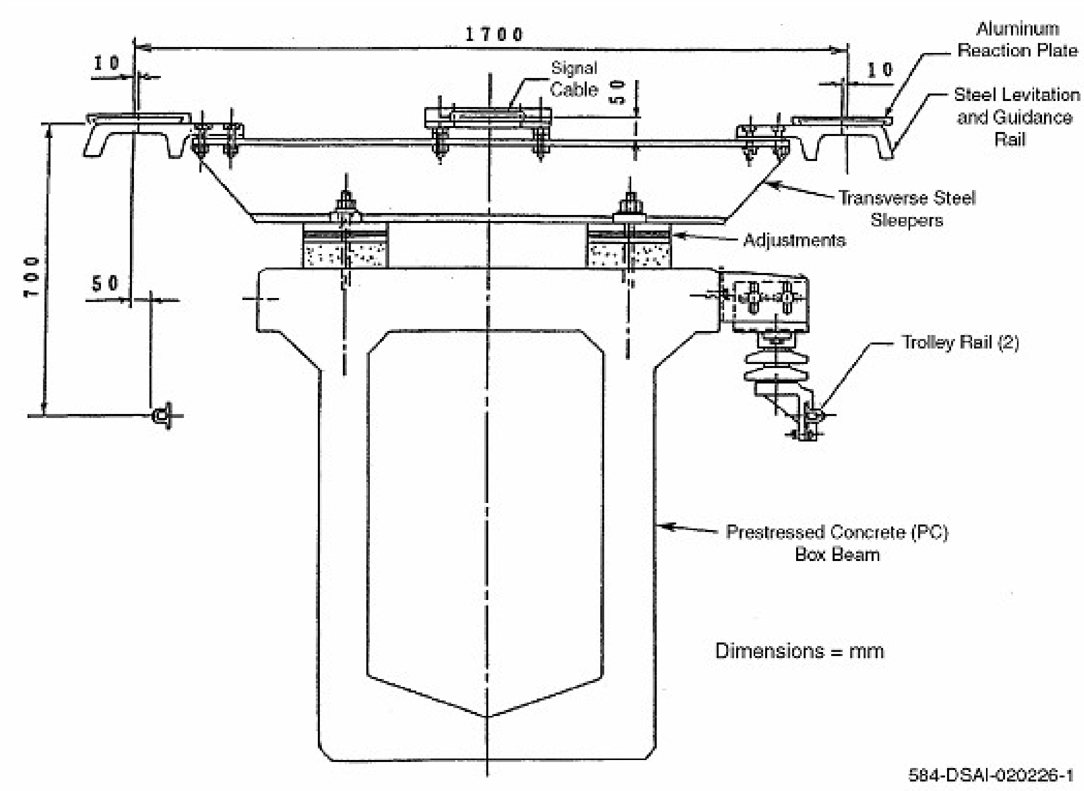


Figure 4. CHSST Maglev Guideway

Vehicle

On the Tobukyu Line (TKL), three cars are used to form a train. Each car has five modules per side that support secondary suspension (air bags) and carry vehicle weights. The vehicles can remain levitated when stopped, such as at a station. Planned deployments would use these basic vehicles with updated exteriors, interiors, required equipment, etc.

System Characteristics

A summary of MUSA/CHSST system characteristics is presented in Table 1.

Table 1. Summary of System Characteristics (MUSA/CHSST)

System Item	Characteristic or Measurement
I. Operational Characteristics	
Max. Operation Speed	100 km/h (62.1 mph)
Max. Initial Acceleration 4.0	4.0 km/h/s (2.5 mph/s)
Max. Deceleration Service Brake	4.0 km/h/s (2.5 mph/s)
Max. Deceleration Emergency Brake	4.5 km/h/s (2.8 mph/s)
Max. Gradient	7%
Min. Horizontal Curve Radius	Side line track 50 m (164 ft), Main line track 75 m (246 ft)
Min. Vertical Curve Radius	1,500 m (4,921 ft)
Max. Super Elevation Angle	8°
Passenger Capacity for Four-Car Train – Seated	104
Passenger Capacity for Four-Car Train –Standing	144 (0.3 sq m/standee (465 sq in))
Passenger Capacity for Four-Car Train – Total	248
Temperature	10°C to 40°C (50°F to 104°F)
Max. Wind Velocity (operational)	25 m/sec (60 mph). Structure is designed for 50 m/sec (120 mph) wind
II. Vehicle Configuration	
Vehicle Type	HSST-100L
Train Formation	Cars: Mcl, M & Mc2
Car Body Length	14 m (45'11") for middle car 13.5 m (44'4") for end cars
Width	2.6 m (8'6")
Height	3.45 m (11'3")
Rail Gauge	1.7 m (5'7")
Empty Weight	17,500 kg/car (32,580 lbs/car)
Fully Loaded Weight (AW2)	28,000 kg/car (61,728 lbs/car)
Car Body Structure - Material	High Strength aluminum alloy
Car Body Structure - Construction	Semi-monocoque
III. Levitation System	
Magnet	Ferro-magnet for levitation and guidance (electromagnets, not superconducting)
Levitation Gap	6 mm (0.24") mechanical gap 8 mm (0.32") magnetic gap
IV. Propulsion System	
LIM (Linear Induction Motor)	10 LIMs per car
Quantity	1,800 mm (5'11") per one LIM
Secondary	Reaction plate (Aluminum plate on rail)
Power Supply	1,500 VDC from trolley rails
Inverter Type	VVVF
V. Suspension System	
Suspension Module	5 flexible pair-modules per car (Module: levitation bogie trucks)
Module Frame	Aluminum alloy
Secondary Suspension	Air suspension
VI. Brake System	
Service Brake	Combination of LIM brake (regenerative or reverse phase) and hydraulic brake (mechanical friction brake)

System Item	Characteristic or Measurement
Emergency brake	Hydraulic brake
Parking Brake	Skids (levitation cut off)
Hydraulic Pressure	210 kg-f/sq cm (2,986 psi)

Contractor Estimated Costs

The costs estimated by MUSA for CHSST are as follows:

System Item	Cost
Basic Guideway (2-way) elevated	~ $50 million/per mile
Vehicle	$2 million
Signaling	$7.78 million
Communication	$2.04 million
Electric Power to Rail	$5.56 million
Substation	$18 million
Superstructure (rails, sleeper, etc.)	$4.26 million
Maintenance Depot	$5.93 million
Stations (close pairs)	~ $2.5 million per station per mile

CDOT Project

This was a goal-oriented project with a focus on the application of Maglev technology along the I-70 route in Colorado, which connects Denver International Airport to Eagle County and covers a distance of about 140 miles. This project was jointly performed by the following major subcontractors:

- Colorado Department of Transportation.
- Maglev Technology Group (MTG).
- Sandia National Laboratories (SNL).
- T. Y. Lin.

The interstate I-70 alignment being considered by CDOT team members is shown in Figure 5. This route has steep gradients and is challenging for any mode of transportation.

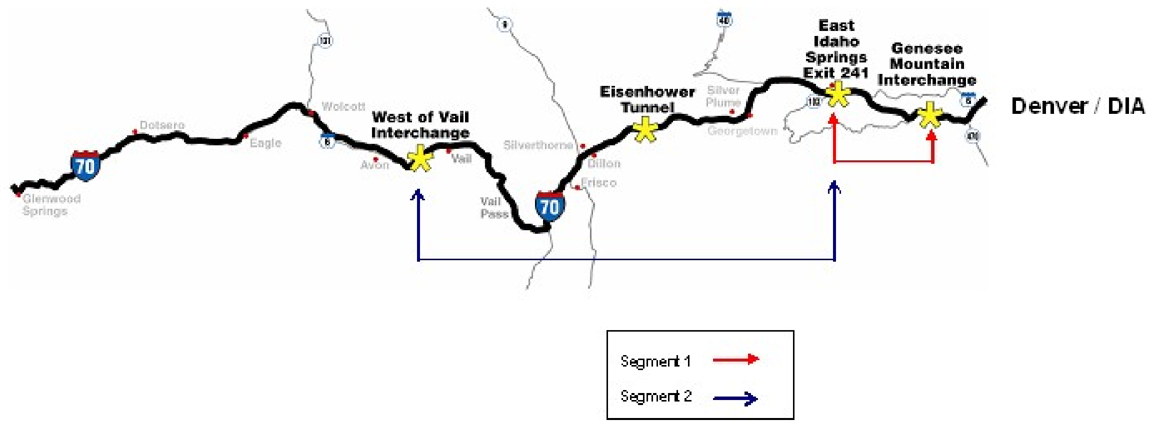


Figure 5. Interstate 70 Route Alignment

Principle of Levitation and Propulsion

The projected baseline technology for this project is the CHSST technology, which is described in Section 2.1.1. However, significant design improvements are being considered for improved speed and motor efficiency to meet the special requirements of the Colorado maglev route.

Guideway

MTG and T.Y. Lin proposed alternative guideway configurations to reduce the cost of the CHSST guideway system. These are shown in Figure 6 and Figure 7. One concept uses a concrete slab integral to the girder to support the steel rail system of CHSST and eliminates the steel ties currently used on the Japanese TKL route. A second concept uses a steel truss guideway, which is very unconventional for Maglev vehicles. It may be considered a high risk, but it looks very attractive and is simpler to erect. For the purpose of this document, we assume that the concrete guideway with reduced risk is the preferred approach for initial evaluations. The proposed U-girder for Colorado is shown in Figure 8.

Figure 6. Precast Concrete U-Girder

Figure 7. Tubular Steel Space Truss

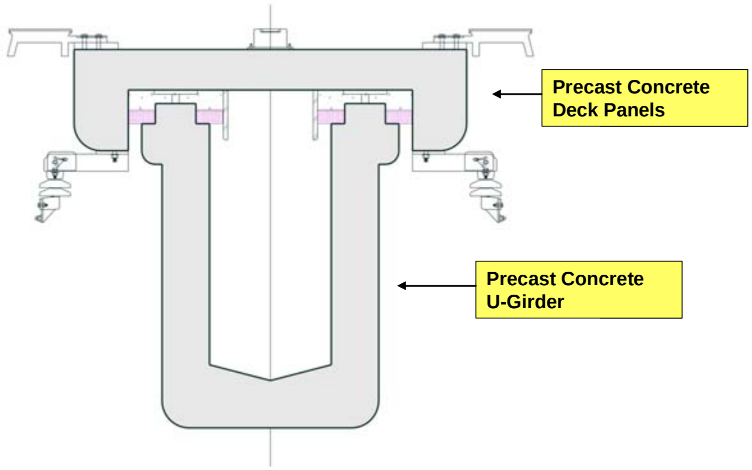


Figure 8. Proposed U-Girder for Colorado

Vehicle

The CDOT concept vehicle is a higher speed vehicle based on the early version of the CHSST vehicle 200 Series. The LIM design in the 100 Series was basically upgraded for higher performance along the following lines:

- Switching LIM to a constant slip mode after a certain speed, up to which constant slip frequency will be used for its operation.
- Using higher voltage.
- Increasing the number of poles.
- Increasing the number of modules per car to 10 on either side instead of 5 as in the earlier CHSST design.

As a result of these and other improvements, the vehicle thrust capacity will increase at higher speeds, up to 200 mph, allowing it no degradation in speed on 7 percent slopes under high wind gusts. Since the vehicle size would be 24 m, the minimum negotiable radius will be 150 m, which was within the requirements for CDOT maglev alignment. The CDOT 200 vehicle is shown in Figure 9.

Figure 9. Colorado 200 Vehicle

System Characteristics

A summary of CDOT system characteristics is presented in Table 2.

Table 2. Summary of System Characteristics (CDOT)

System Item	Characteristic or Measurement
I. Operational Characteristics	
Max. Operation Speed	160 km/h (100 mph)
Max. Initial Acceleration 4.0	1.6 m/sec^2 (.16 g)
Max. Deceleration Service Brake	4.0 km/h/s (2.5 mph/s)
Max. Deceleration Emergency Brake	32 g
Max. Gradient	7% (no degradation) 10% (with degradation)
Min. Horizontal Curve Radius	Side line track 50 m (164 ft), Main line track 300 km
Min. Vertical Curve Radius	1000 m
Max. Super Elevation Angle	8°
Passenger Capacity for Four-Car Train – Seated	197
Passenger Capacity for Four-Car Train –Standing	--
Passenger Capacity for Four-Car Train – Total	197
Temperature	10°C to 40°C (50°F to 104°F)
Max. Wind Velocity (operational)	50 km/h (30 mph). Structure is designed for 140 km/h wind.
II. Vehicle Configuration	
Vehicle Type	CO 200a
Train Formation	Two Cars
Car Body Length	24.3m
Width	3.2 m
Height	3.4 m
Rail Guage	1.7 m (5'7")
Empty Weight	25,370 kkg/car
Fully Loaded Weight (AW2)	41,600 kg/car
Car Body Structure - Material	High Strength aluminum alloy
Car Body Structure - Construction	Semi-monocoque
III. Levitation System	
Magnet	Ferro-magnet for levitation and guidance (electromagnets)
Levitation Gap	6 mm (0.24") mechanical gap 8 mm (0.32") magnetic gap
IV. Propulsion System	
LIM (Linear Induction Motor)	10 LIMs per car
Quantity	1,800 mm (5'11") per one LIM
Secondary	Reaction plate (Aluminum plate on rail)
Power Supply	3000V DC line
Inverter Type	VVVF
V. Suspension System	
Suspension Module	10 flexible pair-modules per car (Module: levitation bogie trucks)
Module Frame	Aluminum alloy
Secondary Suspension	Air suspension
VI. Brake System	
Service Brake	Combination of LIM brake (regenerative or reverse phase) and hydraulic brake (mechanical friction brake)
Emergency brake	Hydraulic brake
Parking Brake	Skids (levitation cut off)

Contractor Estimated Costs

Contractor-estimated system level construction costs are shown in Table 3. Operating costs per passenger mile are not available, however, the total annual operation and maintenance costs are quoted at about $2M per mile.

Table 3. Preliminary System Level Construction Costs

System Item	Cos t[1]
Guideway	$3,410 million[2]
Stations	$420 million[3]
Switches, Rails	$264 million[4]
Communications/Controls	$597 million[5]
Power (Substations/Elec.)	Not provided[6]
Vehicles	$455 million
Total with 25% contingency	$6,434 million
Cost per mile	$33 million

[1]Costs do not include right of way, engineering or construction management.
[2] 156 miles.
[3] 14 stations.
[4] 14 switches, $1.6 million/mile.
[5] $2/mile com. controls.
[6] 32 substations, $1 million/mile.

General Atomics Project

San Diego-based General Atomics, along with their subcontractors in Pittsburgh and elsewhere, have been actively developing a low-speed maglev system initially with the idea of demonstrating the system at California University in Pennsylvania and later introducing the system as a circulator in downtown Pittsburgh.

Principles of Levitation and Propulsion

General Atomics uses an electro dynamic system that gives lift to the vehicle when it reaches a minimum speed on wheels. The vehicle-mounted magnets produce the necessary lift by reacting with Litz wire in the stainless steel tubes mounted on the guideway structure. The equilibrium lift is controlled by the permanent magnets under a Halbach arrangement. The vehicle is propelled by LSM windings on the guideway. At levitation speed, the wheels are folded up by mechanical means. The system is shown in Figure 10 and Figure11.

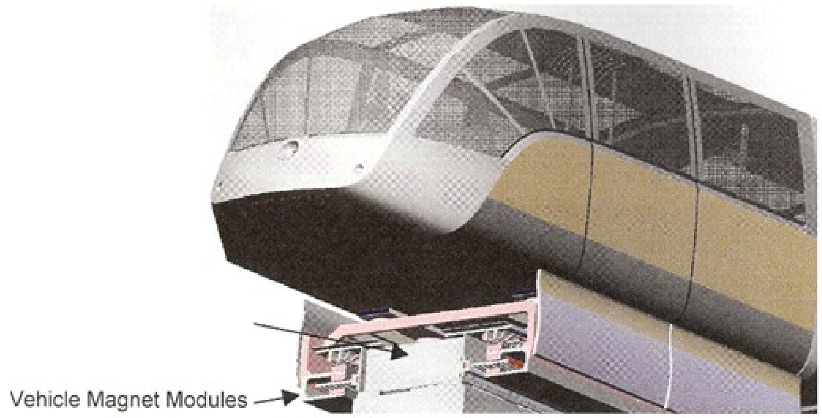


Figure 10. Vehicle on Guideway

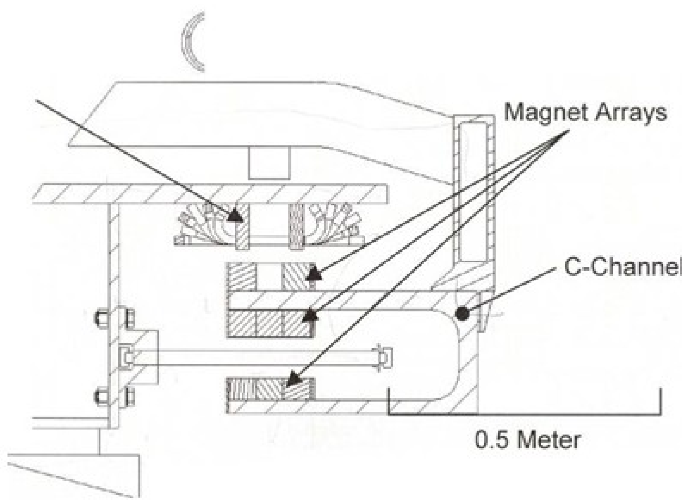


Figure 11. Cross-section of Maglev Guideway Magnet System

The magnet blocks consist of neodymium-iron-boron (NdFeB) rare-earth permanent magnets. The magnet blocks are subdivided into subassemblies that are loaded into the magnet cases, as shown in Figure 12. The top set of magnet blocks interacts with the LSM to provide guidance and propulsion. This arrangement, combined with the LSM rails, is claimed to provide the passive guidance force to keep the vehicle aligned to the guideway. In each subassembly the magnet blocks are placed with their magnetization vectors in the same direction and are contained in a welded, aluminum container. Along the length of the Halbach array, the magnetization vectors rotate in steps of 45 degrees per magnet container subassembly. This rotation of the magnetization vectors provides the Halbach effect, as discussed above, that concentrates the magnetic field lines to increase the lift forces. To complete the assembly of the Halbach arrays, the channels are then mounted to the chassis supports with removable fasteners.

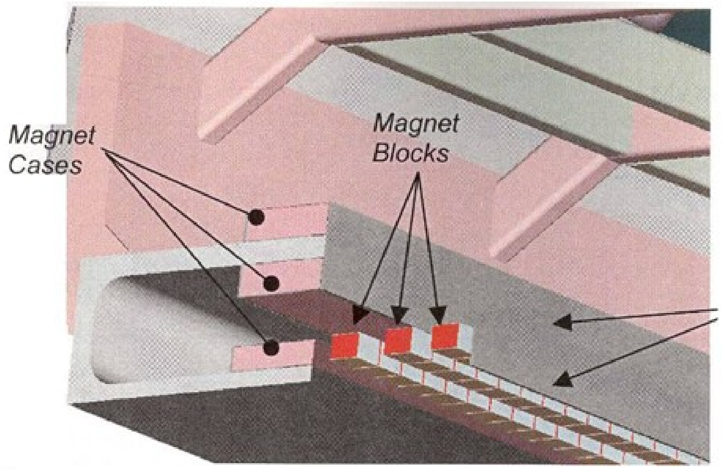


Figure 12. Vehicle Permanent Magnets In Containers

Guideway

The basic guideway structure utilizes guideway modules mounted on a deck that rests on a concrete box beam girder as shown in Figure 13. The guideway modules provide the LSM assembly and the required landing surface for the wheels at station locations and during emergencies. The guideway carries cantilevered elements of Litz wire for the vehicle's permanent magnets to generate reactive levitation forces. Research is also being carried out to replace the Litz wire with a laminated copper sheet track. Litz wire and laminated sheets are both generally considered to be expensive, contributing to the overall cost of the guideway structure.

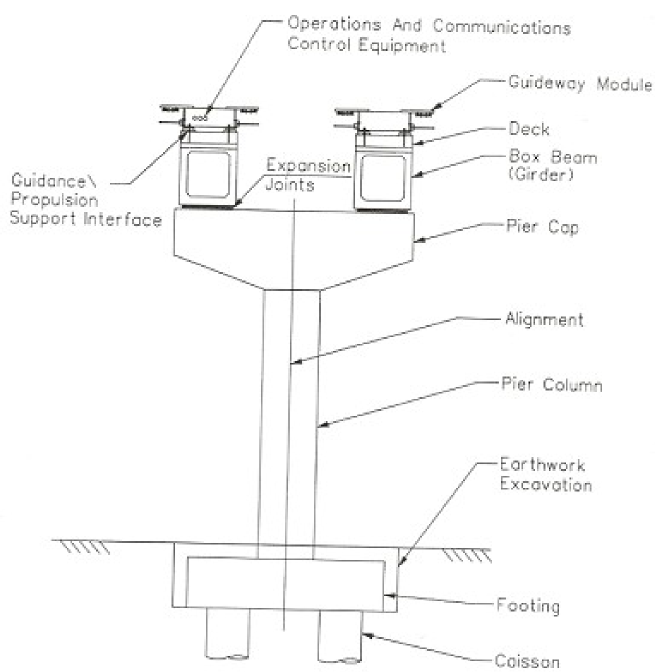


Figure 13. Basic Two-Way Guideway Structure

Guideway Levitation/Propulsion Modules

As illustrated in Figure 14, the guideway module assembly consists of two carbon-steel guideway top plates (1). These plates carry both the LSM assembly (2) and provide the landing surface for the station or emergency wheels. Also, the guideway levitation and propulsion module consists of two stainless steel angle brackets (3), which support the track assemblies (4). Both the LSM top plates and the angle brackets are interconnected with stainless steel guideway frames (5). Running the length of the module on both sides are two stainless steel guideway side plates (6), which are welded to the guideway frames and provide the mounting surface for the track assemblies.

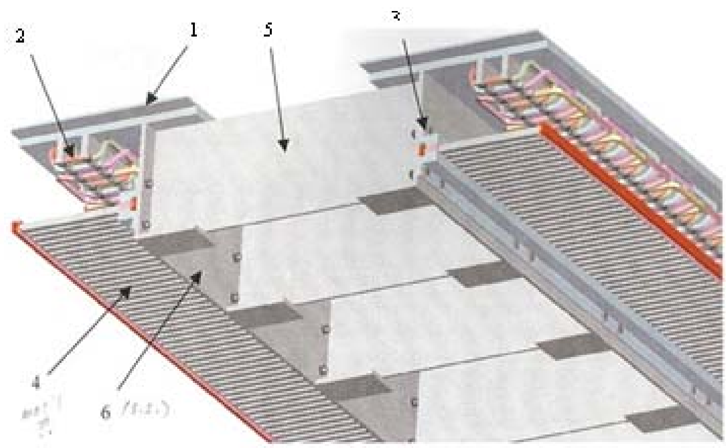


Figure 14. Guideway Levitation/Propulsion Modules

The levitation Halbach arrays, which are attached to the vehicle, move above and below the track. The interaction of these currents with the magnetic fields generates the lift forces.

Vehicle

The vehicle, with a capacity of 100 passengers, is made of multiple modules—one articulation module and two nose modules—to create a vehicle which is 12 m (39.4 ft) long by 2.6 m (8.5 ft) wide and 3 m (9.8 ft) tall, as depicted in Figure 15.

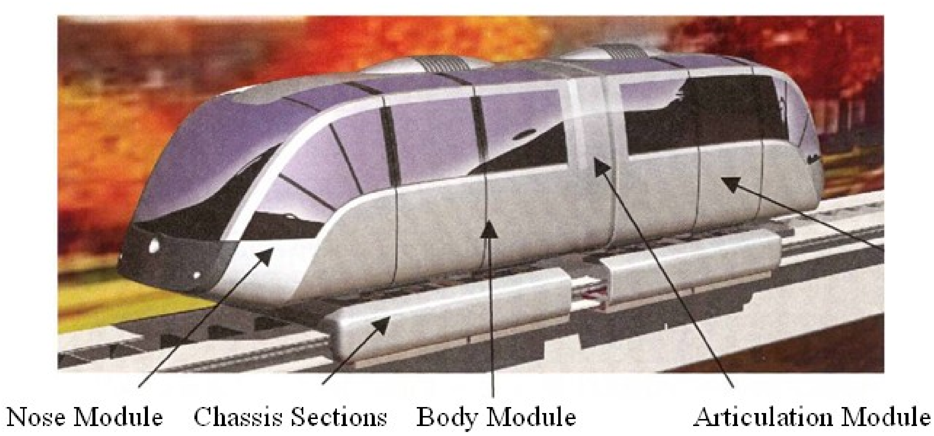


Figure 15. Maglev Vehicle

Under each body module there are chassis modules (Figure 16) that provide levitation, propulsion, guidance, braking, and a secondary suspension. Each chassis is split into two sections to negotiate super-elevated curves. The split chassis also allows use of fixed instead of deployable landing wheels, thus minimizing cost and complexity while increasing safety and reliability.

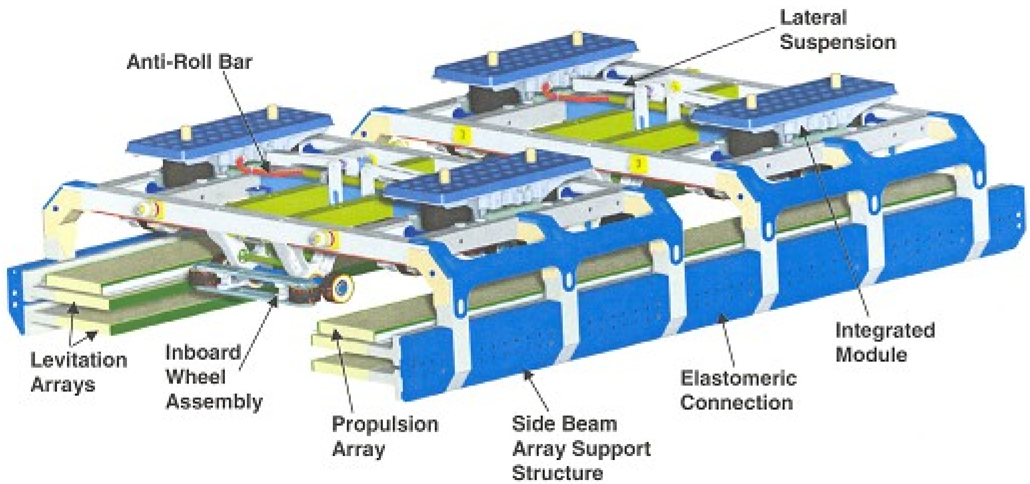


Figure 16. Vehicle Chassis

Since the active component of the motor is in the guideway, heavy on-board power conditioning equipment for propulsion is not required. Power pickup is required to provide 20 kW of housekeeping power.

The levitated vehicle is equipped with three separate braking systems, as required on light-rail vehicles. They are the dynamic LSM service brake, an electromechanical friction service brake, and a permanent magnet fail-safe emergency track brake. Each system will provide up to 0.2 g deceleration. The two friction brakes react against the steel top surface of the guideway LSM supporting member.

The Halbach arrays concentrate the magnetic field on the active side, while canceling it on the opposite side. This magnet arrangement, along with other design features of the GA system, results in low magnetic fields in the passenger compartment.

System Characteristics

A summary of the General Atomics system's characteristics is presented in Table 4.

Table 4. Summary of System Characteristics (GA)

System Item	Characteristic or Measurement
I. Operational Characteristics	
Max. Operation Speed	160 km/h (100 mph)
Max. Initial Acceleration 4.0	1.6 m/sec^2 (.16 g)
Max. Deceleration Service Brake	1.6 m/sec^2 (.16 g)
Max. Deceleration Emergency Brake	3.5 m/sec^2 (.36 g)
Max. Gradient	7% (no degradation) 10% (with degradation)
Min. Horizontal Curve Radius	Side line track 18.3 m (62 ft) Main line track 1000m

System Item	Characteristic or Measurement
Min. Vertical Curve Radius	1000 m
Max. Super Elevation Angle	6°
Passenger Capacity for Four-Car Train – Seated	--
Passenger Capacity for Four-Car Train –Standing	--
Passenger Capacity for Four-Car Train – Total	400
Temperature	10°C to 40°C (50°F to 104°F)
Max. Wind Velocity (operational)	50 km/h (30 mph). Structure is designed for 160 km/h (100 mph) wind.
II. Vehicle Configuration	
Vehicle Type	Modular (body, nose, and articulation)
Train Formation	Four Cars
Car Body Length	12 m
Width	2.6 m (8‘6”)
Height	3 m (9.8 ft)
Empty Weight	11350 kg/car
Fully Loaded Weight (AW2)	18350 kg/car
Car Body Structure - Material	High Strength aluminum alloy
Car Body Structure - Construction	Semi-monocoque
III. Levitation System	
Magnet	Permanent magnet, Halbach array Litz wire track
Levitation Gap	25 mm (1”) mechanical gap, EDS 8 mm (0.32”) magnetic gap
IV. Propulsion System	
LSM (Linear Synchronous Motor)	600V DC
Power Supply	Not provided
Inverter Type	VVVF
V. Suspension System	
Suspension Module	4 chassis frames, 8 secondary suspension units
Module Frame	Aluminum alloy
Secondary Suspension	Air suspension, dampers, struts
VI. Brake System	
Service Brake	electric brake and mechanical brake
Emergency brake	Mechanical brake
Parking Brake	Skids (levitation cut off)

Contractor Estimated Costs

Vehicle Capacity and Vehicle, Station, and Guideway Costs

Item	Cost
Vehicle Size 15m, four vehicle train	Train capacity 400
Deluxe Station Cost	$4.72 million
Capacity @ 1.5 minute headway (10 hours operation)	= 400 x 10 x (60 / 1.5) = 400 x 10 x 40 = 160,000 per day = 16,000 pph
Dual Guideway Average Cost/km	~ $8 million
Dual Guideway Average Cost/mile	**$12.8 million**

Costs for Electric System Over 8.3 miles (13.3 km)

Item	Cost
Energy Supply Substation Power Distribution Wayside Equipment	$115.8 million $54.9 million $10.2 million $48.2 million
Total	$229.1 million
Cost/mile	= ~229/8.3 = ≤ **$22 million per mile**
Total Cost per Mile	= 22 + 12.8 **= $35 million per mile**

MagneMotion System

The MagneMotion system is being developed by a group of people in Acton, MA and is focused on levitation and propulsion with subcontract support from Earthtech and others on guideway structures. The Maglev vehicles are small and are to be operated in platoons to achieve a high capacity of ~ 12,000 pph.

Principles of Levitation and Propulsion

The levitation is based on electromagnetic suspension as in Transrapid or CHSST, but is reinforced with vehicle-mounted permanent magnets to achieve a larger gap, on the order of 25mm. Control coils are used for stabilization of levitation as in the case of Transrapid and HSST. The guideway mount LSM provides the propulsion force to the vehicle, interacting with the permanent magnets.

The MagneMotion design uses a single set of magnets to provide all of the functions of suspension, guidance, and a field for the LSM propulsion. The classic electromagnet-based EMS design has been replaced by one that uses a single set of permanent magnets to provide not only the lift and guidance forces, but also the field for the LSM. Coils wound around the magnets are driven from a feedback control system to stabilize the suspension. The vehicle magnets provide guidance without any active control.

MagneMotion claims that in using LSMs, the savings in propulsive power, vehicle weight, and vehicle cost more than make up for the added guideway cost resulting from the additional motor windings and inverters. Two motors, port and starboard, provide propulsion so that failure of a single motor can be tolerated for short periods of time, albeit with reduced acceleration capability. The use of regenerated power from a braking vehicle to help power a nearby vehicle is also planned. At operational speeds, the LSM is claimed to provide an ample reserve of acceleration compared to most transit systems. For a full-scale design, the motor is driven by a conventional three-phase inverter that operates off of an 800 VDC bus. The inverter uses IGBT power devices of the type used in variable speed drives operating off of 480 VAC power systems. The DC bus links all inverters on the guideway so that vehicles that are braking can supply their braking energy to other vehicles that are accelerating. In a typical installation, the DC bus receives power from 1.5 MW rectifier stations spaced about every 8 km. This compares with the same size rectifier located about every 2 km for light rail applications, and this is claimed to be one of the cost-saving features of the design.

Guideway

The MagneMotion guideway is a trapezoidal cross-section guideway beam with steel plates on each outer upper lip to support the suspension rails. It is similar to but smaller and simpler than the German Transrapid guideway. Two examples of beams currently under consideration are a hollow pre-stressed concrete (with steel reaction plates) and an all-steel version (Figure 17). Later cost estimates also show a composite version. These beams can be mounted on piers for elevated operation or the beam height can be reduced and the beams mounted on ties or pads for at-grade installations.

The aim of the design was to keep the guideway beams as small and light as possible without jeopardizing ride quality. The resulting design is based on stiffness and resonant frequency considerations; the strength of the structures is claimed to be greater than is necessary so there is no compromise with safety issues. If the vehicle is short compared with the pier spacing, MagneMotion asserts that beam precamber can help compensate for most of the beam deflection. This allows the use of lighter beams with greater deflection. The key compromise is between using beams that are too large and expensive and a guideway that does not provide good ride quality.

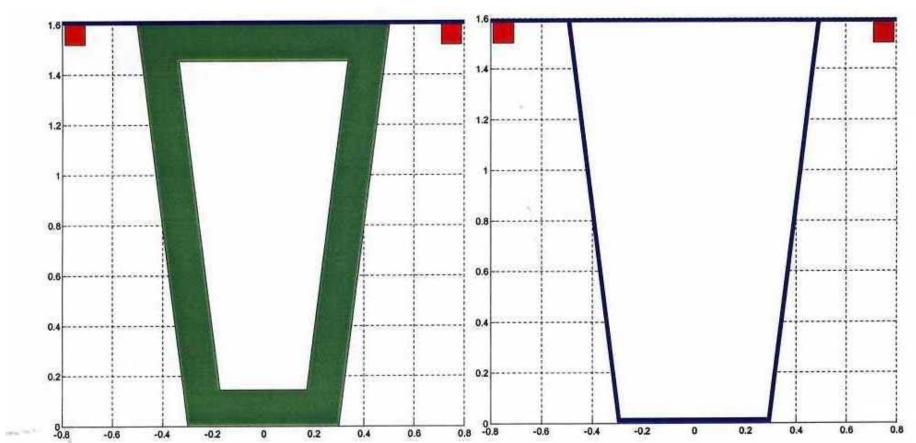


Figure 17. Guideway Beam Designs: Hybrid (Left) and Steel (Right)

Vehicle

The MagneMotion baseline vehicle has the size of a small bus (Figure 18). This vehicle seats 24 with room for 12 standees and uses modest streamlining to reduce drag at the top speed of 45 m/s (101 mph). The magnets are mounted on pivoting pods that allow 18.3 m (60 ft) horizontal turning radius and 250 m (820 ft) vertical turning radius. An initial vehicle design is based on fiberglass construction, but few structural details are available. The HVAC and other equipment is in the nose and tail where streamlining prevents use of that space for passengers.

The primary suspension is provided by the magnets, but there is a secondary suspension that has two components. The magnet pods (Figure 19) have pivots with dampers so as to allow tight turning radii in both horizontal and vertical directions. Pneumatic springs allow improved ride quality and can, if desired, provide active control of ride quality, including tilting. The mechanical details of this complex arrangement have not yet been provided.

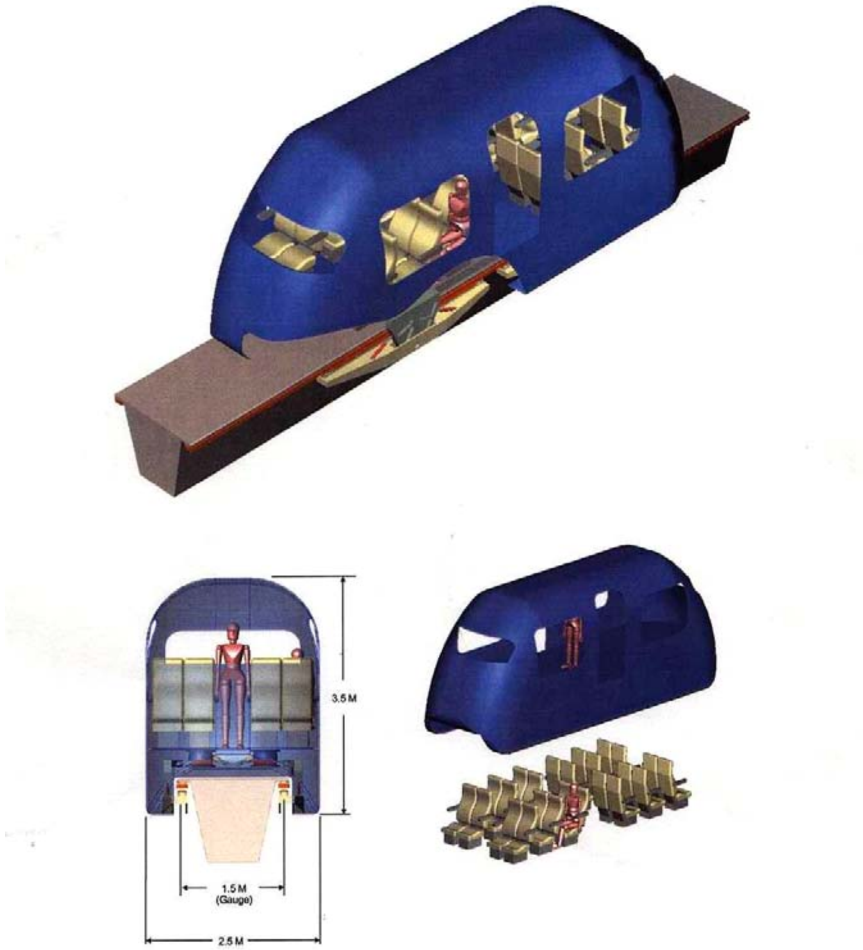


Figure 18. Cutaway Views of Preliminary Vehicle Design

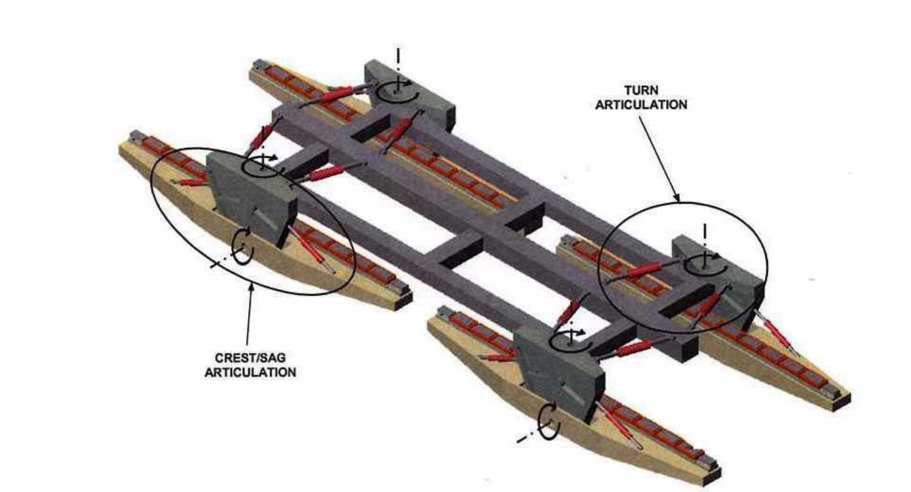


Figure 19. Magnet-pod Suspension System

Vehicle Weight

The empty vehicle weight is claimed to be less than twice the maximum passenger weight. This compares with steel-wheel suspended vehicles, which typically have an empty vehicle weight that is 3 to 4 times the maximum passenger weight.

Comment: This is a very ambitious goal since the total weight, including magnets, all other electrical components, complex suspension, body and interior (including services) would be on the order of only 18,000 lb ±, less than 8 metric tonnes, or the weight of four ordinary passenger cars (but with 36 passengers). This weight budget showing a realistic breakdown is needed.

System Characteristics

A summary of the MagneMotion system characteristics is presented in Table 4.

Table 5. Summary of System Characteristics (MagneMotion)

System Item	Characteristic or Measurement
I. Operational Characteristics	
Max. Operation Speed	160 km/h (100 mph)
Max. Initial Acceleration 4.0	2 m/sec^2
Max. Deceleration Service Brake	4.0 km/h/s (2.5 mph/s)
Max. Deceleration Emergency Brake	Not defined
Max. Gradient	10%
Min. Horizontal Curve Radius	18 m (60 ft)
Min. Vertical Curve Radius	1000 m
Max. Super Elevation Angle	15° includes vehicle tilting
One-Car Train Passenger Capacity - Seated	24
One-Car Train Passenger Capacity – Standing	12
One-Car Train Passenger Capacity – Total	36
Temperature	Not defined
Max. Wind Velocity (operational)	Not defined
II. Vehicle Configuration	
Vehicle Type	Composite body
Train Formation	Cars in platoons, no couplers
Car Body Length	8.2 m
Car Body Width	2.5 m
Car Body Height	3.6 m
Rail Gauge	1.5 m
Vehicle Weight Empty	5 tonnes
Vehicle Weight 75% Loaded (AW2)	7 tonnes
Car Body Structure - Material	Composites (not defined)
Car Body Structure - Construction	Not defined
III. Levitation and Guidance System	
Magnet	Permanent magnets and electromagnets
Levitation Gap	17 mm mechanical gap, 20 mm magnetic gap
IV. Propulsion System	
LSM (Linear Synchronous Motor)	Not provided
Power Supply	480V AC Rectifier from 600V DC Lin
Inverter Type	VVVF
V. Suspension System	
Suspension	4 magnet pods
Module Frame	Unknown

System Item	Characteristic or Measurement
Secondary Suspension	No
VI. Brake System	
Service Brake	Combination of LIM brake (regenerative or reverse phase) and hydraulic brake (Mechanical friction brake)
Emergency brake	Hydraulic brake
Parking Brake	Skids (levitation cut off)

Contractor Estimated Costs

Some estimates have been provided by MagneMotion. The level of detail is moderate in that individual major systems have been estimated, but a network was not used as a model. Capital costs provided by MagneMotion include:

Guideway Costs per 2-way Mile

Item	Cost
Concrete Guideway Structure mile	$8.8 million/mile
Inverters / mile	$2.1 million
LSM / mile	$2.5 million
Electrification	$2.0 million
System Control	$3.5 million
Total	**$19.2 million/mile**

Other System Costs per 2-way Mile

Item	Cost
Add $3.6M for Hybrid Beams	$22.8 million/mile total
Add $9.4M for All-Steel Beams	$28.6 million/mile total
Vehicles (24Pax):	$.25 million each
Stations	$100 thousand to $1 million each

Comment: For example, a guideway system cost in the $20-28 million range for a two-way (assumed) mile was provided, but this is apparently for a basic guideway only. No switches, yard, sidings, etc. —which would be cost adders—were identified. This is a light cross-section, and as-stated costs would need substantiation after rigorous analysis of structural adequacy. Also, station costs vary over a wide range.

Maglev 2000 Project

Maglev 2000 is a company incorporated in Titusville, Florida. Drs. James Powell and Gordon Danby, the early inventors of superconducting Maglev systems based on null flux levitation, are part of the technical team of Maglev 2000. The Maglev 2000 system was designed for high-speed operations (~ 300 mph), and has been adapted to operate between 30 to 120 mph for low speed urban transportation.

Principles of Levitation and Propulsion

The system uses vehicle-mounted superconducting magnets that interact with aluminum coils in the guideway to generate levitating and propulsive forces. The coils are completely encapsulated in polymer concrete panels that are attached to the guideway beam. A levitation of about 6 inches is anticipated between the guideway and the vehicle. Since the system works on the electro dynamic principle rather then the electro magnetic suspension principle, vehicle movement is required to generate levitation. Levitation speed is expected to be within the range of 15 to 30 mph. However, by using active levitation coils in the guideway instead of passive coils for normal running vehicles, levitation at zero speed can be accomplished.

Propulsion is provided by LSM coils on the guideway whose alternating fields interact with the vehicle's superconducting magnets. Guidance forces are also provided by the interaction of magnets with the guideway coils.

Guideway

The guideway is a deep, narrow, reinforced, hollow, rectangular, 72-ft-long beam, as shown in Figure 20. The guideway coils are attached to the sides of the guideway. These consist of propulsion coils, 8-shaped null flux levitation coils, and coils to provide guidance forces. The piers or supporting columns are 72 ft apart. No details are given on the required size of the columns and depth or size of the foundation.

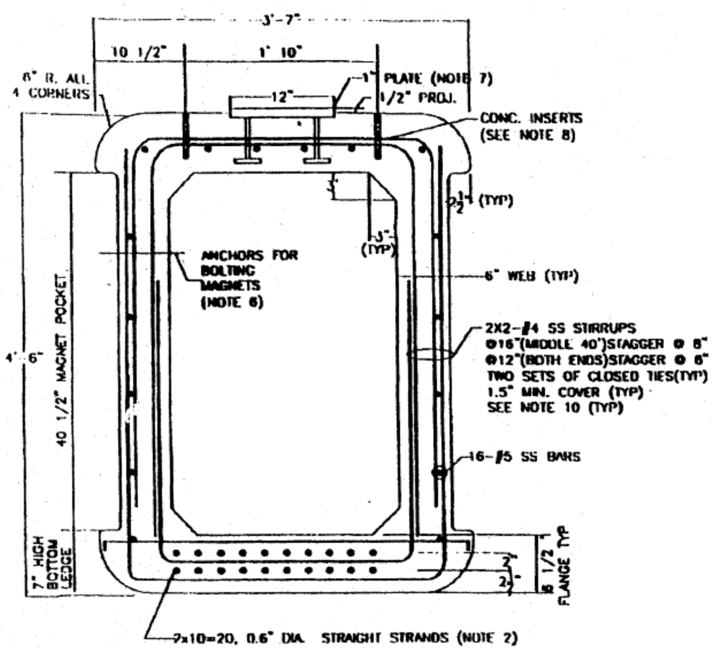


Figure 20. Schematic of Maglev 2000 Guideway

Vehicle

The vehicle is made of aluminum skin with stiffeners in both longitudinal and transverse directions. For suburban applications, a larger vehicle is proposed at a maximum operating speed of 150 mph. For urban operations, the vehicle runs at a maximum speed of 100 mph. The suburban maglev vehicle can carry 100 passengers, is 117 ft long, and weighs 80,000 lb. The urban vehicle carries 50 passengers, weighs 55,000 lb, and is 50 ft long. Both levitate at a speed of 30 mph on a non-powered guideway, and both are apparently designed for 0.2 g acceleration and deceleration rates. Figure 21 shows the long vehicle. The internal layout of the vehicle is shown in Figure 22.

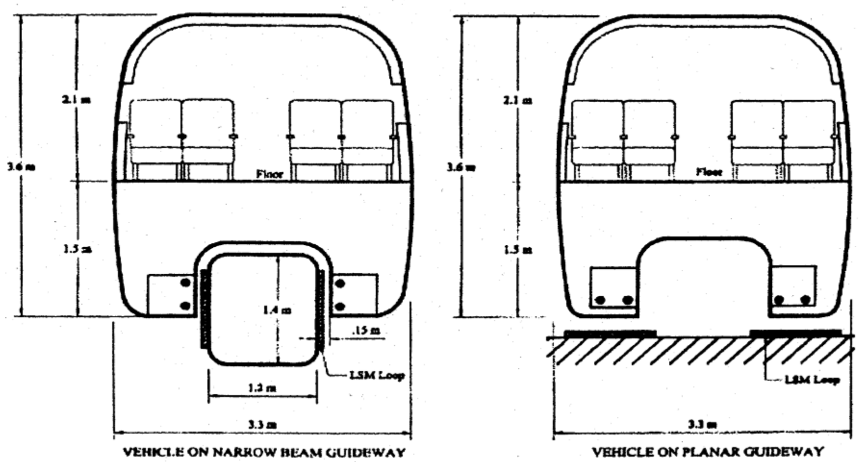


Figure 21. Maglev 2000 117 Foot Vehicle

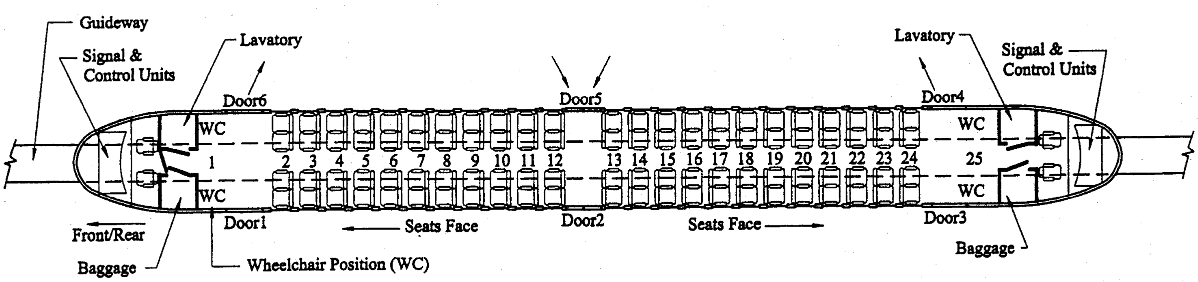
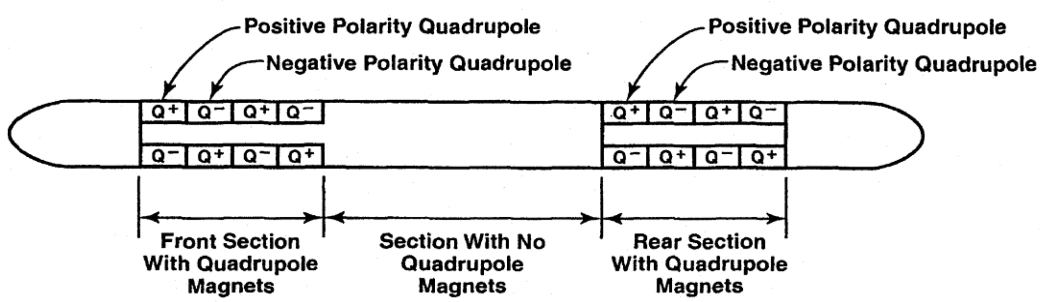


Figure 22. Maglev 2000 Vehicle Internal Layout

The vehicles carry superconducting quadrupoles on each side plus a central refrigeration system for a close operation of the liquid helium to keep the superconducting niobidium-titanium magnet wire at about 4° K. A schematic of the quadrupole arrangement is shown in Figure 23.



(Not to Scale)

Figure 23. Arrangement of Multiple Quadrupole Magnets on Maglev 2000 Vehicle

Although the repulsive system is supposed to be inherently stable, there can be roll and lateral oscillations due to the guideway irregularities or non-centered levitation coils on either side of the guideway. In such scenarios, active control may be required for stability, which is achieved by passing current through the 8-shaped levitation coils.

System Characteristics

A summary of Maglev 2000 system characteristics is presented in Table 6.

Table 6. Summary of System Characteristics (Maglev 2000)

System Item	Characteristic or Measurement
I. Operational Characteristics	
Max. Operation Speed	100 mph (short vehicle), 150 mph (long vehicle)
Max. Initial Acceleration 4.0	0.2 g
Max. Deceleration Service Brake	0.2 g
Max. Deceleration Emergency Brake	Unknown
Max. Gradient	Unknown
Min. Horizontal Curve Radius	300 m reduced speed
Min. Vertical Curve Radius	Unknown
Max. Super Elevation Angle	Unknown
Passenger Capacity for Single-Car Train	50 (short vehicle), 100 (long vehicle)
Temperature	-10°C to 40°C (50°F to 104°F)
Max. Wind Velocity (operational)	> 50 mph
II. Vehicle Configuration	
Vehicle Type	Ellipsoidal Aero shell with aluminum skin with stiffeners
Train Formation	Single cars
Car Body Length	50 ft short vehicle, 117 ft long vehicle
Car Body Width	3.35 m (11 ft) long vehicle
Car Height	3.96 m (13 ft) long vehicle
Rail Gauge	1.21 m (3.97 ft)
Empty Weight (long veh.)	27,300 kg (60 kips)
Fully Loaded Weight (AW2) (long veh.)	40,000 kg (88 kips)
Car Body Structure - Material	High Strength aluminum alloy
Car Body Structure - Construction	Skin/stringer
III. Levitation and Guidance System	
Magnet	Liquid helium cooled superconducting electrodynamic system with 8 shaped sidewall levitation
Levitation Gap	> 4 in
IV. Propulsion System	
LSM (Linear Synchronous Motor)	100 ft block length
Power Supply	5KV LVDC distribution line on guideway
V. Suspension System	
Suspension Module	5 flexible pair-modules per car (Module: levitation bogie trucks)
Module Frame	Aluminum alloy chassis
Secondary Suspension	Air suspension
VI. Brake System	
Service Brake	Combination of LSM brake (regenerative) and hydraulic brake
Emergency brake	Hydraulic brake
Parking Brake	Skids (levitation cut off)

Contractor Estimated Costs

Maglev 2000 provided estimated costs for fixed facilities, vehicles, and operating costs. A specific system and route network description was not provided, so all costs are for separate components; i.e., completed guideway per two-way mile, individual stations (without station spacing or a network description), two different styles of vehicles, etc. The operation and maintenance cost data reflects a high-speed (300 mph max) system, 240 miles in length with 6 stations, each having different choices for configurations. These choices arise out of Maglev 2000's statement that depending on capacity and demand, various combinations of off-line sidings, switches, etc. would need to be provided, making overall costing possible only with a defined system configuration. Further, no low-speed, urban-style maglev system configuration was identified, and this has a much different effect on costs due to frequent stations and slower speeds, but high demand and throughput.

Guideway

The following elements were quoted by Maglev 2000 for a two-way basic, narrow beam guideway:

Item	Cost/2-way mile
Guideway beams	$4.48 million
Loop panels (coil sets)	$3.25 million
Footings & piers	$1.11 million
Erection (structure)	$0.84 million
Power & distribution	$1.42 million
Safety systems	$0.16 million
Communication & Control	$0.11 million
Total	**$11.37 million**

Comment: This cost is much lower than that for systems such as TR or CHSST, which have been built and are in operation in test form. The Maglev 2000 figures appear too optimistic. Also, switches were not identified, but their cost was mentioned as a minor contributor. Lastly, the only form of guideway to be demonstrated is the planar guideway, but costs for this and the associated switching, transitions, etc., were not provided. Likewise, the need for sections of powered loop guideway for approaching and departing stations is not costed, but is likely to be substantially higher than the baseline narrow-beam guideway.

Vehicles

Two different vehicles were costed: a 20-metric ton (MT), 50-passenger vehicle and a 40-MT, 100-passenger vehicle. The guideway above is costed for the larger vehicle, but the guideway cost for the smaller vehicle is only $1 million less per mile. Which of these was intended for consideration was not specified. These apparently do not operate in consist. The construction is identified only as airplane-type, which is taken to mean aluminum sheet-stringer fuselage construction. The larger vehicle is 123 feet long, and the smaller vehicle is still on the order of 70 ft. With either, there is the issue of turn radius, especially with urban networks, that would seem to be inconsistent with that application. Again, the system for which this data was constructed seems to be a high-speed, long-distance network with gentle curves only. The following elements were costed:

Item	Cost/50 Passenger Vehicle	Cost/100 Passenger Vehicle
Vehicle body	$0.19 million	$1.14 million
Superconducting magnets	$1.14 million	$2.28 million
Cryo & refrigeration systems	$0.74 million	$1.13 million
Ride control systems	$0.22 million	$0.22 million
Safety systems	$0.83 million	$1.13 million
Communication & Control	$0.07 million	$0.07 million
Total	**$3.74 million**	**$5.97 million**

Comment: Costs are low, but seem comparable to estimates for other systems.

Fixed Facilities

Three different types of facilities were identified and costed: passenger or freight stations, maintenance, and traffic control. Again, since no specific low-speed, urban-style maglev system configuration system was identified, and the actual number of each facility type is not defined relative to guideway and vehicles. Additionally, the station size and costs are highly dependent on the combinations of off-line sidings, switches, etc., that would be needed, making overall costing possible only with a defined system configuration. The powered guideway sections (not costed) would need to be accounted for either in guideways or in stations.

The following facilities are costed as individual items:

Item	Cost/Facility
Passenger/Freight Station	
No off-line guideway	$14 million
Off line guideway; higher turnout speeds	$39 million
Station	$64 million
Maintenance Facility	$3.4 million
Traffic Control Facility	$1.88 million
Total	**$122.28 million**

Comment: The station costs are undetermined without a relationship to capacity, service plan, vehicle/consist speed profiles, station spacing, etc. They do, however, provide parking lots and an average size station building to handle 10,000 passengers per day (not the 12,000 per hour for an urban system). Overall, this needs to be re-estimated for an urban-style operation. The cost for a maintenance facility, which would include a yard-like setup, seems low considering the need for switching, hoisting on/off guideway, etc. The traffic control facility equipment cost would appear elsewhere, it is assumed.

Operation and Maintenance Costs

These are provided for a high-speed system only: 240 miles long (two-way), average speed of 240 mph, and 5,000,000 passenger trips annually. This latter is an order of magnitude less than the urban, low-speed system. Also, since only six stations are included, the operating characteristics of this network are widely different than the low-speed, dense, urban network under consideration in this study.

The same two (50 and 100 passenger) vehicles were costed, as expressed in operating cost per vehicle mile with 60 percent load factor. The following elements were costed:

Item	Cost/50 Passengers Vehicle Mile	Cost/100 Passengers Vehicle Mile
Operating personnel	$0.69 million	$1.23 million
Energy	$0.56 million	$0.73 million
Materials & Equipment	$ .20 million	$2.40 million
Total	**$2.45 million**	**$4.36 million**

Appendix C. Glossary of Terms

alignment – the route or path of a maglev guideway.

electrodynamic suspension (EDS) – A form of suspension that uses the repulsive force of magnets to suspend a vehicle above a track. Such systems are inherently stable and do not need active levitation control.

electromagnet – A magnet comprised of a coil of insulated wire wrapped around a soft iron core that is magnetized only when current flows through the wire

electromagnetic suspension (EMS) – A form of suspension that uses the attractive force of magnets to suspend a vehicle above a track. Such systems are inherently unstable and need active levitation control.

gap control – The effort to maintain a constant distance between the maglev vehicle and the magnets that are levitating it.

guideway - A riding surface (including support structure) that physically guides vehicles specially designed to travel on it.

Halbach array – An arrangement of permanent magnets which augments the magnetic field on one side of the device while cancelling the field to near zero on the other side. The Halbach array repels buried loops of wire after the vehicle has been accelerated to a low speed, creating suspension of the vehicle.

hybrid girders – Guideway girders that are made of a combination of reinforced concrete – which provides rigidity, noise absorption, and low cost – and structural steel.

headway - The interval between the passing of the front ends of successive vehicles moving in the same direction along the same lane, track, or other guideway.

induction motor – An type of motor in which an electric current flowing in the motor's secondary member (the rotor) is induced by the alternating current flowing in its primary member (the stator). The power supply is connected only to the stator. The combined electromagnetic effects of the two currents produce the force to create rotation.

linear induction motors (LIM) – A linear induction motor provides linear force and motion rather than rotational torque. See **induction motor**.

linear synchronous motors (LSM) – Motors driven by primary coils installed on the guideway, and energized in synchronization with the forward (linear) motion of the vehicle.

Litz wire - from the German word "litzendraht," meaning woven wire. Generally, it is a wire constructed of individual film-insulated wires that are bunched or braided together in a uniform pattern of twists and length of lay. This multi-strand configuration minimizes the power losses otherwise encountered in a solid conductor due to the tendency of radio frequency current to be concentrated at the surface of the conductor.

low speed magnetic levitation – A form of maglev that travels at slower top speeds; suitable for an urban transit function rather than a long distance transport function.

Maglev - magnetic levitation.

magnetic gap – The distance between the magnet and the metal structure that is levitated by means of magnetic attraction or repulsion. The smaller the gap, the lower the current or the smaller the volume of magnetic material (permanent magnet or steel) needed to reach a given magnetic field.

magnetic levitation - Support technology that keeps a vehicle separated from its guideway by riding a surface of magnetic force.

permanent magnets - A magnet that retains its magnetism after being removed from a magnetic field.

propulsion coils – Embedded in the guideways, these loops of superconducting wire allow an alternating current to flow through them, causing a continuously varying magnetic field. The coils have a figure eight shape, and the current flowing through them induces magnetic poles in both the top and bottom halves, ensuring that the magnets on the maglev vehicle are repelled by the bottom half and attracted by the top half, resulting in levitation.

Appendix D. SI* (Modern Metric) Conversion

FACTORS APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
		APPROXIMATE CONVERSIONS FROM SI UNITS		
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.