ABSTRACT: Shanghai Maglev Demonstration Line is the first commercial application of high speed maglev transportation system in the world. The past 5 years witnessed its safe and punctual operation. None of the accidents, though occurred, caused passenger or operation staff casualties or interruption of the operation. It has also passed through the test of typhoon, rainstorm, heavy snow and other atrocious weather. The present paper summarizes the status of operation, failures and maintenance work on the line, showing safety and usability of high speed maglev system. It also puts forward some improvements, and last but not least describes Shanghai-Hangzhou Maglev Project.

1 GENERAL INFORMATION ABOUT SHANGHAI MAGLEV DEMONSTRATION LINE

Shanghai Maglev Demonstration Line is the first and so far the sole high speed maglev line in commercial service in the world. It is 30km long, connecting Shanghai Pudong International airport and Longyang Road Subway Station. On December 31, 2002 the trial run on single track succeeded. On May 1, 2004 it was put into trial commercial operation. Since then, the train has been running on the line with the highest speed of 430 km/h. Operation punctuality rate reaches 99.5% and 99.8% of the operation schedule is fulfilled.

Since the successful trial run on a single track on December 31, 2002, the maglev train has run for more than 2000 days in accumulative total and covered a mileage of over 5 million kilometer. No operation accidents that endangered the passengers or attendants on the train had happened.

During the past more than five-year operation, the maglev system has undergone such atrocious weather as heavy snow, gale and rain storm, but its operation schedule has never been changed due to weather changes, which demonstrates the system’s availability of withstanding extreme weather.

2 OPERATION PRACTICE

2.1 Major events that occurred during operation

1) At the beginning of 2005, a tight-wire supporting the overhead cable across the maglev guideway hanged down and invaded into the vehicle dynamic clearance as the power maintenance workers violated the maintenance regulations while repairing the cable. The steel rope clashed the glass of the vehicle front window and slid through the vehicle top when the vehicle passed there at high speed, but only the antenna cover on the top was damaged. In spite of the accident, the maglev train still ran in accordance with the operation schedule.

2) In 2005 one guideway switch had a mechanical failure, resulting in one hour and 57 minutes delay of the normal operation. After occurrence of this failure[1] the design of the failed component was already improved.

3) In August, 2006, one section of the maglev train was found smoking in the station. After the passengers took off, the train ran away from the station and stopped in the designated point proper for putting out the fire. The section of the train was partly burned by the battery fire which was caused by the internal failure of one unit of battery cells and the operation schedule was disturbed by the accident, but
no personnel was injured. At present the burned vehicle is under repairing.

2.2 Operation in bad weather

1) At the end of 2004, Shanghai witnessed a heavy snow that reached 40 mm in thickness in Pudong area particularly in the place close to Pudong International Airport. In result, the highway connecting the city to other places was completely closed. But the maglev train still ran normally and was not affected (Figure 1).

![Figure 1. The maglev train’s running is not affected by the snow on the guideway.](image)

2) In August, 2005, the typhoon “MATSA” made a direct attack on Shanghai and its speed on the ocean surface near Pudong International Airport reached 31.7 m/s. Both the airports and highway had to be closed. However, Shanghai Maglev Demonstration Line was still carrying the passengers normally.

3) In August, 2008, Shanghai was attacked by a torrential rain that reached 147mm of precipitation per hour and the highway traffic was completely blocked. However, the maglev train still ran punctually according to the operation schedule.

2.3 Statistic of system failures and system availability

Table 1 shows the statistic of subsystem failures that caused more than 2 min operation delay in the past five years. Table 2 lists the statistic of the rate of operation punctuality and schedule fulfillment.

Table 1 Statistic of subsystem failures that caused more than 2 min operation delay.

<table>
<thead>
<tr>
<th>Sub-systems</th>
<th>Vehicle Propulsion</th>
<th>OCS</th>
<th>Guide-way</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of failures</td>
<td>27 13 11 5 17</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Rate of operation punctuality and schedule fulfillment in the past years

<table>
<thead>
<tr>
<th>Year</th>
<th>Rate of operation punctuality</th>
<th>Rate of schedule fulfillment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>98.48</td>
<td>99.43</td>
</tr>
<tr>
<td>2005</td>
<td>99.94</td>
<td>99.95</td>
</tr>
<tr>
<td>2006</td>
<td>99.74</td>
<td>99.86</td>
</tr>
<tr>
<td>2007</td>
<td>99.97</td>
<td>99.98</td>
</tr>
</tbody>
</table>

Note: Punctuality is defined that the operation delay does not exceed 2 min.

2.4 Maintenance work

Shanghai Maglev Demonstration Line is configured with 3 trains each consisting of 5 sections, 2 propulsion substations, one operation control center and one maintenance base. Generally speaking, the maintenance workload of maglev transportation system is not big and the majority of it is scheduled inspection, the reason of which is that the large numbers of the electric components are structurally modularized for easy on site replacement. According to the statistic, scheduled maintenance work time makes up 76% of the total maintenance work time.

3 TECHNICAL IMPROVEMENT

3.1 Noise inside vehicle

The present noise inside the carriage of the maglev train running on Shanghai Maglev Demonstration Line is on the high side in regard to long distance passenger transportation. On the basis of the tests and analysis of the characteristics of the sound source and sound spreading inside the vehicle, the modification solutions are made and planned to be used on the newly designed reference train.

3.2 Vehicle air conditioning system

As the vehicle’s air conditioning system on Shanghai Maglev Demonstration Line was designed according to the climate condition in Germany, The vehicle’s air conditioning system can not adapt well to the summer climate in Shanghai featuring in high temperature and high humidity. In the season of midsummer, it can not attain the expected temperature. In addition, it is discovered that the compressor’s ventilation volume drops markedly, resulting from the wind effect when the train runs at high speed. We have studied solutions to improve the refrigeration capacity of the air conditioning system and increase its fresh air volume and planned to use them in the new reference train.
3.3 Battery

The original vehicle battery used on Shanghai Maglev Demonstration Line had the potential risk of such failures as locally over heating, short circuit, and burning, which are hard to be discovered by the monitoring and diagnostic system beforehand. After the vehicle burning accident caused by the battery failure, the technicians from both the German and Chinese side have made careful analysis about the cause and brought forward such measures as reinforcing insulation, improving temperature monitoring, adding voltage monitoring and improving charging management. These measures have been used in the trains running on Shanghai Maglev Demonstration and the new reference train under developing.

4 PLANNING FOR NEW MAGLEV PROJECT

To further verify the usability and economic efficiency of high speed maglev transportation in medium and long distance line with multi-stations and multi-sections, in March 2006, the Chinese government approved the project proposal for Shanghai-Hangzhou Maglev Project proposal; at present the engineering feasibility study for the project is being carried out. The line of Shanghai-Hangzhou Maglev Project will be 191km long in total (Figure 2) including the following new built stations: Shanghai South Station, Hongqiao Station, Jiaxing Station and Hangzhou East Station. It also includes the 31 km new-built airport link in Shanghai. Its highest speed for commercial operation will be 450km/h and the highest demonstration speed 500km/h.

At present the main obstacle in the project feasibility study rests with the economic efficiency of the project in particular the high unit price of the system equipment. The possible reasons for the high price are that the equipments are produced in small quantities and can not create scale effects. It is also possible that the suppliers are impatient to get the returns of the development cost from the limited order of the initial project. All parties participating in the project need to show great foresight to jointly solve this problem. I believe that the fundamental way for continuous application of high speed maglev transportation is to make breakthrough in its economic effects.

5 CONCLUSIONS

The over five-year operation practice of Shanghai Maglev Demonstration Line verifies that conventional conductive high speed maglev technology is generally safe and usable.

In comparison with car and airplane that are powered by oil, high speed maglev transportation system has noticeable advantages in energy saving and environment protection and therefore is more suited to the conditions of China with large population, vast territory and not rich in oil resources.

The decision of cancelling Munich Maglev Project the German government made has not shaken the confidence of the Chinese government in developing application of maglev technology. Preparations for Shanghai-Hangzhou Maglev Project are being carried forward as planning approval procedure.

Figure 2. Layout of Shanghai-Hangzhou Maglev Line
Outlook of the Superconducting Maglev

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ABSTRACT: The Superconducting Maglev has been developed as an ultra-high speed mass transport system. It makes use of modern superconducting magnets (SCMs), which enable a large gap Electro-Dynamic Suspension and an efficient linear motor propulsion. Running tests have been conducted smoothly on the 18.4 km long Yamanashi Maglev Test Line since 1997 and reaped the harvests such as the maximum speed of 581 km/h, relative speed of 1,026 km/h on two trains passing test and on-board high temperature SCM running tests. In March 2005 the Committee under the Ministry of Land, Infrastructure and Transport appreciated that “all the technologies of the Superconducting Maglev necessary for the future revenue service were established.” Based on this situation, JR Central has decided to expand the existing Test Line as well as renew the existing facilities and equipment into those of the future revenue service level. Furthermore, the Company has decided to promote the Tokaido Shinkansen Bypass project utilizing the Superconducting Maglev system.

1 SUPERCONDUCTING MAGLEV SYSTEM AND ITS CHARACTERISTICS

The Superconducting Maglev has been developed as an innovative transportation system for the next generation. It uses an Electro-Dynamic Suspension (EDS) system, and each truck of trains is equipped with superconducting magnets (SCMs) on both sides. Moving magnetic fields of the SCMs induce current in “8” figured levitation ground coils attached on the side walls of the U-shaped guide-way. The current produces the levitation force, interacting with the magnetic field of the SCMs. Corresponding levitation ground coils on both side walls are connected each other and produce the guiding force as SCMs pass by. EDS enables a large gap and stable running with no control. This system tends to have rather a low levitation/drag ratio, but the Superconducting Maglev has greatly improved the ratio, adopting a null-flux levitation and null-flux guidance system.

The Superconducting Maglev is driven by Linear Synchronous Motor (LSM). SCMs act as the field of the motor. The driving power is supplied to the propulsion ground coils, which are laid along the full length of the guide-way and divided into sections of a certain length. Only the section on which the train is running is fed from a substation. As the vehicle need not have driving equipment except SCMs, it is very light in weight and compact in spite of its high power.

2 HISTORY

Basic researches on ultra-high speed mass transport systems began in 1962. Among many candidates, Japanese National Railways (JNR) has chosen the Superconducting Maglev because of its high speed ability and great possibility. After fundamental tests, the 7 km long test track was constructed in Miyazaki, south west of Japan. The first test vehicle on the Miyazaki Test Track recorded 517 km/h in 1979. Then the test track was remodeled from the inverted-T shape cross section to the more practical U-shape, and the manned vehicle began to run in 1981. Basic tests with four types of test vehicle were conducted over the twenty-year period from its opening in 1977...
to its closure in 1996. In this period, the development duties of the Superconducting Maglev were succeeded to Railway Technical Research Institute (RTRI) from JNR. These tests contributed to the progress of the Superconducting Maglev technologies. However, due to facility limitations at Miyazaki, such as a lack of tunnels, gradients and curves, it became necessary to construct a new full-scale test line to conduct tests under actual service line conditions.

The new Maglev test line was constructed with subsidies from the government, in Yamanashi, about 100km west of Tokyo. Thereafter, RTRI and JR Central commenced test operations at the new test line.

Figure 1. The first test vehicle on the Miyazaki Test Track “ML-500” recorded 517 km/h in 1979.

3 YAMANASHI MAGLEV TEST LINE (YMTL)

The test line, which is double-tracked partially, is 18.4km long and has curved sections with a radius of 8,000m and a maximum gradient of 40‰. Approximately 87% is tunnels, and the longest open section is about 1.5 km in length. The Test Center and the power conversion substation are located here.

The vehicles (MLX) are of an articulated truck type having a truck at each end. This type was introduced in order to reduce the strength of the magnetic field in the cabins. This configuration also contributes to a decrease in the crosssectional area of the vehicle, which results in low aero drag force and reduction of the crosssectional area of tunnels. The vehicles are equipped with aerodynamic brakes and wheel disk brakes for emergency. Usually, trains are decelerated by electric regenerative brake. The SCM mounted on

the vehicle contains four vertical superconducting coils and a helium tank with a built-in refrigerator.

Figure 2. Configuration of the YMTL

Figure 3. The test vehicle MLX01

4 RUNNING TESTS

4.1 Outline of the Test Schedule

The running tests on the YMTL started in April 1997. In the first three years, the basic running tests and the general functional tests were carried out in order to verify the technical practicality as an ultra-high speed mass transport system. In the next five years, main themes of the running tests were the evaluation of durability and reliability, and the improvement of cost performance and aerodynamic characteristics. With these test results for eight years in total, the Superconducting Maglev technology was evaluated overall. Further improvements in core technologies and further evaluation of durability have been carried out since fiscal 2005.

4.2 Test Results

First, the basic running tests, such as wheel running tests, levitated running tests, speed increasing tests,
and maximum speed verification tests, were carried out step by step, confirming the running stability. These tests proceeded smoothly. The maximum speed exceeded 500km/h in November 1997, and reached 550km/h as the designed maximum speed in the next month.

Next, the general functional tests, such as substation cross-over tests, high-speed passing tests and multiple-train control tests, were carried out. Through these running tests at the speed of 500km/h, the stability performance of vehicles motion, braking and speed control of the Superconducting Maglev were verified. The high-speed passing tests were carried out at the relative speed of up to 1,003km/h.

![Figure 4. In the high-speed passing tests, relative speed of 1,003 km/h was recorded in 1999.](image)

In the next five years, high speed running tests were continued to evaluate durability and reliability. Average travel distance per year was about 70,000km. The travel distance of 2,876km in one day was attained with 89 round trips on the YMTL. However, some equipment – ground coils, trucks – had difficulty in verifying longer durability during the running tests for eight years. The durability of such equipment was confirmed by the bench tests.

Through the running tests it was confirmed that the technological developments for the further cost reduction fulfilled the designed performance and the estimated amount of cost reduction.

Two new vehicles were developed for the YMTL. One was a leading car, and the other was an intermediate car. For the further improvement of aerodynamic characteristics, the length of the leading car nose was stretched. And new vehicles had the rectangular cross section in the lower part, in order to reduce aerodynamic phenomena.

Among these tests, the maximum speed attained 581.7 km/h, exceeding the maximum designed speed on the YMTL and the potential maximum speed in the revenue service. The top speed was recorded twice on the same day, and many researchers confirmed its ride quality. It was verified that this system had enough capability in high speed operation. Besides, further high-speed passing tests of 1026.3km/h were carried out, exceeding the potential passing speed for the revenue service. The stability of vehicle and ground equipment was confirmed.

In addition, several tests under severe and abnormal conditions were conducted, such as rescue operation tests and lightning tests. It was confirmed that there were no serious problems for the Superconducting Maglev.

![Figure 5. The running curve of the 581 km/h run of the Superconducting Maglev and the comparison with those of other high speed trains](image)

5 OVERALL EVALUATION

In March 2005, the Maglev Technological Practicality Evaluation Committee under the
Japanese Ministry of Land, Infrastructure and Transport appreciated that “all the technologies of the Superconducting Maglev necessary for the future revenue service were established as a result of great progress in running tests and technological developments by the end of fiscal 2004.” This appreciation means that the Superconducting Maglev Technologies are ready for their application to the potential revenue service.

6 CURRENT STATUS OF DEVELOPMENT

For the further evaluation of durability and the further improvements in core technologies of the Superconducting Maglev, running tests have been carried out on the YMTL. The cumulative travel distance exceeded 670,000km.

The High-Temperature Superconducting (HTS) magnet is a typical example of the improvement of core technologies. The HTS magnet using bismuth-based high-temperature superconducting wire enables stable superconductivity at -253°C, which is higher by 16°C than the conventional Low-Temperature Superconducting (LTS) magnets. The running tests of the Superconducting Maglev vehicle fitted with the HTS magnet began in November 2006. The train exceeded 500 km/h on the first day of the HTS running tests. Through the running tests, it was verified that HTS magnets had applicability to the Superconducting Maglev system.

7 EXTENSION OF THE YMTL

The Superconducting Maglev technologies as well as their peripheral technologies have been progressing dramatically through the running tests for more than eleven years. Based on this current situation, JR Central has decided to expand the existing Test Line as well as renew specifications of the existing facilities and equipment into those of the future revenue service level. Through the expansion and renewal of the Test Line, the appropriateness of the upgraded specifications will be verified, responding to technical themes such as running tests for longer distance or through longer tunnels at the potential maximum cruising speed with longer train, and the maintenance system of the revenue service level will be established.

7.1 Main Features of Facility and Outline of New Experiments

- Expanding the existing 18.4km Test Line to 42.8km
- Upgrading the specifications of the ground coils and electrical facilities into those appropriate for longer trainsets
- Introducing fourteen new test vehicles and conducting running tests of longer trainsets at 500km/h

![Figure 7. The outline of the extended YMTL](image-url)
• Setting up more efficient maintenance system for the vehicles and ground facilities
• Building a full scale test facility which simulates a deep underground structures and conducting technical studies in such an environment

7.2 Project Costs
• Costs of ground facilities such as tunnels, elevated tracks, electric facilities and train depots : JPY 319 billion
• Cost for introduction of new test vehicles : JPY 36 billion

7.3 Project Schedule
• Project period for plan of renewal of facilities and equipment, extension of the Test Line and Running Test using renewed facilities : From FY 2006 to FY 2016
• Running test will start after the completion of Test Line extension in the end of FY 2013. The renewal of facilities and equipments continues until FY 2016.

8 PROMOTION OF THE TOKAIDO SHINKANSEN BYPASS

With respect to the Tokaido Shinkansen Bypass utilizing the Superconducting Maglev system, JR Central has deliberated on “promoting and realizing, on its own initiatives and as the first phase, the inauguration of commercial operation between the Tokyo Metropolitan and the Chukyo regions in 2025, the end of the first quarter of the twenty-first century.” After making deliberations, the Board of Directors has concluded that the construction of the necessary line (the “Bypass”) in this first phase as the “Chuo Shinkansen” under the Nationwide Shinkansen Railway Development Law on the premise that the Company would bear the cost for the project will contribute to a sustainable and stable management of the Company with payment of stable dividends. As a result, the Company has decided to take actions to promote the project on the basis of the above initiative on the premise that the Company would bear the cost for the project.

It is estimated that JR Central will spend approximately JPY 5.1 trillion as construction costs and rolling stock expenses for approximately 290km line of the Super-conducting Maglev system, which are exclusive of the expenditure for intermediate stations and related costs that should be borne by local municipalities. After the inauguration of the Bypass, the Company will make investments for maintenance and renovation of facilities.

9 ACKNOWLEDGMENT

This work is financially supported in part by the Ministry of Land, Infrastructure, Transport and Tourism of the government of Japan.

10 REFERENCES

S. Fujiwara, T. Fujimoto, “Characteristics of the combined levitation and guidance system using ground coils on the side wall of the guideway” Maglev ’89, pp. 241-244, July 1989
ABSTRACT: A 25,000 mile National Maglev Network interconnecting all major U.S. cities is described, using the 2nd generation superconducting Maglev-2000 system. Between cities, high speed Maglev vehicles travel on low cost, prefabricated elevated monorail guideways alongside Interstate Highways. In urban/suburban areas, levitated Maglev vehicles travel on existing RR tracks, interacting with thin aluminum loop panels on the cross-ties (scheduled trains can still use the tracks). Appropriate Maglev vehicles transport passengers, personal autos, highway trucks, and freight containers on the same guideway. Carrying 3000 trucks daily on a Maglev route (1/5th of trucks on a typical Interstate) generates revenues equal to 180,000 passengers per day. The Maglev route can be paid back within 5 years, enabling private financing. Transcontinental service starts in 2019, with the full Network completed by 2030. Construction cost is 625 Billion dollars over 18 years compared to today’s 700 Billion dollars per year for oil imports.

1. INTRODUCTION

America’s three main transport systems – motor vehicles (autos, buses & trucks), airplanes, and conventional rail – operate as national networks. From any given area in the U.S., passengers and freight can drive, fly, or go by bus or train to any other area in the U.S. To reach a particular location, it may be necessary to transition from one system to another; e.g., one can fly from one airport to another airport, with a short drive to one’s final destination. However, such minor transitions are usually easily accommodated.

For Maglev to be an important mode of transport in the 21st century, it must function as a National Network. A few isolated Maglev routes in the U.S., while helpful to local travelers, will provide only small benefits. They will not substantially reduce U.S. oil consumption and greenhouse gas emissions, and not significantly increase domestic jobs and exports.

The potential 25,000 mile National Maglev Network (Figure 1) would interconnect virtually all major metropolitan areas in the U.S. The Maglev routes, following the vision of the late Senator Daniel Patrick Moynihan, would primarily be on the rights of way of the Interstate Highway System. Had his 750 million dollar 1990 Senate passed legislation for a U.S. Maglev R&D program not been killed in the House of Representatives, America would be well on its way to the National Maglev Network.

One of the unique features of the 2nd generation Maglev-2000 system, described later, is the ability of Maglev-2000 vehicles for levitated travel along existing RR tracks, to which thin panels holding aluminum loops have been attached to the cross ties.

Figure 1. 25,000 mile National Maglev-2000 Network
(Conventional trains can continue to use the RR tracks, given appropriate scheduling). This capability to use existing RR tracks enables Maglev-2000 vehicles to travel in densely populated urban and suburban areas, without needing to construct very expensive new infrastructure, with its inevitable disruptions to the existing infrastructure and the local population. Combined with high speed elevated Maglev guideways between metropolitan areas, this would result in fast convenient travel by Maglev, both within a given metropolitan area, and from one metropolitan area to another.

While the National Maglev Network has many benefits and attractive features compared to present transport systems, its ability to effectively and cheaply transport passengers and freight without the need for oil will become extremely important in the following decades as World oil runs out.

2. WHY A NATIONAL MAGLEV NETWORK IS NEEDED

World oil production has plateaued and will start to decline within the next few years (Figure 2). At the same time, World oil demand is rapidly increasing, as China, India, and other countries rapidly industrialize and adopt American life styles, driving up oil prices. America’s present per capita oil consumption is 25 Barrels per person per year, while the rest of the World averages only 3.7 Barrels per person per year. As the developing World industrializes, not only will Americans pay much more for oil, but their per capita share will drop precipitously.

Our present transport systems – autos, trucks, busses, airplanes, and most trains – cannot operate without oil. Without it, U.S. living standards, the economy, national security and defense capability would be seriously affected. The U.S. currently spends 700 Billion dollars annually on oil imports, almost 90% of the 800 Billion dollar annual trade deficit. Oil import expenditures will dramatically increase, reaching 1000 Billion dollars or more annually. Over the next 20 years this will be at least 20,000 Billion dollars – a major drag on the U.S. economy – at a cost far greater than a National Maglev Network.

Various alternative fuels have been proposed as substitutes for oil, but they have major problems that prevent large-scale implementation. Biofuels can only supply a tiny fraction of transport fuels needs, and dramatically drive up food prices and food availability. 20% of the U.S. corn crop now makes 6 Billion gallons of ethanol. When its lower combustion value (2/3 of gasoline) and the energy used to fertilize, grow, harvest, transport, and process the corn to ethanol is deducted, present production then equals 1.5 Billion gallons of gasoline, less than 1% of the 180 Billion gallons of gasoline and diesel fuel the U.S. consumes annually. Manufacturing hydrogen fuel takes an enormous amount of energy. Making hydrogen equivalent in energy to annual U.S. transport fuel usage by electrolysis would require doubling U.S. electrical production from 4 trillion KWH per year to 8 trillion KWH. Hydrogen also has serious safety and security problems as a fuel for vehicles. Synfuels from coal and oil shale are possible, but generate large emissions of carbon dioxide from the production process, greatly accelerating global warming. On average, each of America’s 200 million cars emits 10 tons of carbon dioxide annually using oil. When synfuels plant emissions are included, this increases to 20 tons per year.

The best solution for large scale U.S. transport in the coming decades is electric transport. It does not depend on ever scarcer and more expensive oil, is environmentally benign, non-polluting, energy efficient, comfortable and quiet. Electric transport will have two components – electric autos for local trips of 50 miles or so, and a high speed National Maglev Network for longer trips.

3. DESIRED CAPABILITIES FOR A NATIONAL MAGLEV NETWORK

The desired capabilities for a U.S. National Maglev Network include:
1. low guideway cost,
2. able to transport passengers, personal autos, highway trucks and freight containers on dual-use guideways with high energy efficiency in all weather conditions,
3. able to be privately financed without need for government funding and subsidization for construction and operation,
4. rapid installation of guideways with minimal disruptions and modifications to existing infrastructure,
5. high speed electronic switching to off-line stations, with service to multiple convenient stations in metropolitan areas,
6. Earth ambient magnetic field levels in passenger cabins.

Construction costs for the Japanese and German 1st generation Maglev systems are high, e.g., 50 million dollars or more per 2-way mile\(^{(6)}\). To be widely implemented in the U.S., construction cost should be less (Capability #1), comparable to or less than High Speed Rail (HSR) systems, which have been on the order of 20 to 30 million dollars per 2-way mile\(^{(7)}\).

![Annual Outlays, Current and Future, for US Transport Modes](image.png)

Figure 3. Annual Outlays, Current and Future for U.S. Transport Modes

The National Maglev Network should not just carry passengers, but also intercity highway trucks, personal autos, and freight containers (Capability #2). U.S. transport outlays for intercity highway trucks - over 300 Billion dollars – are much greater than for passenger air – 60 Billion dollars annually – and dwarf passenger rail – only 3 Billion dollars per year. (Figure 3)\(^{(8)}\).

Highway trucks are preferred for high value freight transport over conventional rail because of their much faster delivery and their convenient service, direct from origin to destination. Shipping by rail involves much longer delivery times and less convenience of service. The average haul distance for highway trucks is ~ 500 miles. Truckers would be very attracted to Maglev, since they would need far fewer trucks to deliver the same volume of goods if they went by Maglev at 300 mph instead of by highway at 60 mph, and at less cost per ton mile delivered.

Similarly, drivers could take their personal autos with them on Maglev vehicles configured to carry 15 to 20 autos and their passengers. Travel would be cheaper and much faster than by highway, counting fuel, lodging and auto maintenance costs.

Private financing is essential for a National Maglev Network (Capability #3) because of the very high government debt levels and the reluctance to raise taxes. Passenger only Maglev systems will not attract private financing. Even if they did not require government operating subsidies – which is unlikely – time to payback construction cost would be too long to attract private investment. Transporting just 3000 trucks daily on a Maglev route (1/5th of the truck traffic on a typical Interstate) generates as much gross revenue as 180,000 passengers daily, based on 25 cents/ton mile (30 cents is the average U.S. outlay for high truck transport, including all costs),\(^{(9)}\) for Maglev truck transport, 30 tons per truck, and 10 cents per passenger mile. With truck revenues alone, the construction cost of a Maglev-2000 route could be paid back in less than 5 years. Additional revenues would come from the transport of passengers, personal autos, and freight containers.

The capability to rapidly install guideways with minimal disruption and modification of existing infrastructure (Capability #4) minimizes both the cost and any local opposition to the construction of a Maglev route. This is especially important in densely populated urban and suburban areas. Whenever possible, existing infrastructure should be used in ways that will not cause disruptions to local inhabitants.

High speed electronic switching (Capability #5) is very desirable. Not being able to switch off the main line, or having to mechanically move long cumbersome sections of guideway significantly slows...
down the average speed of a ground transport system. For example, HSR systems, though capable of maximum speeds of ~200 mph, have considerably slower average speeds when stations stops and the slow acceleration and deceleration rates are taken into account. The HSR Seville to Madrid train only averages 95 mph.\(^{(10)}\) Electronic switching to off-line stations will enable Maglev vehicles to by-pass at high speed stations they are not scheduled to stop at, maintaining high average speeds. This will allow multiple more closely spaced stations within a metropolitan area, for convenient access.

Earth ambient magnetic field levels in passenger compartments (Capability #6) are not only desirable, but a necessity. The American public is very environmentally conscious, and strongly resists new technologies that appear to deviate from the normal environment they live in. There is very strong opposition to nuclear reactors and radioactivity introduced into the environment. There is similar strong opposition to pesticides, mercury and other toxic materials released from coal-fired power plants.

There is no evidence that DC magnetic fields of a few gauss have any effect on the body (there is a limit of 5 gauss for people with pacemakers) and people experience much greater fields at the kilogauss level during MRI’s, without problems. However, to avoid any possible controversy and opposition to large scale implementation of Maglev, it is very desirable to keep the magnetic field inside passenger cabins at Earth level.

4. THE MAGLEV-2000 SYSTEM AND THE NATIONAL MAGLEV NETWORK

In 1966, Powell and Danby published and patented a description of superconducting Maglev,\(^{(11)}\) a new mode of high speed ground transport, which became the basis for the Japanese 1\(^{st}\) generation superconducting Maglev system now operating in Yamanashi, Japan. Superconducting Maglev has been proven practical, and holds the World ground guided transport speed record of 361 mph.

Powell and Danby, building on their earlier work, have more recently developed the 2\(^{nd}\) generation superconducting Maglev-2000 system, which enables lower construction cost through mass production of simple prefabricated components and much greater revenues by transporting highway trucks and freight containers as well as passengers on dual-use guideways.

Figure 4 shows a cross section of the Maglev-2000 superconducting quadrupole, the unique heart of the Maglev-2000 system. The M-2000 quadrupole magnet module has 2 superconducting loops of width \(W\), separated by the distance \(W\). The 2 loops carry oppositely directed superconducting currents, resulting in 4 magnetic poles, alternating as one proceeds around the circumference of the quadrupole. The 2 loops can be separate electrical circuits, or be connected together to form a single circuit. Fabrication and testing of full scale Maglev-2000 superconducting quadrupoles is described in an accompanying paper.\(^{(12)}\)

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The 4 pole feature enables the superconducting quadrupole to magnetically interact with aluminum

\[
(B_d)_o = \left(\frac{N_i}{2\pi R}\right)I_o W \left[D^2 + \left(\frac{W}{2}\right)^2\right] \text{ Tesla (1)}
\]

guideway loop panels positioned vertically on the sides of a monorail guideway beam, using the

Figure 5. Maglev-2000 Vehicle on monorail and Planar Guideways using Quadrupole Magnets.
magnetic pole from the vertical face of the quadrupoles, or with aluminum guideway loop panels positioned on a planar guideway beneath the Maglev vehicle, using the magnetic pole from the bottom surface of the quadrupole (Figure 5).

Maglev-2000 vehicles can smoothly transition between the 2 types of guideway, from monorail to planar, and back to monorail. For high speed operation on elevated guideways, for most of the route (90% or more), the vehicles will operate on the monorail guideway (Figure 6). It is lower in cost, visually more attractive, and easier to erect.

Figure 6. Artist’s drawing of Maglev-2000 Passenger Vehicle on Monorail Guideway

Off-Line Loading for Maglev Freight/Passenger Service

- Station Spacing Will Be Relatively Close
- Maximize Passenger/Freight Revenues
- Political Reasons
- On-Line Stations Seriously Degrade Average Speed
- Maximize Guideway Traffic Capacity

At locations where switching to off-line stations is desired, vehicles would transition to a planar guideway holding 2 lines of planar guideway loops. Initially closely overlapping, the 2 lines would gradually diverge laterally at a rate corresponding to the lateral acceleration level acceptable to passengers, e.g. 0.1 g. The straight ahead line of loops is the main high speed guideway, while the laterally diverging line of guideway loops leads to the off-line station. Each loop has an electronically controlled switch that either establishes whether the aluminum wire loop is in an open or closed circuit condition. If the straight ahead line of loops is in a closed circuit condition and the diverging line of loops in open circuited, the Maglev-2000 vehicles will by-pass the off-line station at high speed. If the straight line is open circuited and the diverging line of loops is close circuited, the Maglev-2000 vehicles will go into a secondary guideway segment, decelerating to a stop at the off-line station. After unloading/loading is complete, the Maglev-2000 will accelerate on the segment that leads out of the station and switch back onto the main guideway (Figure 7). At 300 mph the length of the planar switch section is 460 meters, sufficient to separate the centerlines of the 2 lines of loop by 6 meters at 0.1g lateral acceleration.

Figure 8 shows passenger and truck carrying Maglev vehicles on the same monorail guideway segments to access off-line stations for unloading/loading operations.

Figure 8. Maglev-2000 Passenger and Truck Carrier Vehicles on Dual-Use Guideways

Figure 9 shows the payback time for a Maglev route as a function of the number of trucks transported daily, for the operating parameters summarized in Table 1, assuming zero passenger
revenues (curve A). At 3000 trucks daily (20% of typical highway truck traffic on an Interstate) the payback time is less than 5 years. At 6000 trucks daily (40% of truck traffic) payback time is less than 2.5 years. Without trucks, payback time is many decades for realistic passenger ridership levels of 10,000 to 20,000 passengers daily. (curve B).

Superconducting quadrupoles have considerably lower fringe fields than dipoles, enabling Earth level fields in the passenger compartment, which allows the magnets to be located along the vehicle body, instead of just at the ends. This results in greater load carrying capability.

The fringe field on the centerline of a dipole of width $W$ (meters) at distance $D$ (meters) from a dipole carrying a current $I_o$ (amps), Assuming dipole length greater than its width,

$$ (B_D)_D = \left(\frac{\mu_0}{2\pi}\right) I_o W \left[D^2 + \left(\frac{W}{2}\right)^2\right]^{-1} \text{ Tesla} \quad (1) $$

5 M $ vehicle cost, 10 year Amortization, 5%/year maintenance; 100 passenger or 30 ton capacity; 80% load factor; 12 hours op/day; 250 mph average speed; 3 MW propulsion power for passenger vehicles, 4 MW for trucks; 6 cents/KWH

<table>
<thead>
<tr>
<th>Revenues &amp; Costs</th>
<th>Passengers (cents/pm)</th>
<th>Trucks (cents/ton mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Rev</td>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>Energy Cost</td>
<td>1.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Am&amp; M Cost</td>
<td>0.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Personnel Cost</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Net Rev.</td>
<td>7.4</td>
<td>17.7</td>
</tr>
</tbody>
</table>

while for a quadrupole, it is

$$ (B_D)_Q = \left(\frac{\mu_0}{2\pi}\right) I_o W \left[D^2 + \left(\frac{W}{2}\right)^2\right]^{-1} - \left[(D + W)^2 + \left(\frac{W}{2}\right)^2\right]^{-1} \text{ Tesla} \quad (2) $$

The rate of dipole fringe field to quadrupole fringe field is then

$$ R = \frac{(B_D)_Q}{(B_D)_D} = \frac{\left[D^2 + \left(\frac{W}{2}\right)^2\right]^{-1}}{\left[D^2 + \left(\frac{W}{2}\right)^2\right]^{-1} - \left[(D + W)^2 + \left(\frac{W}{2}\right)^2\right]^{-1}} \quad (3) $$

At 3 meters, for example, the dipole has a fringe field of 0.0060 Tesla (60 gauss), while the quadrupole fringe field is only 0.0014 Tesla (14 gauss). In practice, the quadrupole fringe field will be considerably smaller since the quadrupole length is short, ~ 1 meter, and pairs of quadrupoles alternating in magnetic polarity are located along the vehicles. Detailed 3D analysis of Maglev-2000 fringe fields indicate that the magnetic fields in the passenger compartment can be held at the 1 gauss level using a modest amount of iron, e.g. ~ 1000 Kg, for local shielding.

Figure 10 shows a drawing of the Maglev-2000 aluminum loop guideway panel, while Figure 11 shows a photo of a fabricated panel. There are 3 sets aluminum loops in the panel, comprised of 1) a sequence of four figure of 8 null flux loops, 2) a sequence of four 2 dipole loops, and 3) a single dipole that extends the full length of the 2 meter long
panel. The Figure of 8 and dipole loops are fabricated as multi-turn loops of aluminum wire (electrically insulated by a nylon coating), with each loop forming a separate electrical circuit. The aluminum loops are enclosed in a strong, all weather capable, polymer concrete matrix to form the completed panel. The fabrication process is described in an accompanying paper.\(^{(12)}\)

When mounted on the side walls of the monorail guideway, the superconducting quadrupole magnets on the moving vehicles induce currents in the Figure of 8 null-flux loops that levitate and vertically stabilize the Maglev vehicles. In the null flux geometry, the induced amount in the aluminum loop is zero when the quadrupole is symmetrically centered on the Figure of 8 loop. If the quadrupole moves to the left or right of the center of symmetry, an induced current develops in the aluminum loop that magnetically interacts with the quadrupole, pushing it back to the center. In the monorail configuration, the vehicle drops down slightly below the center of symmetry to the point where the upwards magnetic restoring force equals the weight of the vehicle. The nominal equilibrium position is \(\sim 2\) centimeters below the symmetry center, for a loop width of 45 centimeters. If an external force acts to vertically displace the vehicle from its equilibrium suspension point, the inherent magnetic restoring force automatically counters the external force. The M-2000 vehicle suspension is designed so that it would require an impossibly large external force, over twice the weight of the vehicle, to make it contact the guideway.

The dipole loop in the panel on the left side of the monorail is cross connected with the corresponding dipole loop on the right side to form a closed null flux circuit. When the Maglev-2000 vehicle is centered on the guideway, no induced current flows in the null-flux current. If an external force acts to move the vehicle laterally off its centered equilibrium position, a net flux and current develop to push the vehicle back to its centered position.

The single loop in the panel carries an applied AC current that propels the vehicle in a linear synchronous motor (LSM) mode. The propulsion loops in the succession of panels on the guideway are connected together to form an energized block, \(\sim 100\) meters in length. As the vehicle leaves an energized block, the AC power input to the block is switched off and switched onto the block that the vehicle is entering. Vehicle speed and the spacing between vehicles on the guideway is automatically controlled by the frequency of the AC power fed to the energized block. To accelerate, frequency increases; to decelerate, frequency decreases, with the kinetic energy of the vehicle fed back into the electrical grid.

For operation on planar guideways, the guideway panels are placed on the flat planar surface, rather than mounted vertically. The Figure of 8 null-flux loops then function to provide lateral stability, while the dipole loops remain as single loops, not connected to other dipole loops. Each dipole then magnetically interacts with the quadrupole to levitate and vertically stabilize the vehicle. The LSM loops function in the same way as they do on the monorail type of guideway.
The guideway panels can also be mounted on the cross-ties of existing RR tracks (Figure 12), enabling levitated travel of Maglev-2000 vehicles along existing RR tracks in a planar guideway mode. The panels do not interfere with the operation of conventional trains, which could continue to use the tracks for bulk freight transport, given appropriate scheduling, probably at night-time. The ability of Maglev-2000 vehicles to travel as individual units would enable much more frequent and convenient passenger service, rather as long trains of many RR cars. Also, because the Maglev vehicle loads are distributed along the vehicle and not concentrated at wheels, its local track loading is much less than conventional trains, resulting in much longer track life and reduced maintenance.

The capital cost of the monorail guideway has been examined in detail, based on fabrication experience and costs of magnets, panels, and the guideway beam. In 2000 dollars, the projected cost was 11.4 million dollars per 2-way mile for “greenfields” construction (no land acquisition or infrastructure modification costs). In 2008 dollars, the corresponding construction cost would be ~ 25 million dollars per 2-way mile. The cost to adapt existing RR tracks for Maglev-2000 operation would be much less, on the order of 4 million dollars per 2-way mile, since an elevated guideway would not be required. More complete descriptions of the Maglev-2000 system are given in a separate report.

Table 2 summarizes the nominal operating parameters for the Maglev-2000 system. A principal objective of the Maglev-2000 system, and a key element is its low construction cost, is to mass produce its prefabricated components in large factories. The components, beams with attached panels, piers, controls, etc. can then all be shipped to the construction site and quickly erected at low cost on pre-poured concrete footings using conventional cranes. The components can also be readily exported to other countries. A container ship, for example, can carry 20 miles of pre-fabricated 2-way guideway.

Table 2: National Network & Maglev-2000 System Parameters

<table>
<thead>
<tr>
<th>Network</th>
<th>25,000 miles, 300 mph max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Vehicles</td>
<td>100 passengers</td>
</tr>
<tr>
<td>Truck Carriers</td>
<td>2 Types (1&amp;2 Trucks)</td>
</tr>
<tr>
<td>Auto Carriers</td>
<td>15 Autos + Passengers</td>
</tr>
<tr>
<td>Travel</td>
<td>Either as single units or multi-unit consists, depending on traffic</td>
</tr>
<tr>
<td>Quadrupole Magnets</td>
<td>600,000 Amp Turns</td>
</tr>
<tr>
<td>18 inch width, Hi Temp Superconductor, 8 Magnets for passenger vehicle, 16 magnets on truck and auto carriers</td>
<td></td>
</tr>
<tr>
<td>Magnetic Suspension</td>
<td>10 cm gap between vehicle &amp; guideway, 0.3 g/cm automatic magnetic restoring force</td>
</tr>
</tbody>
</table>

5. IMPLEMENTATION OF THE NATIONAL MAGLEV NETWORK

While much of the individual components of the 2nd generation Maglev-2000, e.g., magnets, guideway loop panels, etc. have been fabricated and successfully tested. It will be necessary to assemble and test vehicles on an operating guideway. This will require a 4 to 5 year program, depending on funding level, at a total cost of ~ 600 million dollars. Continued running tests at high speeds, up to 300 mph, will be necessary on a long guideway, e.g. 20 mile or more. Lower speed tests on converted conventional RR tracks will also be necessary. A phased testing program appears desirable, starting with lower speed operation, e.g. 100 mph on shorter guideways, e.g. a mile in length, followed by tests at higher speed on longer guideways.

Following successful testing, construction would begin on the first portion of the National Network, the “Maglev Golden Spike Project”, with the goal of
completing a transcontinental East-West route by 2019, the 150th Anniversary of the completion of the Transcontinental Railroad at Promontory Utah, in 1859. As part of Maglev Golden Spike, 2 North-South routes would also be constructed, one on the West Coast from San Diego to Seattle, and one on the East Coast, from Boston to Miami with a total route mileage of ~6,200 miles. Additions to the Network would then continue, with the full 25,000 mile Network completed by 2030. While ambitious, the rate of construction would actually be slower than for the Interstate Highway System in the 1950’s and 60’s.

As discuss earlier, it is anticipated that the National Maglev Network could be privately financed using private-public partnership arrangements, once the maglev technology has been demonstrated. The demonstration, however, will probably require government financing.

The national benefits of electric transport – will be very important, including:

1. elimination of almost all oil imports and their associated large trade deficit expenditures
2. major reductions in greenhouse gas emissions now coming from present transport systems
3. creation of a domestic Maglev industry that will provide hundreds of thousands of new jobs, and Billions of dollars in exports
4. increased economic productivity through more efficient, faster transport of goods and people at lower cost

6. REFERENCES

(2) Association for the Study of Peak Oil and Gas [ASPO]).


(4) Bureau of Economic Analysis, Table F.1. U.S. International Transactions in Goods and Services


(7) Transportation and Infrastructure Committee, U.S. House of Representatives, June 24, 2008 Connecting Communities: The Role of the Surface Transportation Network in Moving People and Freight


(10) http://www.o-keating.com/hsr/tgv.htm


