A National Maglev Network for the U.S. – Design and Capabilities

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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.(1) 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.

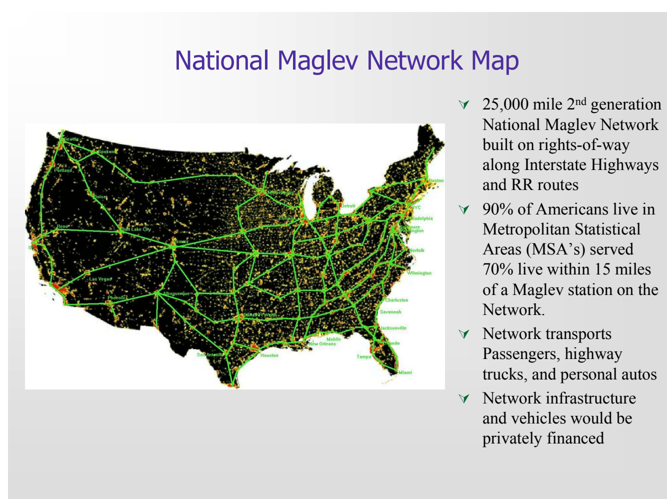


Figure 1. 25,000 mile National Maglev-2000 Network

(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

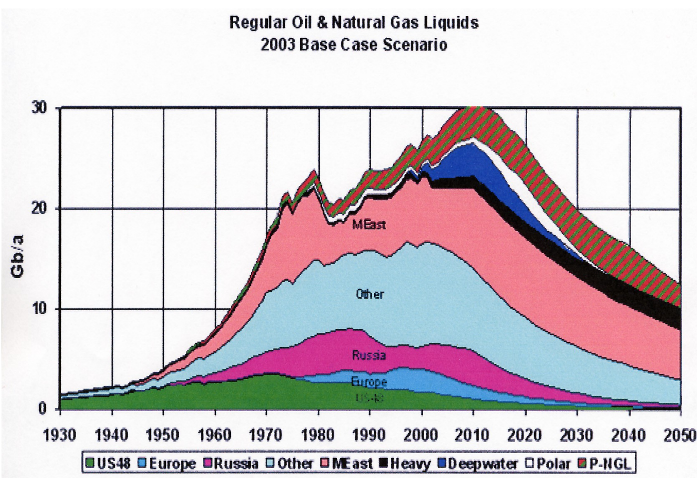


Figure 2. World oil production, historical and projected, as a function of time

World oil production has plateaued and will start to decline within the next few years (Figure 2).[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,[3] 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.[4] 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.[5] 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].

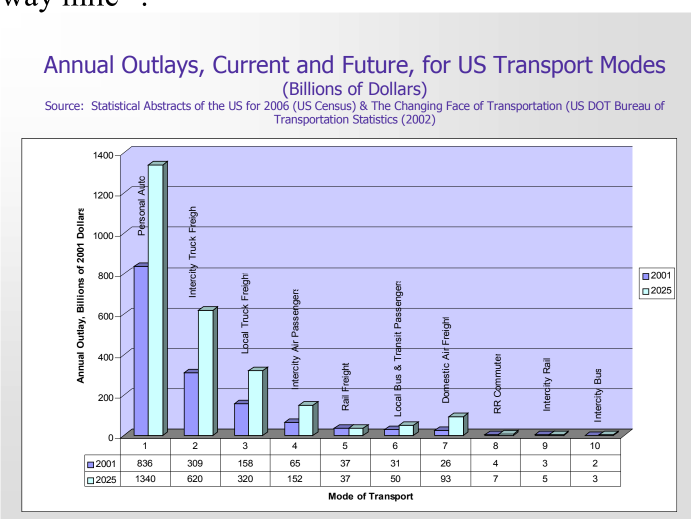


Figure 3. Annual Outlays, Current and Future for U.S. Transport Modes

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 1st 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 2nd 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]

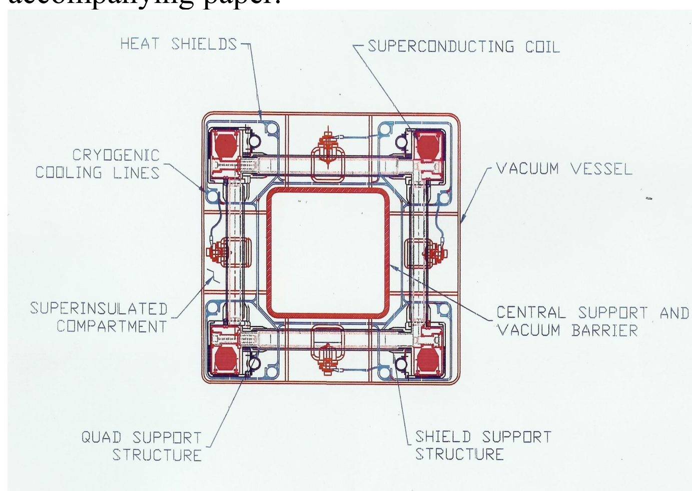
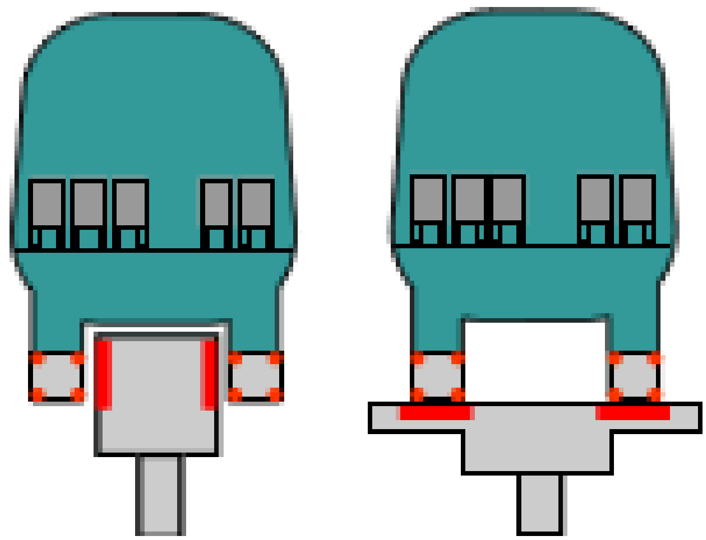


Figure 4 Superconducting Maglev-2000 Quadrupole Magnet Cross Section



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

$$(B_D)_D = \left(\frac{N_0}{2R}\right) I_0 W \left[D^2 + \left(\frac{W}{2}\right)\right] \quad \text{Tesla} \quad (1)$$

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

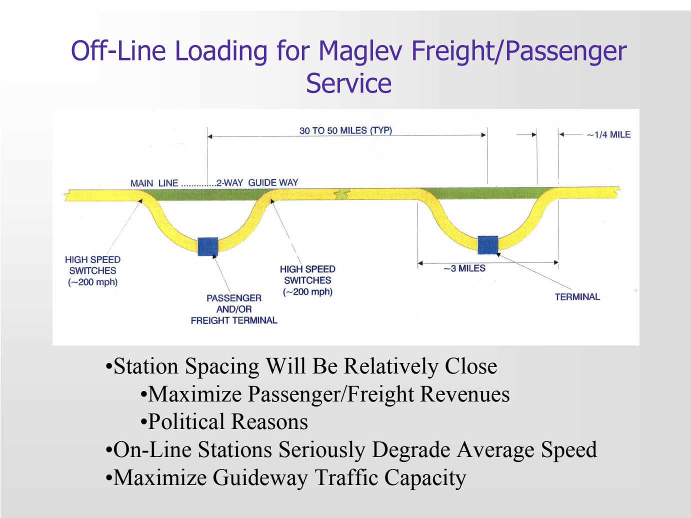
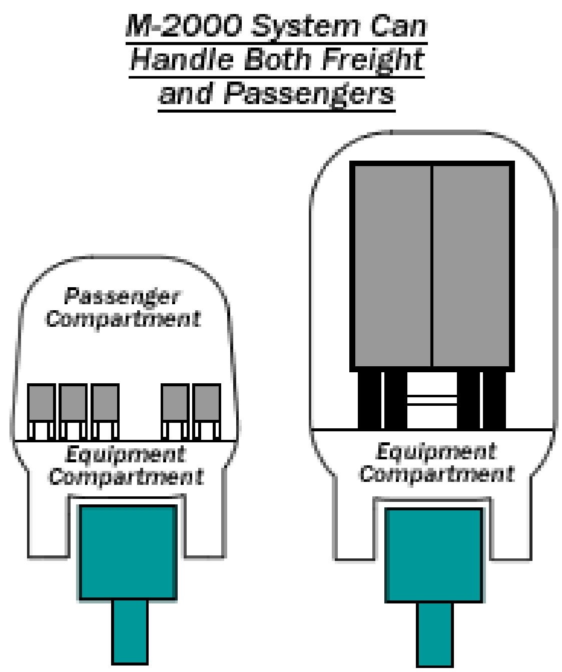


Figure 7. High Speed Electronic Switching of Maglev-2000 Vehicles From Main Guideway to Off-Line Stops

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 on 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.



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igure 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).

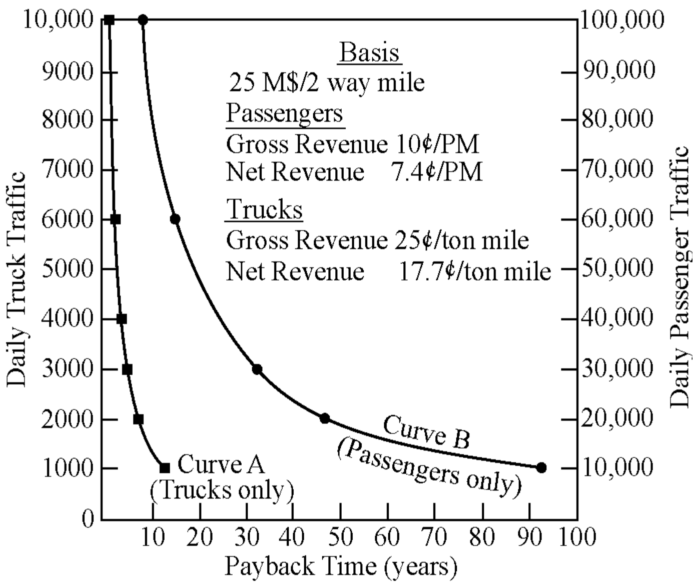

Figure 9. Payback time for Maglev-2000 Guideway as a function of truck and passenger traffic.

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,

$$(B_D)_D = \left(\frac{\mu_0}{2R}\right) I_0 W \left[D^2 + \left(\frac{W}{2}\right)^2\right]^{-1} \quad \text{Tesla} \quad (1)$$

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

Revenues & Costs	Passengers (cents/pm)	Trucks (cents/ton mile)
Gross Rev	10	2.5
Energy Cost	1.2	4.0
Am& M Cost	0.9	2.8
Personnel Cost	0.5	0.5
Net Rev.	7.4	17.7

while for a quadrupole, it is

$$(B_D)_Q = \left(\frac{\mu_0}{2R}\right) I_0 W \left\{\left[D^2 + \left(\frac{W}{2}\right)^2\right]^{-1} - \left[(D+W)^2 + \left(\frac{W}{2}\right)^2\right]^{-1}\right\} \quad \text{Tesla} \quad (2)$$

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

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

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)

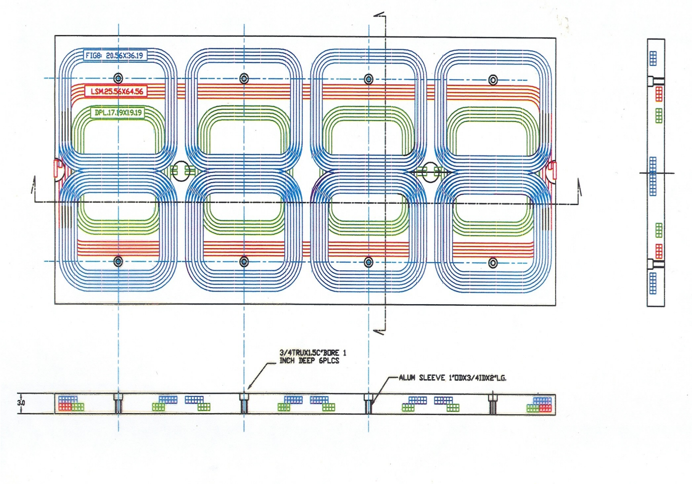

Figure 10. Drawing of aluminum loop guideway panel providing vertical lift and stability, lateral stability, and linear synchronous propulsion.

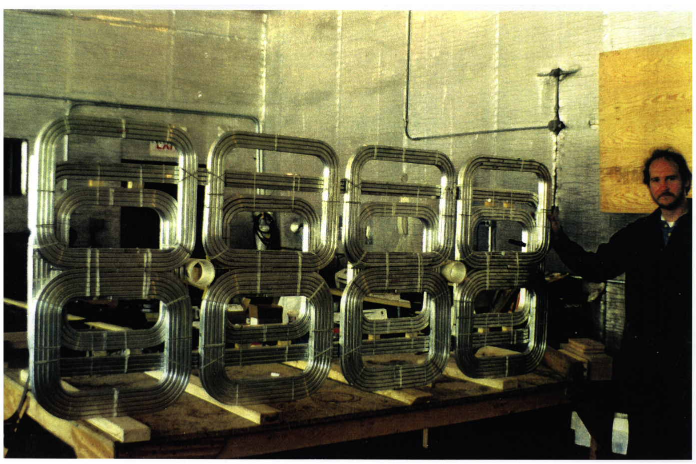

Figure 11. Photo of full size fabricated guideway loop panel.

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 ~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, ~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.

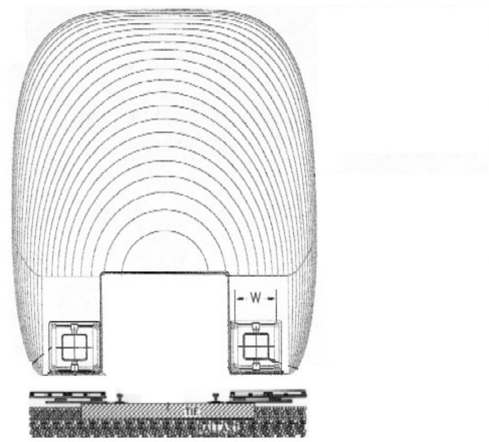

Figure 12. Drawing of levitated Maglev-2000 vehicle traveling on conventional RR track to which aluminum loop panels have been attached to the cross-ties.

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)[13]. 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.[14]

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.

<u>Table 2: National Network & Maglev-2000 System Parameters</u>

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

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

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