The Magtube low cost maglev transportation system

O.J. Fiske
LaunchPoint Technologies, Inc., Goleta, California, USA

ABSTRACT: Over the past few decades "maglev train" has become a single concept, resulting in maglev mass transit systems that are too large and expensive for many prospective applications. Alternative designs created without preconceived notions to fully exploit maglev's potential, however, can provide revolutionary operating characteristics and economics. LaunchPoint Technologies has created just such a design, and constructed a prototype. Features of the Magtube system include small vehicle size, narrow guideway, a novel wide-gap permanent magnet suspension, a high efficiency wide-gap linear induction motor (LIM) on board the vehicle, and a high speed guideway switch with no moving components. Magtubes can provide high acceleration, very high speed, short headway between vehicles, extreme safety, high passenger and/or freight capacity, low operating costs, and greatly reduced capital investment requirements compared with conventional maglev approaches. Variations on the design are suitable for intra-city or inter-city transportation on open guideways or in evacuated tubes.

1 INTRODUCTION

1.1 Maglev Conventions

A commercial cargo ship arriving in port is unloaded, reloaded and sent on its way as quickly as possible. The same with commercial aircraft. Airlines and shipping companies maximize revenue by keeping their assets working.

Rail companies are in a very different situation. Their most precious assets are their rights-of-way and tracks, which are idle most of the time. How can rail companies afford to stay in business? Only because, in most cases, the land was acquired and the tracks laid down long, long ago. Even so, in many countries railroads are heavily subsidized, particularly for passenger transport.

New rail transit systems are constrained to follow established standards in order to make use of existing rail lines and facilities. Although this enables them to leverage prior investments and would appear to reduce costs, in fact it has locked them into outmoded system designs with far higher land, construction and operating costs than are necessary or sustainable. Maglev systems have fallen into the same trap, even though they have no requirement, or even capability, to use existing tracks. Almost without exception, "maglev trains" have been designed to follow the same conventions as railroads, with all of the same constraints and costs. An outside observer would therefore expect a similar economic result.

This, in fact, was corroborated by a US Federal Railroad Administration report (FRA 1997), which analyzed the potential costs and benefits of maglev and various high-speed rail options for nine US transportation routes. In no corridor was high-speed ground transportation projected to be commercially feasible. In every case examined, total system costs over the period studied far exceeded total system revenues, primarily due to the very large initial investment required.

This need not be the case.

1.2 A Question of Size

What vehicle size is most likely to provide economic success in a new maglev system? Large vehicle size is often desirable in transport systems, and in some cases may even be a requirement for economic success. For example, large vehicle size may be beneficial if:

– The vehicle is manually operated and many passengers or a considerable amount of cargo must be carried to offset crew salaries and overhead;

- A great quantity of fuel must be carried to provide long range without refueling;
- Fuel efficiency improves with increasing size, as in aircraft and ships; or
- Large size is the only way to meet required transport capacity.

For many potential maglev applications, however, none of these conditions apply. Automated operation can eliminate the need for a crew; energy can be supplied by electric transmission lines; size has too small an effect on energy efficiency to be a primary consideration; and numerous small vehicles can be used to achieve very large transport capacity.

1.3 Pipelines

Consider pipelines, which carry more than 10 percent of total US freight volume. The petroleum and natural gas transmission and distribution network in the US includes over 2.2 million kilometers (1.4 M miles) of pipeline (BTS 2001), and thousands of kilometers are added by private industry each year. Pipeline technology now in use is highly developed and well understood, and common-carrier status, deregulation and competition have made cross-country pipelines extremely cost effective. Transporting a ton of oil by pipeline is 5 times cheaper than shipping a ton of freight by rail, 50 times cheaper than by truck, and 170 times cheaper than by air. Pipelines are also the safest of all transport modes and the least disruptive to the environment.

The basis for pipeline success is readily apparent: a pipeline's diameter is selected to be large enough to suit its application – and no larger. Constructing a 4-meter diameter pipeline to carry oil and then using it one percent of the time would not be considered wise. Train tracks and maglev guideways have generally been constructed to conform to an arbitrary historical standard and are most often empty and idle, but pipelines are sized to meet their capacity requirements and are then kept full and in service virtually all of the time. Capital costs are surprisingly small. This would seem to present a more promising metaphor for maglev, i.e. "maglev pipelines" are much more likely to provide economic success than "maglev trains".

1.4 Magtube Design Criteria

Thus, the driving principle behind the Magtube system design has been to make vehicle and guideway dimensions as large as they must be to carry people and freight – but no larger – and to keep the guideway busy most of the time. The resulting effect? Costs plummet, performance improves, and the breadth of suitable applications increases.

2 THE MAGTUBE MAGLEV SUSPENSION

2.1 Halbach Arrays

The maglev suspension technology developed for the Magtube design makes use of high-strength neodymium-iron-boron permanent magnets assembled in a configuration known as a Halbach array (Halbach 1985). A typical array of this type and its magnetic field are shown in Figure 1.

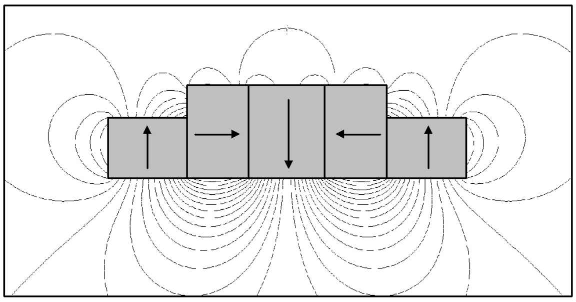

Figure 1: Halbach Array Magnetic Field

The polarities of individual magnets in the array are arranged such that the fields reinforce each other on the "active" face, producing a very strong magnetic field, and largely cancel each other on the "inactive" face, leaving almost no field at all.

2.2 The Repulsor

To create a maglev suspension or "Repulsor", two Halbach arrays are employed, as shown in Figure 2.

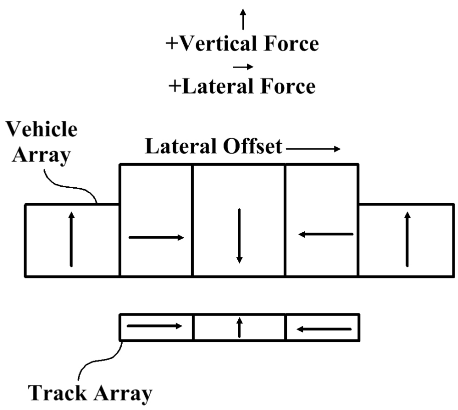

Figure 2: Repulsor Configuration

The active face of the vehicle array points downward, while the active face of the stationary track array points upward. The vehicle array is much larger in cross section than the track array to provide sufficient lift force while minimizing track costs. The Repulsor design produces in excess of three times the force of an equivalent mass of magnet material configured as simple dipoles of opposing polarity, and also confines the field to a much more localized area. The vertical and lateral forces produced by the Repulsor are illustrated in Figure 3.

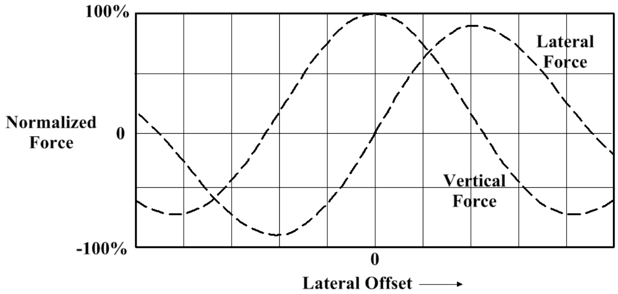

Figure 3: Repulsor Force vs. Offset

With the vehicle and track arrays vertically aligned as shown in Figure 2 (offset = 0), vertical force is maximized and lateral force is zero. As the lateral offset increases, the magnitude of the lateral force grows and tends to increase the offset even more, i.e. the Repulsor is laterally unstable.

2.3 Stabilization

To compensate for lateral instability, voice coil lateral stabilizers are mounted beneath the vehicle magnets to interact with the track magnets, resulting in the vehicle suspension shown in Figure 4.

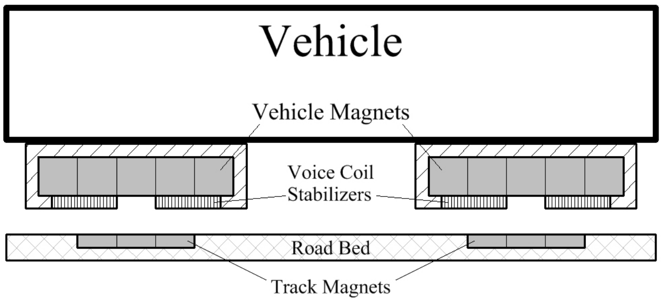

Figure 4. Repulsor Vehicle Suspension

A feedback control system monitors the alignment of the Repulsors with respect to the rails and varies electric current in the voice coils to keep the vehicle centered. The vehicle magnet arrays extend for most of the length of the vehicle. With practical magnet dimensions, they can provide a levitation gap of three to eight centimeters at all speeds, with no levitation power requirement and essentially no drag. Using "virtual zero-power" control, stabilization system power is on the order of 100 watts per ton of vehicle weight. The Repulsor design confines magnetic fields almost entirely to the levitation gap, thus preventing high intensity fields from penetrating the vehicle above and adversely affecting cargo or passengers.

2.4 Turn Radius

In a typical vehicle, the Repulsors are segmented into front and rear assemblies or "bogies", each of which pivots to maintain track alignment in turns. This can enable a vehicle to negotiate corners with a 10-meter (33-foot) turn radius or less.

3 MAGTUBE SYSTEM DESIGN

3.1 Propulsion Motor

The Magtube system utilizes a dynamically reconfigurable linear field generator installed on the vehicle, which produces a variable-wavelength magnetic field that propagates along the underside of the vehicle at variable speed, allowing several operating modes.

3.1.1 LIM Mode

In its simplest form, the propulsion system uses the field generator as a Linear Induction Motor (LIM). The traveling magnetic field produced by the field generator interacts with a conductive rail, in the center of the track between the two suspension rails, to produce thrust. The wavelength of the field produced can be continuously varied according to vehicle speed, with short wavelengths providing high efficiency at low speeds and longer wavelengths for high efficiency at high speeds. Power can be supplied by an on-board battery or fuel cell. For longer un-refueled range, off-board power can be provided through non-contact power transfer (linear transformer). The design of the field generator allows a significantly larger operating gap between the motor and rail than conventional LIM designs.

3.1.2 LSM Mode

Higher propulsion power for faster acceleration and/or higher top speed can be provided by the Linear Synchronous Motor (LSM) mode. Here, the on-board field generator produces a static field with the wavelength chosen to correspond to stator windings in the guideway. A wayside motor commutation system varies the current to the stator windings, as in a conventional LSM, to interact with the field on the vehicle and produce thrust.

3.1.3 Mode Selection

The choice of motor operating mode depends upon the needs of each installation, or even particular segments of an installation. Where guideway costs must be kept to a minimum, for example, the LIM mode with on-board power can eliminate the need for active motor commutation or power distribution in the guideway, resulting in very low guideway construction costs. With an open-air guideway where high speed vehicle operation is desired, the LSM mode provides high thrust capability. If evacuated tunnels are used to minimize air drag, they can be divided into "boost" zones and "glide" zones. Boost zones, utilizing the LSM mode, would be installed wherever vehicle speed must be increased, such as tunnel entrance points, long hill climbs, or after a long glide zone. Once a vehicle reaches cruise speed, its near-frictionless operation would allow it to glide for tens of kilometers with little reduction in speed – "ballistic cruise" – through glide zones. If the vehicle must be stopped for any reason within a glide zone, the LIM mode with on-board power can then be used to accelerate it to a modest speed until it reaches the next boost zone. The net result is that much of the guideway can be built with no stator windings or power distribution, providing savings in both capital costs and maintenance.

3.2 Brakes

In normal operation, the vehicle linear field generator can provide eddy-current braking simply by applying a static field to the LIM rail. The field generator can also be operated in a generator mode, in which braking energy is collected and stored (regenerative braking). In emergency situations, the vehicle can be de-levitated to one side of the guideway or the other to provide contact braking.

3.3 Router

Routers are track bifurcations or "forks" installed at junctions to permit vehicles to select the appropriate route to their destination as directed by a central network control computer. The router is totally passive with no moving parts or electric components. Route selection is accomplished by dynamically modifying Repulsor control fields in each vehicle allowing it to select one or the other path with minimal impact on speed. Delays between successive vehicles can be as short as a fraction of a second, giving the system very high traffic capacity, analogous to the packet switching networks used for Internet communication, but in this case, carrying people or material goods rather than data.

3.4 Guideways

A variety of guideway designs can be employed, again depending upon installation requirements. Guideways can be evacuated tubes ("Magtubes") or open to the air ("Magways"). They can be installed below ground, at ground level, or elevated. They can include motor stator windings, power distribution lines, both, or neither.

3.5 Performance

The Magtube design not only decreases system complexity and cost, it also greatly improves performance both in terms of speed and energy efficiency.

3.5.1 Speed

Repulsor levitation places no fundamental limits on speed. In theory, a straight-line Magtube containing a hard vacuum would allow a maximum vehicle speed easily exceeding 1600 kph (1000 mph). In practice, vehicle speed in typical installations will be limited primarily by payload and levitation system lateral acceleration limits in curves and by aerodynamic drag caused by residual air in the pipeline. With air pressure below 10^{-3} atmospheres, straight-line vehicle speed capability will exceed 800 kph (500 mph). Speed through corners will depend upon the actual radius of each turn. In open country, high speed rail lines sometimes achieve a minimum turn radius of 3500 meters or more. Assuming lateral G-forces are limited to 0.5 G's to protect payload, a 3500-meter turn radius will allow a vehicle speed of nearly 500 kph (300 mph).

3.5.2 Energy Efficiency

When used in evacuated tunnels, the Magtube design nearly eliminates the primary energy sink confronted by all other high-speed transport modes – aerodynamic drag – resulting in extremely high energy efficiency. Table 1 compares the energy efficiency of conventional modes (CTA 1998) to Magtube vehicles carrying 1200 kg of payload.

Table 1: Energy Efficiency Comparison

Mode	Speed (mph)	BTU/ ton-mile	Ton-miles/Gal. (diesel equiv. *)
Railroad	65	368	377
Long-haul truck	65	1151	120
Truck (avg)	65	2793	50
747-400F	500	10,800	12.5
Air Freight (avg)	500	20,000	7
MagTube	300	<60	2000+

*Diesel contains 138,700 btu/gal

Magtube vehicles traveling at 300 mph (500 kph) are over 7 times more efficient than railroad, 20 times more efficient than long-haul trucks, and 200 times more efficient than a 747 per ton-mile.

4 APPLICATIONS

The flexibility of the Magtube system design allows its use in a variety of capacities, from low speed to very high speed, for passengers or for freight.

4.1 Freight Transportation

4.1.1 Freight Capsule Design

Figure 5 shows a freight capsule inside a Magtube. The basic structure consists of a rugged aerodynamic shell with repulsors mounted in the undercarriage. End hatches (Figure 6) provide access to a payload bay large enough to accept standard 40” x 48” cargo pallets or Euro-pallets, with sufficient payload capacity (1200 kg) for a wide variety of freight.

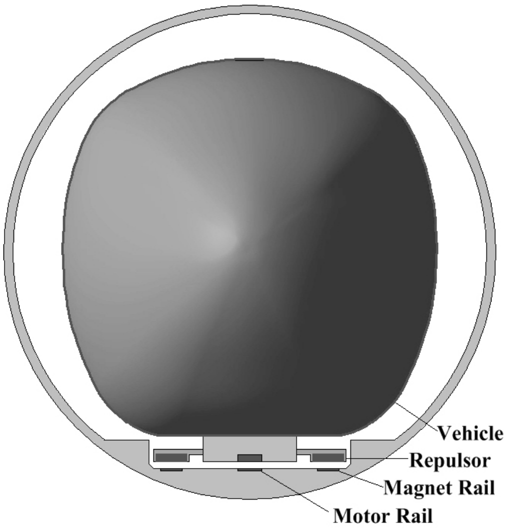

Figure 5: Freight Capsule and Magtube

When used with Magtubes, the payload bay is pressurized to maintain a benign environment for cargo. Capsules are designed to be simple, rugged, and durable for long-term use with little maintenance.

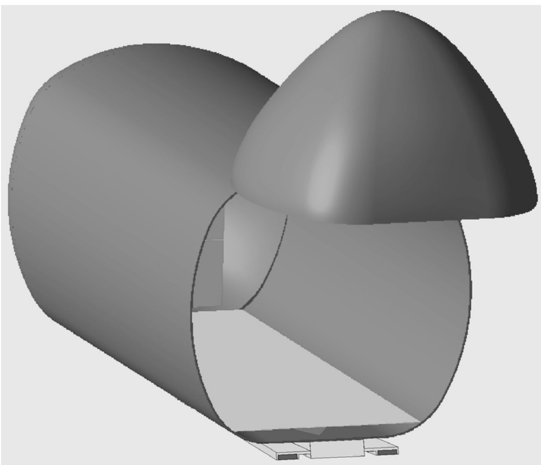

Figure 6. Freight Capsule

In addition to pallets, shipping containers of various dimensions may be used. A particularly useful container would be one-half of the length, width, and height of a standard twenty-foot shipping container (TEU), or about 44 inches by 44 inches by 10 feet (1.1 x 1.1 x 3m). Eight of these “sub-containers” would fit inside a TEU for enhanced compatibility with existing transportation modes. Another container type could conform to the internal dimensions of the capsule payload bay, providing the maximum possible volume for low density freight. Other configurations are also possible, such as a 40 inch by 48 inch by 8-foot (1 x 1.2 x 2.4m) container to carry sheets of construction materials, or low-profile tanker capsules to carry bulk liquids.

4.1.2 Freight Capacity

The Magtube is a pipeline, and as such is capable of very high capacity if fully utilized. Utilization efficiency depends on capsule speed and the delay between successive capsules. The maximum theoretic capacity for a capsule speed of 150 meters per second (540 kph or 336 mph) with capsules physically coupled in a train (5 meters per capsule) is 30 capsules per second which equates to 142,000 tons per hour or over 3.4 million tons per day. In practice, this level of throughput is not sustainable due to operational considerations, but even at two capsules per second, about 7% of maximum capacity and a level that should be readily achievable, capacity is close to 10,000 tons per hour for a single pipeline. This compares to a capacity of 7,000 to 18,000 tons per lane per hour for heavy trucks on an uncongested highway. Truck lanes planned for the Los Angeles area are projected to cost over $120 million per mile.

4.2 Maglev PRT

As described previously, prior maglev systems have utilized large vehicles to implement high speed “maglev trains” at very high cost. At the other end of the mass-transit spectrum lies Personal Rapid Transit (PRT), which employs a lower-cost guideway with many small, low-speed wheeled vehicles to provide high passenger capacity. Thus far, PRT advocates have avoided maglev technology due to its perceived complexity and high cost. With the advent of the permanent-magnet Repulsor, however, this is no longer necessary. Repulsor suspension applied to PRT can result in systems with all of the advantages of wheeled PRT, and similar costs, but with lower mechanical complexity, lower maintenance requirements, much higher speed capability, and a much broader range of applications. Figure 7 shows what a maglev PRT system on an elevated Magway might look like.

5 COMMERCIAL OPERATIONS

5.1 Point-to-Point Installations

The basic Magtube installation is a simple point-to-point configuration. A terminal on each end contains vehicle loading and unloading stations, system operation and maintenance facilities, and interfaces to the outside world. This type of installation would be appropriate for bypassing transportation system bottlenecks, such as congested border crossings, or interconnecting two major shipping nodes, such as an automobile assembly plant and a parts supplier factory.

5.2 The Mag Net

In a more extensive system, a cross-country network of Magtubes, Magways, routers, and terminals

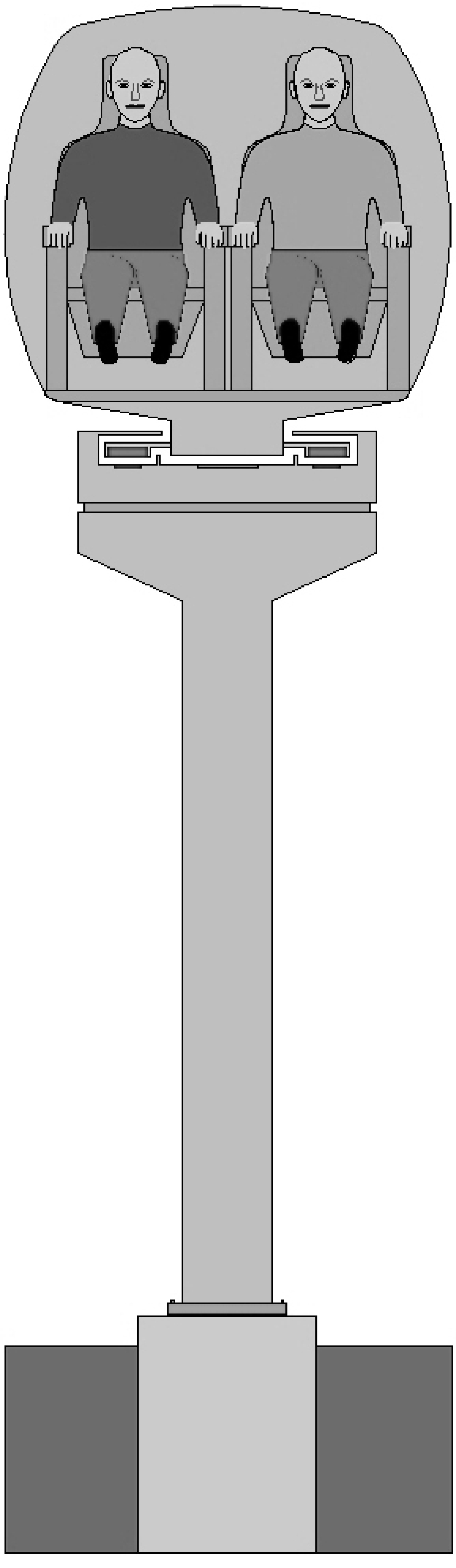

Figure 7: Maglev PRT

will form the Mag Net – a system analogous to the fiber-optic links and data routers that make the packet-switching Internet possible, but now carrying physical packages or passengers instead of data. The narrow width of Magtubes, in elevated or subterranean installations, and Magways, in elevated or ground level installations, will make the Mag Net compatible with existing rights-of-way such as railroads, highways, and even power lines, providing a huge inventory of potential routes. Much of the US railroad and interstate highway mileage is suitable for Magtube installation. Selection of routes will depend upon customer needs and path curvature (straighter paths allow higher speeds and lower construction costs). A bi-level network is shown in Figure 8.

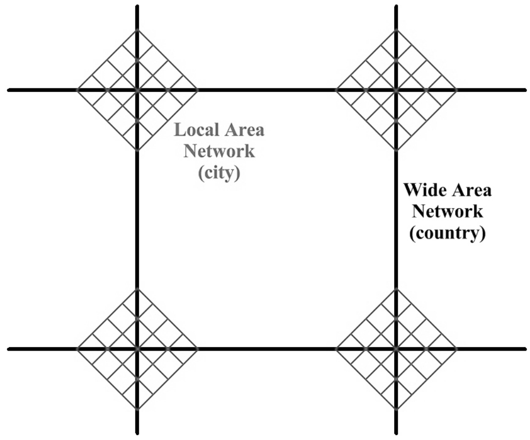

Figure 8: Bi-Level Network

As with communication networks, this structure consists of Local-Area Networks (LAN's) and Wide-Area Networks (WAN's). LAN's will service limited areas, such as cities or regions, with terminals, Magtubes, routers, and Magways. WAN's will interconnect multiple LAN's. If any link is out of commission, e.g. for maintenance, or is experiencing heavy traffic, alternate paths may be utilized. This gives the system a high degree of redundancy and very high load capacity.

5.3 A Network Cell

Figure 9 depicts a typical network cell consisting of 4 nodes and their interconnecting Magtube links. Each link provides one-way transportation resulting in four tubes per cell rather than the eight required to carry traffic in both directions. The speed and energy efficiency of Magtubes makes it practical to send return vehicles "around the loop". For example, a shipment from node 1 to node 2 would travel direct, but the return shipment would travel from node 2 to node 3 to node 4 and finally to node 1.

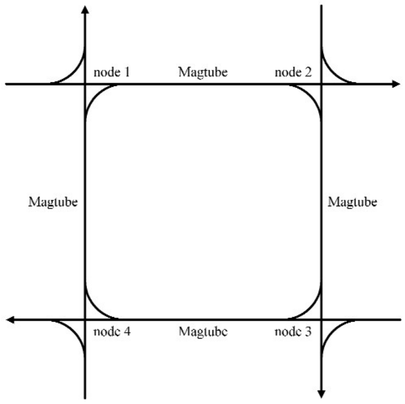

Figure 9: A Network Cell

5.4 A Network Node

Figure 10 shows the layout of a single node. An incoming vehicle encounters a router where it switches onto the path to the local terminal, passes straight through, or switches onto the alternate outgoing route.

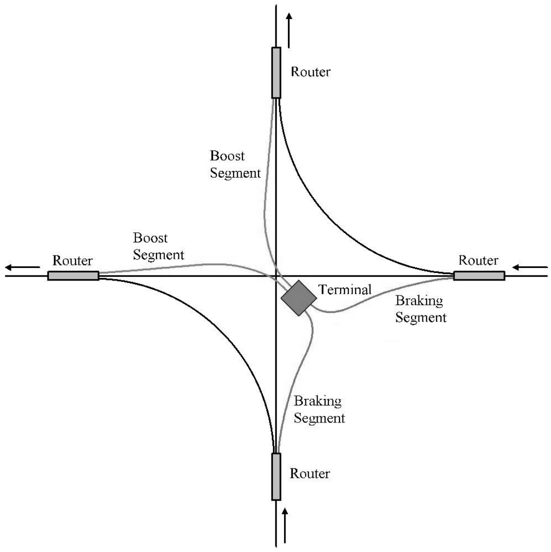

Figure 10: A Network Node

6 COSTS

The three dominant expenses associated with conventional transport modes are labor, energy, and capital costs. The Mag Net offers major improvements in all three.

6.1 Labor

Because it is automated, the Mag Net provides significant increases in productivity. Labor required in freight terminals should be comparable to that required in conventional terminals, but even here the opportunity for productivity improvement exists. Standardized shipping containers could allow the use of fully or partially automated loading/unloading equipment. Spur lines could also be constructed direct to major shipping customers, allowing the Mag Net to become, in effect, an integral part of a production line spread out over several cities, states, or even countries. In some cases, this could radically streamline the logistical chain by eliminating the need to transfer cargo from source to truck, truck to aircraft, aircraft to truck, and truck to destination. It would also allow more precise scheduling for just-in-time manufacturing, even with a factory and its suppliers separated by hundreds or thousands of miles.

Construction of the Mag Net will obviously require large numbers of skilled laborers. As the Mag Net expands, it will also provide many new high-skill jobs in service-related positions, such as logistics and system maintenance.

6.2 Energy

As described previously, even when moving vehicles at very high speed the Magtube will be highly energy efficient. This gives it a major cost advantage in the short run and an even larger advantage as the cost of petroleum-based fuels increases.

6.3 Construction Costs

The petroleum and natural gas industries have installed large diameter transmission pipelines throughout the world, some more than a meter in diameter and built to handle over 6.9 MPa (1000 psi). Magtube will be similar, but must only support a pressure differential of one atmosphere. A variety of materials are suitable for tube fabrication, including steel, aluminum, concrete and composites. Pipelines using these materials have a service lifetime exceeding 50 years with minimal maintenance in much more demanding applications than Magtubes. Here the lifetime is likely to be over 100 years.

Magnetic levitation, propulsion, and control system elements – and the desire to make the tube as straight as possible to maximize vehicle speed – will contribute to costs. Preliminary estimates indicate a capital cost of less than $3 million per kilometer ($5 million per mile) of freight Magtube in underground, cross-country installations. Of course, the cost of specific installations will vary widely. Construction in urban areas will be more expensive than rural areas, and elevated construction costs will be different than underground construction.

Passenger systems will incur additional costs to ensure safety, comfort, and convenience. Detailed estimates of passenger system construction costs have not yet been calculated, but PRT systems have been estimated to cost just under $10 M/km (2005 dollars) in one case (Burke 1979), and $10-15 M/km in another (SkyWeb 2006). Magtube PRT with similar complexity is likely to have a comparable cost.

Because of their simplicity and durability, freight capsules will constitute a relatively minor expense, even in large quantities. Passenger vehicles for open Magways will be more expensive, and for evacuated Magtubes more expensive still, with construction much like pressurized aircraft, but this will be a small fraction of the cost of guideways.

7 PROJECT STATUS

A prototype freight capsule, with Repulsor suspension and track has been constructed (Figures 11-13). The photograph in Figure 13 shows a Repulsor without the lateral stabilization system.

Future project goals include the construction and test of an extended track with routers, Magways, Magtubes, central control, and a vehicle communication system.

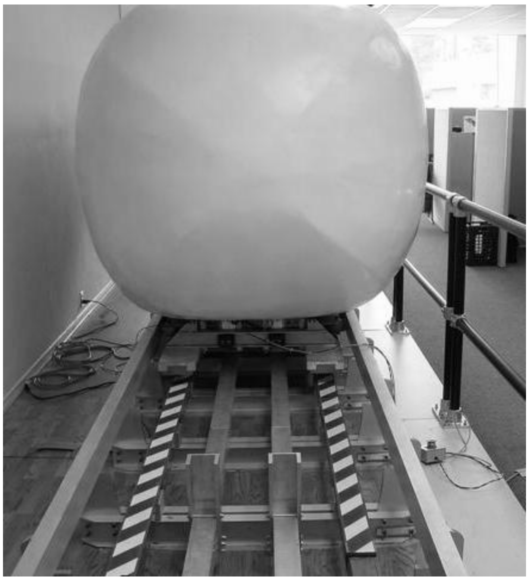

Figure 11: Prototype Freight Capsule

Figure 12: Prototype Rear View

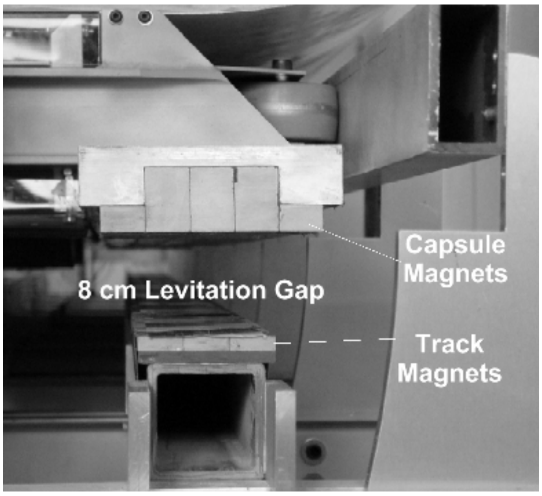

Figure 13: Prototype Repulsor

8 CONCLUSIONS

A prototype vehicle and track have been constructed to demonstrate the feasibility of the Magtube low-cost maglev transportation system. Preliminary construction costs and performance capabilities have been calculated. In developing countries, Mag Net construction could replace new highways, railroads, and airports, greatly reducing capital expenditures, saving huge tracts of land and avoiding the need for millions of petroleum vehicles. Since the Mag Net itself will be very close to silent and accident-free, it is reasonable to assume that noise, congestion, and accident rate reductions will correspond to reductions in road traffic.

Top speeds well in excess of 1,600 kph (1,000 mph) are achievable, but with operating costs orders of magnitude lower than supersonic airliners. Freight could be transported in less time than air freight, and at a lower cost than rail. Passenger terminals for long distance travel could be located throughout city centers, and in suburbs, rather than in remote airports. A nation-wide Mag Net passenger system would provide a level of speed, safety, comfort, convenience, and efficiency not previously possible.

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