Perspective on Maglev Transit and Introduction of Personal Rapid Transit Maglev

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A critical review of maglev trains and conventional wheeled trains is presented in an attempt to identify the performance advantages of maglev. Traditionally claimed advantages of maglev were not found to hold up to wheeled train systems incorporating similar non-contacting propulsion; however, performance advantages were identified for velocities greater than 500 mph (805 km/hr). Because travel at atmospheric pressure is not practical at these high velocities, an analysis was made for applications in tubes of reduced pressures. The feasibility of a personal rapid transit (PRT) system designed with maglev suspension and for travel in tubes of reduced pressure is evaluated. The PRT maglev appears to have superior service capabilities yet no obvious technological barriers. An economic comparison to maglev train systems suggests that the PRT maglev would cost about 40 percent less while providing appeal to a broader audience. Proposed performance advantages of the PRT maglev include reduced energy consumption, reliance on electrical power, and significantly reduced transit times compared to air or train systems. A practical approach to implementation is presented and consists of initially using lower velocities, higher tube pressures, and PRT vehicles connected as train units. Proposed evolution of the system includes attaining higher velocities and incorporating superconductive elements in the rail embodiments.

As noted by Sinha (*1*), it was not until the 1960s that fast electromechanical control gears and the advent of solid-state electronics made maglev vehicles feasible. In 1958 Polgreen (*2*) filed for one of the first maglev patents on a maglev transit system based on the repulsion of permanent magnets placed on the vehicle and along the guideway. Shortly thereafter, Silverman (*3*) filed for a patent based on attractive levitation using overhead rails and electromagnets on the vehicle. These patents during the late 1950s and early 1960s constitute the genesis era of maglev technology.

While maglev systems could be conceived of in the early 1960s, it was not until the late 1960s that technical innovations such as stable suspension, low-speed switching, and manageable rail tolerances made maglev transit a reality. Powell (*4*) led the way in truly feasible systems with the unprecedented introduction of (*a*) inductive suspension allowing vehicle-rail gaps greater than 3 in., (*b*) electrodynamic lateral stability, (*c*) incorporation of superconducting magnets, and (*d*) non-contact propulsion via jet engines. During this pragmatic era other advances were made, including (*a*) switching (low speed) without moving parts (*5,6*), (*b*) linear induction motors that allowed the engine noise and fuel weight to be removed from the train (*7,8*), and (*c*) control methods for stable suspension (*9,10*).

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These and other advances led to several maglev demonstration projects (*11*) in the early 1980s. Throughout the 1980s attractive electromagnetic suspension systems were advanced in Germany, and repulsive suspension (electrodynamic suspension) systems were advanced in Japan. During this time no significant projects were sponsored by the U.S. government. The EDS system technology developed during this era is currently being offered for sale by the HSST Corporation of Japan.

The latest era of maglev transit in the United States is perhaps best described as the romantic era, spawned by a growing fascination with the idea of rapid transit over a cushion of air without wheels. Federal funding made available in the early 1990s was motivated by a desire to gain superiority in this intriguing technology. The most significant development of this era was a report of maglev system cost estimates titled, *Compendium of Executive Summaries from the Maglev System Concept Definition* (*12*). While several U.S. markets have considered implementing maglev train systems, no routes greater than a few miles appear to be likely in the near future.

MAGLEV SUSPENSION VERSUS WHEELED SUSPENSION

Cited advantages of maglev trains over wheeled trains (*1,12*) include the following:

1. Wheels produce medium to high environmental noise levels.
2. Wheeled systems rely on propulsion through wheel-rail friction, and the high aerodynamic drag forces lead to upper speed limits due to limited wheel-rail adhesion.
3. Maglev vehicles can accelerate and decelerate rapidly and bank steeply on curves.
4. Suspension through point contact (up to 70,000 psi or 482 MPa) on wheeled systems leads to increased structural requirements and increased wear and maintenance.
5. Maglev trains have a certain romantic appeal.

Advocates or wheel-based trains point to an already extensive rail network to justify high-speed, wheel-based systems. Existing rail networks may not be the only reason to continue using wheel-based systems. As discussed subsequently, several cited advantages of maglev have a weak foundation.

Although wheels are generally noisier than magnets, at high velocities aerodynamic noise greatly exceeds that of wheels (J. Harding, former director of U.S. Maglev Initiative, personal communication, July 1993). In perspective, minimal noise reductions are achieved by high-speed maglev.

In a similar comparison of propulsion systems, linear synchronous motors (LSM) are capable of overcoming greater aerodynamic drag than wheels and have greater acceleration and deceleration capabilities than wheels. This non-contacting propulsion can be used with wheeled suspension and maglev systems alike. Combinations of LSM propulsion with wheeled suspension would provide needed propulsion without the expense of an entirely new rail system. The Detroit Metro already uses non-contacting linear induction motors (LIM) for propulsion (*13,14*). Among its many advantages over conventional wheel propulsion are lighter-weight vehicles, reduced height of train cars (*15*), and improved traction in all weather conditions, velocities, and grades. Figure 1 shows how the LSM propulsion system of the Magneplane concept (*12*) can be readily incorporated into the vehicles and tracks of a conventional train system. Cited advantages 2 and 3 are specific to LSM propulsion, not maglev suspension, and can be attained by wheeled and maglev systems alike.

An analysis of maintenance costs is simplified when assuming that maintenance costs are directly proportional to the weight of the vehicle. Such an assumption would be exact for a hypothetical system designed to have the same weight on all wheels, and in which reductions in weight would result in eliminating some wheels.

For wheeled propulsion, additional weight helps provide needed traction; however, lighter-weight vehicles would be preferred with LSM propulsion. A 70 percent reduction in vehicle weight would be feasible (*1*) and would result in a 70 percent reduction in maintenance costs. The application of high performance polymers and shock absorbers incorporating magnetic forces could further reduce maintenance costs.

Despite their complexities, maglev trains tend to have a romantic appeal. This appeal and several successful demonstrations of maglev systems make maglev trains a tempting alternative. However, for typical applications the slightly higher cost of maglev train systems and the advantages of using existing routes for wheeled alternatives make wheeled systems the more practical choice.

Maglev trains have limited advantages and significant disadvantages compared to high-speed wheeled trains using the latest non-contacting propulsion technology. To that end, the most advantageous applications of maglev appear not to be with conventional train systems. Alternatively, transit in low-pressure environments and transit by PRT vehicles are two applications in which maglev appears to have performance advantages.

USE OF PRT VEHICLES FOR INTERCITY TRAVEL

PRT concepts were considered dead in 1992, but the funding of the PRT2000 (*16*) demonstration may revive the expectations of PRT systems (*17*). In particular, PRT systems have the advantages of (*a*) reducing traffic congestion through automation, (*b*) reducing travel time by providing nonstop service from origin to destination, (*c*) reducing travel time by having access to a continuous supply of vehicles rather than periodic, and (*d*) relying on electrical energy.

Disadvantages (personal conversation with J. Perkowski, Bechtel, San Francisco, May 1994) identified during the 1970s included (*a*) performance limitations of available control technology, (*b*) perceived high cost of the extra number of vehicles, (*c*) distasteful appearance inside cities, and (*d*) potentially poor ride quality due to

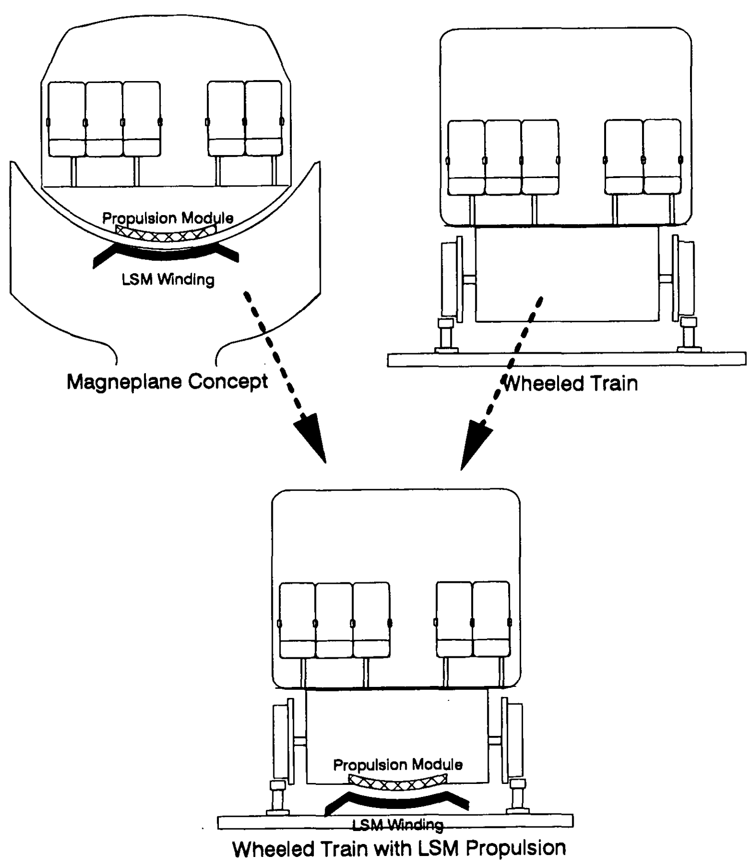

FIGURE 1 Concept for using LSM propulsion with conventional train.

routing problems. Advances in electronics since the 1970s should eliminate some of these disadvantages. Improvements in control technology and the ability to mass produce smaller vehicles are two examples. Remaining disadvantages on appearance and routing are design-specific.

Routing is made easier and more accommodating due to the small cross-sectional areas of the PRT tubes as illustrated by a comparison of the PRT structure with the Bechtel concept (*12*) structure. The over-under arrangement of Figure 2 could be made even more accommodating by separating the bi-directional tubes when necessary for routing. Single-vehicle tubes of 6 ft in diameter could actually go through buildings. The low-pressure environment and maglev suspension reduce noise levels and make such routing practical. Tube walls could be designed similar to the enclosed walkways presently used to connect buildings over busy streets in cities. Routing at-grade and under highways would also help alleviate distasteful appearances. In addition, reduced pressures would allow smaller tubes to be used and these tubes would have greater routing flexibility. The use of maglev suspension would also reduce vehicle maintenance costs. All in all, the combination of PRT with maglev is a good match.

A common concern with maglev for intracity transit is the high magnetic drag at low velocities for EDS suspension. This problem could be addressed by using control technologies that provide nonstop service to minimize low velocity travel and by incorporating magnets in rails at station locations. Nonstop service would also allow higher velocities to be effectively used and would improve system performance. Cruising velocities greater than 100 mph (161 km/hr) would be practical in many cities due to (*a*) greater acceleration, (*b*) nonstop service, and (*c*) transit corridors of reduced pressure.

Finally, a PRT maglev operating in tubes of reduced pressure would be practical for intracity and intercity service with the same system. PRT systems may not have been considered for routine intercity service previously; however, reduced aerodynamic losses in low-pressure tubes, and the dynamic formation of trains would

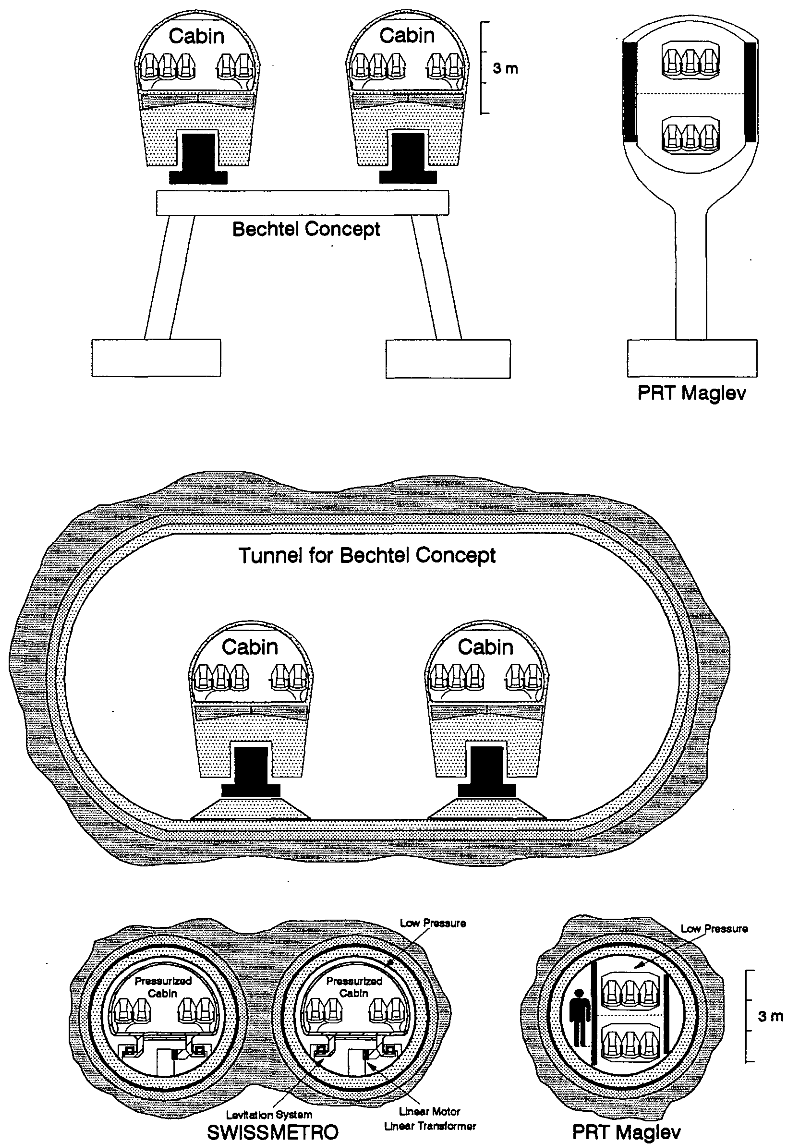

FIGURE 2 Comparison of elevated (*top*), underground (*middle*), and passageway (*bottom*) guideways.

alleviate the disadvantages for this application. Intercity transit is perhaps the best application of PRT, since it is during intercity transit that passengers spend hours awaiting the departure of jets or making connections. Proposed intercity service of SWISSMETRO (*18,19*) would have transit times of 12 min between cities, innately eliminating advantages of larger train-size vehicles.

Figure 2 compares the guideway of a PRT maglev to that of SWISSMETRO and the Bechtel concept. For the PRT maglev, vehicular suspension structures are located in front of and behind the passenger cabin. A cost comparison is given in Table 1 (*20*).

TRANSIT IN TUNNELS AND AT REDUCED PRESSURES

Goddard (*21,22*) first proposed transit (non-maglev) in evacuated tubes; however, it was not until the 1973 RAND study (*23*) detailed the synergism of maglev and low-air resistance that high-speed transit in evacuated tunnels became feasible. Development of these concepts continue with NASA's New Millenniums Concept (J. Rather, NASA Headquarters) and with SWISSMETRO (*18,19,24*). Modifications to the base concept include using gravity to store energy (*25,26*) and extending the concept to PRT (*27,20*). The extension to PRT service can actually have a greater impact on transit time than higher velocities.

The 1973 RAND study laid the course for maglev transit in evacuated tubes and identified all-encompassing technologies that were available in 1973. It also identified the greatest hurdle to implementation: tunneling technology, or rather, tunneling costs.

Suppes (*20,27*) addressed these tunneling costs by identifying methods for reducing tunnel diameters, reducing the number of necessary tunnels, and allowing above-ground tubes. Both reduced tunneling costs and at-grade routing were made possible by using smaller vehicles that could travel in smaller tubes. Figures 2 and 3 illustrate the vehicle and tube sizes for the PRT maglev. As shown in Table 1, these PRT tubes would actually cost less than high-speed train routes.

SWISSMETRO uses two tunnels connecting the stations (see Figure 2), and the tunneling costs represent about 75 percent of the capital costs. The PRT maglev could offer bi-directional service in one tunnel (see Figure 2). Eliminating one tunnel would reduce the SWISSMETRO cost by about 37.5 percent.

Initially proposed tunnel pressures for SWISSMETRO and the PRT maglev are similar to those surrounding supersonic aircraft at cruising altitudes. As on aircraft, the passenger compartments would be pressurized to maintain passenger comfort. By using pressures ranging from about 0.01 to 0.1 atm, SWISSMETRO would use smaller-diameter tunnels to reduce capital costs while simultaneously reducing the energy consumed by the trains. Key advantages of SWISSMETRO to the Swiss public are reduced energy consumption and reduced environmental impacts due to smaller tunnels.

For many commuters, the concept of travel in low-pressure environments is distressing; however, low-pressure travel environments are routinely used by commercial aircraft. While the human body is accustomed to pressure of 1 atm (101 kPa) on the earth's surface, at typical passenger jet cruising altitude of 30,000 to 40,000 ft (9000 to 12000 m), the pressure ranges from 0.30 to 0.20 atm (30 to 20 kPa). In aircraft, scoops and compressors gather air to maintain pressure in the passenger cabin. Similar methods would be used for SWISSMETRO and the PRT maglev. It would be prudent to design initial PRT maglevs to operate at the lower pressures (0.2 atm) presently used by commercial aircraft to minimize initial development needs. Optimal pressures for low-pressure applications would depend on travel velocity and would vary from approximately 0.2 atm (20 kPa) to approximately 0.001 atm (0.1 kPa).

ENERGY CONSUMPTION

Aerodynamic Drag

The upper curve of Figure 4 estimates (but does not account for transonic and supersonic variations in drag) a constant aerodynamic drag and shows how pressure can be reduced to compensate for otherwise increased drag at higher velocities. Optimal pressures depend on many factors, including the dynamic use of train units, and the use of aerodynamic designs, tube diameters, and technology on propulsion systems. The walls of the tube would increase drag, and for purposes of this study the walls are assumed to double the

TABLE 1 Cost Estimate Summary of Average Maglev Train System to PRT Maglev System

	Bechtel System Reduced 1 Cost ($ million/mile)	PRT A Maglev ($ million/mile)
Structure Only	7.7	3.4
System Guidance	0.9	0.9
System Propulsion & Levitation	4.5	2.25
Guideway Electrification	-- Provided by Utility Companies	
System Guidance, Command, & Control	1.1	1.1
Stations & Parking	1.0	0.5
System Evacuation Facilities		0.5
Vehicles (5000 PRT cars) (6 passengers per car)	2.7	1.35
Total of Above	**17.9**	**10.0**
Annual Energy Consumption ($0.08/kWh, 10 million roundtrips)	0.85	.38

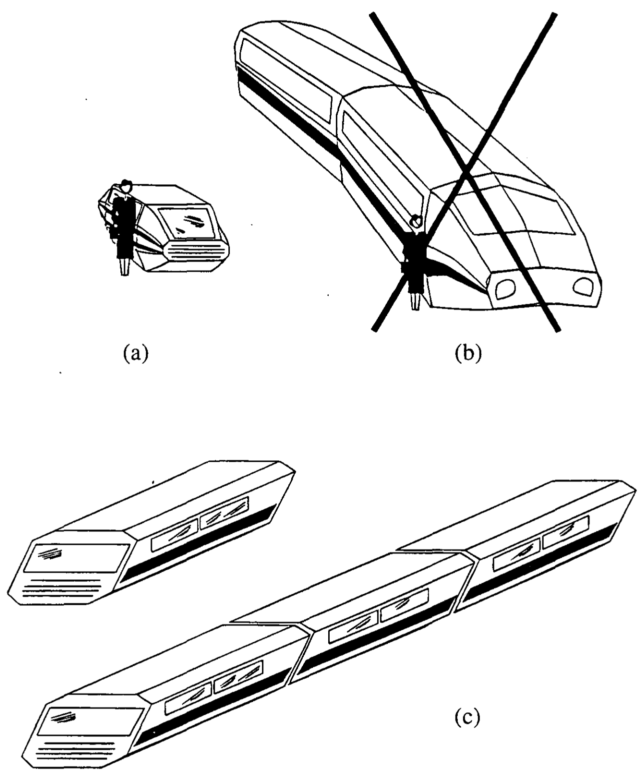

FIGURE 3 Schematic view of PRT maglev (*a*) next to maglev train (*b*); alternative PRT maglev design (*c*) is streamlined as connected train unit.

aerodynamic drag. To streamline the PRT maglev trains, the lower vehicle design of Figure 3 would be preferred.

To calculate the drag (R_a) of a train of length L and perimeter P_c, A. I. Totten (*28*) has proposed Equation 1:

$$R_a = [0.0020\, P_c \left(\frac{L}{100}\right)^{0.8} + K]\, v_x^2 \qquad (1)$$

Equation 1 accounts for formation of train units. Wall effects were incorporated into Equation 1 by multiplying R_a by a factor of 2. Air density is taken into account by multiplying by a further factor equal to the tunnel pressure in atmospheres pressure.

To minimize systematic errors, calculations using Equation 1 were made relative to the Bechtel concept. The perimeter of a train is assumed to be approximately 2.7 times greater than that of the PRT maglev, and the length of the PRT maglev train is a factor of two greater due to only having three passengers seated across rather than six (although only five are pictured, the Bechtel concept proposes six seats across) as with the Bechtel concept. Another 50 percent increase in length is added to accommodate improved comfort and PRT vehicle constraints. In total, a PRT maglev train would have an average length approximately three times greater than a train accommodating the same number of passengers.

On the basis of this analysis summarized in Table 2, at 300 mph (482 km/hr) and 0.2 atm (20 kPa) of pressure, the PRT maglev would have 63 percent less aerodynamic drag than a 300-mph (482-km/hr) train operated at atmospheric pressure. Using similar calculations at 500 mph (805) and 0.05 atm (5 kPa), the PRT maglev would consume 75 percent less energy than the train to overcome aerodynamic drag. To reduce greenhouse gas emissions, combinations of low pressure and velocity could be used to reduce energy consumption to 50 percent, 20 percent, 10 percent, . . . of the energy consumed by the best available alternatives.

Magnetic Drag

For electrodynamic suspension, magnetic drag losses are proportional to the weight of the vehicle and are inversely proportional to travel velocity. The generally accepted form of the drag equation is given by Equations 2 and 3 for high velocities.

$$F_y \propto \frac{n\, I^2}{h} \qquad (2)$$

$$F_x \propto \frac{-1}{\sigma\, t\, v_x}\; F_y \propto \frac{-n\, I^2}{\sigma\, t\, h\, v_x} \qquad (3)$$

where

F_y = vehicle weight,
n = total number of coils in magnets,
I = current in each coil,
h = height of levitation,
t = thickness of conductive track, and
σ = conductivity of track.

For the Bechtel 64 Mg maglev train traveling at a velocity of 300 mph (483 km/hr), the magnetic drag energy consumption is estimated at 0.64 MW, while the aerodynamic drag energy consumption is estimated at 5.4 MW. Aerodynamic drag dominates the energy consumption for both the Bechtel concept and the present

TABLE 2 Factors Used To Compare Aerodynamic Drag of PRT Maglev to Bechtel Concept

	PRT A Relative to Train	PRT C Relative to Train
Pressure (atm)	0.2	0.05
Perimeter	1:2.7	1:2.7
Length (m)	$3^{0.8}$	$3^{0.8}$
Wall Effects	2	2
Velocity	$(300/300)^2$	$(500/300)^2$
% PRT Aerodynamic Drag Relative to Bechtel Concept	**37%**	**25%**

PRT maglev concept operating at 0.2 atm (20 kPa). At 500 mph (805 km/hr) and approximately 0.03 atm (3 kPa), magnetic and aerodynamic drag would be approximately equal, and at less than 500 mph (805 km/hr) and 0.01 atm (1 kPa) the presence of magnetic drag significantly diminishes advantages of lower tube pressures.

Analysis such as this can be used to define feasible pressure versus velocity profiles such as that shaded in Figure 4. Figure 4 is specific to the PRT maglev. Larger vehicles, lower magnetic drags, and different vehicle-tube clearances would change the window of opportunity.

System Evacuation

Comparison with Train Systems

Energy consumption for tube evacuation would originate from three needs (*a*) periodic "total" tube evacuation, (*b*) evacuation associated with vehicle/passenger entry and departure, and (*c*) air leaks of the tube system. Of these, further information is needed to evaluate the impact of air leaks. In practice the cost of leaks would justify use and development of advanced leak detection methods and coatings, which would bring leaks under control.

The cost of total tube evacuation would be incurred periodically when the tube is exposed to atmospheric pressure for maintenance or for emergency procedures (e.g., emergency evacuation by flooding the tubes with air and having passengers walk to a tube exit). Standard adiabatic compression calculations were used to estimate the compression energy. Compression was modeled as a dynamic process with tube pressure decreasing as evacuation progressed.

For four tube evacuations per year, a compression efficiency of 80 percent, and a tube length of 800 km, 3.6, 5.6, 8.4, and 9.2 million MJ are required to remove 16 Gg of air and produce a pressure of 0.2, 0.1, 0.01, and 0.001 atm, respectively. As listed in Table 3, this translates to 360 to 920 J per passenger mile or < \$0.00002 per passenger mile. A similar calculation for the evacuation of the volume of a vehicle exterior for entry of a vehicle into the tube equates to < \$0.0001 per passenger mile.

While periodic tube evacuations and vehicle entries have evacuation costs that level out at lower pressures, compression costs associated with continuous removal of air (from leaks) increase rapidly with lower internal pressures. At pressures less than 0.02 atm (2 kPa), these compression costs could become significant. Insufficient data are available to make estimates on these costs.

Comparison with Air Travel

In addition to comparing evacuation costs of the PRT maglev to train system costs, these evacuation costs should also be compared to corresponding costs for air travel. For air travel, energy is expended to overcome earth's gravity to achieve higher altitudes where lower pressures are available. At a mass of 500 kg/seat and a cruising altitude of 12,200 m (40,000 ft), 59.8 MJ of energy are consumed in overcoming gravitational forces. This compares with approximately 2.5 MJ of evacuation energy per passenger. Considering other factors such as energy for aircraft takeoff and the initial and final travel at atmospheric pressure by the aircraft, more than 40 times more energy is consumed to transport a passenger to low pressures by an aircraft than would be needed to maintain or enter low pressures in PRT maglev tubes on the earth's surface.

DISCUSSION OF RESULTS

System Costs

The cost estimates of Table 1 include both capital and energy consumption costs. A basis of 10 million round trips per year (3,500 passengers per hour per direction for 8 hr a day for 365 days in a year) was used to allow capital and energy consumption costs to be compared.

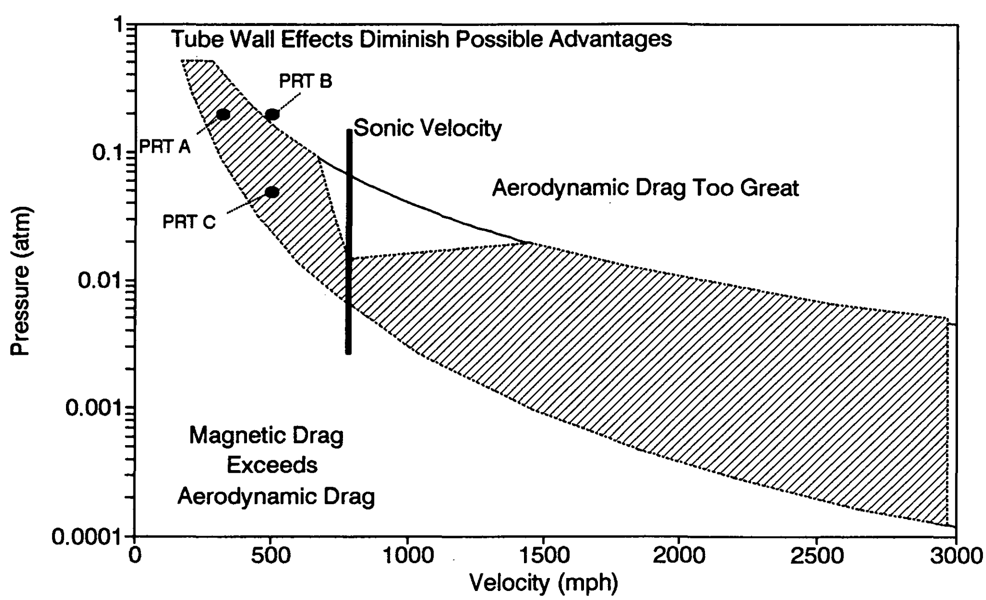

FIGURE 4 Feasible combinations of pressure and velocity for PRT maglev, which would offer reduced aerodynamic drag. On bottom line of region magnetic drag is equal to aerodynamic drag.

TABLE 3 Comparative Energy Consumption of Various Travel Modes

	Weight (kg/seat)	Cruise Velocity (km/hr)	Energy Consumed (Wh/Seat km)	Energy & Capital (¢/mile)
PRT Maglev	533	483	88	**5.900**
Aerodynamic Drag				1.400
Magnetic Drag				0.470
Periodic Evacuation				0.012
8% Capital Interest				4.000
Bechtel Concept	533	483	198	**11.410**
Aerodynamic Drag				3.780
Magnetic Drag				0.470
8% Capital Interest				7.160
Automobile[1]	300	90	105	
DC-9[1]	467	909	656	
B-757[1]	509	852	352	
TGV[1]	900	260	35.4	
EDS Maglev Train[1]	215	450	93.2	
PRT Maglev (0.2 atm)	533	805	198	
PRT Maglev (0.05 atm)	533	805	66	

Note: [1]**Sinha, 1987. Energy sources include gasoline for the automobile, kerosene for aircraft, and electrical for others. Comparative energy consumption of various travel modes.**

Energy consumption is based on Bechtel's (*12*) one-way trip energy consumption of 19,000 kW·h for a 497-mi (800-km) trip. (The 19,000 kW·h is from Table A-3 of Reference 12 and is based on the total trip and not just cruising velocities.) At 60 percent occupancy, 120 seats per vehicle, and $0.08 per kW·h, the electrical energy costs $42.2 per passenger round trip or $0.85 million per year per mile of bi-directional track. As shown in Table 2, the 0.2-atm 300-mph PRT maglev has about 37 percent of the aerodynamic drag of Bechtel's concept, or about $0.38 million/year per mile of bi-directional track with similar magnetic drags. These costs, as well as vacuum and magnetic drag costs, are also summarized in Table 3.

Capital costs are based on a direct comparison to Bechtel's reduced first cost estimate (*12*), which uses a higher cost for electrical power ($0.08 per kW·h versus $0.055) with the advantage that local electrical companies would construct and manage guideway electrification facilities. Cost savings in the PRT maglev capital reside in (*a*) reduced structure costs, (*b*) reduced propulsion costs, (*c*) reduced costs for stations and parking, and (*d*) reduced vehicle costs.

A 40 percent reduction in structure costs is based on a less expensive combined structure illustrated in Figure 2. A further 25 percent reduction (*12*) is based on at-grade construction, which is feasible due to a smaller cross section of the PRT maglev route.

Reduced propulsion system costs are claimed due to a 55 percent reduction in the combined aerodynamic and magnet drag of the PRT maglev, as well as the use of a train unit, which is three times longer for the PRT maglev. In total, the cruising propulsion requirements of the PRT maglev are only 15 percent of those of Bechtel's concept on a thrust per length of guideway basis.

Reduced station costs are associated with the smaller size of stations and incorporation with local metro service. Reduced vehicle costs are based on reaction injection molding production methods and shorter transit times, leading to a need for fewer seats.

In a final comparison of costs and energy consumption, Table 3 compares the present calculations to those calculated in the analysis of a Canadian maglev system (*1*) as well as to the Bechtel concept. The largest expense with maglev trains is the interest on capital, the second largest expense is for electrical power. Costs to produce a tube pressure of 0.2 atm are negligible. A cost estimate including interest and energy costs amounts to a mere $0.059/mi of travel.

The advantages of train systems over aircraft can be readily seen. The savings in energy between the 300-mph, 0.2-atm PRT maglev (483 km/hr, 20 kPa) and a B757 translate to about 264 W·h per seat per kilometer or about $0.013 per mi of track at an energy cost of $0.03/kW·h.

Comparison of Performance with Air Travel

An initial PRT maglev system operating at 300 mph and 0.2 atm (483 km/hr and 20 kPa) would be faster and more convenient than any other land-based transportation system; however, air travel would have advantages at greater distances. To calculate the point at which air travel would have reduced transit times compared to the

PRT maglev, certain assumptions must be made on the transit to airports, wait before departure, layovers, and wait after arrival. Table 4 lists the assumptions used for a comparative analysis. The source of the data includes published sources (*29*), airlines (recommendations on when to arrive at airport before departure), and personal experience.

The only difference between the two air transit scenarios is that Air 1 is a direct flight and Air 2 includes a layover. The main difference between the PRT maglev scenarios is that PRT A operates at a maximum velocity of 300 mph (483 km/hr) and PRT B operates at a maximum velocity of 500 mph (805 km/hr). Both PRT maglev systems assume access from several locations within both cities and therefore have the average 10-min transit time to the station.

As illustrated in Table 4, a PRT maglev with a maximum velocity of 300 mph (483 km/hr) would have shorter transit times than air travel at distances less than 907 mi (1,460 km). With a maximum travel velocity of 450 mph (724 km/hr), the PRT maglev would have shorter travel times for all travel within the continental United States. Based on these results, initial PRT maglev systems having a maximum travel velocity of 300 mph would be the most efficient means of transportation for destinations up to 907 mi distant. A later increase in velocity to 500 mph led to service better than any alternative in the continental United States.

Transportation Network

The PRT maglev system could become a transportation network similar to the present highway system based on the interstate highway network. Local metro PRT maglev tubes would be connected to interstate tubes, and each section would have a speed limit (speed set-point) for normal operation. Propulsion power would be supplied by linear motors along the tracks. Auxiliary propulsion from the vehicle would allow deviation from the speed set-point to allow the dynamic formation of trains to accommodate entering and exiting traffic. As high-temperature superconductivity becomes reality, electric-powered cars could be manufactured with magnetic suspension systems located within the four quarter-panels and, similar to high-occupancy vehicle (HOV) lanes, wheeled vehicles could literally drive onto and into a maglev transit corridor where automated maglev suspension would take over for much of the trip.

Local metro service could provide much-needed pollution-free service to cities. For cities, typical maximum upper speed set-points would initially be approximately 100 mph (161 km/hr). Depending on the distance of travel, service could be in low-pressure tubes or open to the atmosphere. The interstate network would be connected to local metro lines, and for the interstate network initial upper speed set-points would be approximately 300 mph (483 km/hr) with later speed set-points up to 3,000 mph (4,830 km/hr).

The network of local, intercity, and even transcontinental routes would provide PRT service from a location close to travel origination to a location close to the final destination. The low-pressure environments would make very fast travel possible and minimize environmental impacts. PRT operation would be similar to an elevator's, in which reservations are not necessary and railway stations are equipped with elevator entrances at multiple locations within cities. The high energy efficiency, low maintenance (due to very few moving parts and isolation from environment), and comparatively low capital costs make PRT maglevs cheaper than other modes of transportation. Reliance on electrical power allows ecological impact and cost to be reduced as new technology improves electrical power generation.

Areas for Advancement

The PRT maglev concept is new, and as such, is subject to improvements.

One important area already emphasized is operation at reduced pressures. It would be advantageous to operate initial systems at 0.2 atm (20 kPa) since this is an established standard for commercial aircraft, the equipment is available, and the public has already accepted transit with vehicle exteriors at these pressures. Advancing to travel at increasingly low pressures leads to increased velocities, reduced energy consumption, and reduced travel times.

Improved tunneling, structures, and routing methods could reduce costs by reducing the guideway structural costs. Much could be gained from additional research and development on this subject.

Additional advantages could be realized by reducing the vehicle weight. Weight reductions should be able to match the specific weights for an automobile (300 kg/seat). Reduced vehicle weight leads to reduced forces on guideways and reduced magnetic drag.

Another improvement would be to incorporate superconducting rails for repulsive levitation. The National Maglev Initiative (NMI) study (*12*) lists magnetic drag as ranging from 6 to 40 kW/ton for conventional conductors. Superconducting rails would reduce these values manyfold and allow lower pressures to be used to reduce energy consumption costs to approximately $1 for a 1600-km round

TABLE 4 Comparison of Air and PRT Maglev Transit

Assumptions	Air 1	Air 1	PRT A	PRT B
Transit to Port (min)	30	30	10	10
Parking to Takeoff (min)	45	45	10	10
Average Transit Velocity (mph)	440	440	250	400
Cruise Velocity (mph)	560	560	300	500
Layover (min)	0	50	0	0
Baggage Claim (min)	15	15	1	1
Time to Parked Vehicle	10	10	5	5
Transit to Destination (min)	30	30	10	10
Total Transit Times for Distances of:				
907 miles	254	304	254	172
1,389 miles	319	369	369	244
6,893 miles	1070	1120	1690	1070
10,560 miles	1570	1620	2570	1620

trip. Such advances would make parcel service (*30*) of all sized packages feasible with maglev. Automated transit during off-hours could ship such freight with minimal increased capital and significantly increased profits. Without superconducting rails, freight could be shipped at costs of approximately $0.000023/kg/mi during off-peak hours (11:00 p.m. to 6:00 a.m.) at lower velocities of approximately 200 mph.

CONCLUSIONS

Compared to 300-mph (483-km/hr) maglev trains, a 300-mph, 0.2-atm (20-kPa) PRT maglev would require approximately 56 percent of the infrastructure cost at $10 million per mi compared to $17.9 million per mile of bidirectional guideway. The energy requirements of the 300-mph maglev would be approximately 45 percent of that corresponding to a train system. Such a 300-mph, 0.2-atm PRT maglev would operate at low pressures typically encountered by commercial aircraft, and no new developments or breakthroughs would be needed for maintaining cabin pressure.

A similar PRT maglev system at 500 mph (805 km/hr) would offer a 25 percent reduction in travel time due to higher velocities and even further time reductions due to PRT service. However, a 500-mph, 0.2-atm PRT maglev would consume a similar amount of energy as the 300-mph Bechtel concept and would have similar system costs. An option for alleviating the higher costs at 500 mph is to reduce internal tube pressures to between 0.03 atm and 0.1 atm (3 to 10 kPa). Increasing velocities to 500 mph and decreasing pressures to 0.05 atm could be performed as evolutions to an initial system operated at 300 mph and 0.2 atm.

The proposed PRT maglev is similar to SWISSMETRO, which is being developed in Europe; however, the PRT maglev would require 37.5 percent less capital in the form of tunneling costs. In addition, many U.S. routes would have preferred routing at-grade instead of in underground tunnels. At-grade routing would reduce costs but may limit travel velocities. For the present study, acceleration and comfort considerations were defaulted to be those used by the NMI studies (*12*).

Based on the results of this preliminary study, a PRT maglev designed with a cruising velocity of 300 mph in tubes at 0.2 atm would be faster than present alternatives up to distances of 907 mi (1,460 km). In addition, the energy needed to maintain the tube vacuum is at least 40 times less than the energy needed to attain altitudes of similar low pressure. The PRT maglev would evolve such that lower tube pressures and increased velocities would allow it to shorten travel times for all travel routes viable with surface routing. A mature system would feature velocities up to 3,000 mph (4,830 km/hr) and connections between Asia and America.

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Publication of this paper sponsored by Committee on New Transportation Systems and Technology.