Presented to the
High Speed Ground Transportation Association
1999 Annual Conference
Seattle, June 6-9, 1999

MAGLIFT MONORAIL

A High-Performance, Low-Cost, and Low-Risk Solution for High-Speed Ground Transportation

Tom Hopkins
Transport Ventures

Julio Pinto Silva
Eurotren Monoviga, S. A.

Barry Marder, Bob Turman, and Bruce Kelley
Sandia National Laboratories

Abstract

In the 1990s, significant experience has been gained with high-speed passenger rail technologies. On the one hand, high speed versions of conventional-configuration trains, such as the French TGV, have proven themselves in service; on the other hand, magnetic levitation (maglev) trains such as the German Transrapid, which some expected to supplant conventional trains in some high speed applications, have not yet proven themselves and face a problematic future. This is because of maglev's high capital cost, the magnetic drag which it introduces, and the high development risks associated with this complex technology. This paper examines a new form of high-speed train expected to be capable of speeds of 300 mph, the Maglift Monorail. The Maglift Monorail was developed by simplifying and improving two well-understood technologies – wheelsets and LIMs – and then integrating them. The solution is a vehicle with flangeless wheels mounted in two axes, powered by a high-efficiency and light-weight LIM, positioned to give magnetic lift (maglift), i.e., electromagnetic force in the vertical direction which reduces the vehicle weight on the suspension, and thereby reduces static and rolling drag. Maglift can be considered a form of maglev as it uses the same electromagnetic forces to lift and propel the vehicle. This solution is presented in a Spanish-designed monorail system which has a unique suspension designed to minimize friction while giving great stability and turning capability. This monorail vehicle is propelled by the Seraphim motor (SEgmented RAil PHased Induction Motor) which virtually eliminates magnetic drag and provides significant maglift. The Maglift Monorail achieves lower operating costs and a greater overall reduction in drag than conventional noncontact maglev does, and it does so without incurring maglev's high capital costs or its technology development risks.

Introduction

The early 21st century may be the era of high-speed trains which can effectively compete against automobiles and air travel between city-pairs which are 150 to 500 miles apart. High-speed trains have an advantage for city-pairs which are more than 150 miles apart but less than 500 miles apart:

- For city-pairs which are less than 150 miles apart, the convenience of an automobile gives that mode of travel a significant advantage and governments will naturally widen their highways to accommodate the relentless build up of automobile traffic until they run out of space or noise and air pollution becomes excessive. An unfortunate effect of widening highways has been urban sprawl as people live further and further away from a metropolis and then commute from ever greater distances.
- For travel between city-pairs which are more than 500 miles apart, the reduced travel time from flying at 600 mph in a jet aircraft more than justifies the extra time needed to get to a crowded airport and then wait until the aircraft is boarded and taxis to takeoff.

Intercity rapid transit systems which can travel at 250 to 300 mph are very competitive in the intermediate range, between city-pairs which are 150 to 500 miles apart. Because of the high air density at ground level, speeds above 300 mph are uneconomic because the aerodynamic drag becomes excessive and the extra power needed to overcome this drag is expensive.

There has been a hunt for an appropriate technology for this intermediate range market which demands a train which can operate at 250 to 300 mph. Problems for conventional heavy trains are rolling friction and the tendency to become unstable at high speeds. This rolling friction is mainly from three sources: friction in the wheelset bearings, contact friction between the wheels and the rails, and dry contact between the wheel flanges and the rails which occurs on curves. The tendency to hunt (a side to side dynamic instability) at high speeds is largely due to the aggressive interaction between the flanged wheels on fixed axles and the rails. Noncontact maglev was developed to allow trains to move at 250 to 300 mph by overcoming this rolling friction and tendency to instability at high speeds. Unfortunately, noncontact maglev introduces other problems – it introduces magnetic drag, it sometimes requires a broad vehicle which can increase aerodynamic drag, and it requires expensive levitation and cooling systems in the vehicle and active coils and systems along the guideway which make a noncontact maglev system expensive to build.

Simulation Analysis Approach

The spread-sheet based simulation program, *Performer*, was developed and used to compare the performance of three trains: a conventional-configuration heavy train typified by the French TGV, a noncontact maglev typified by the German Transrapid TR06 and TR07, and a new hybrid train described as the Maglift Monorail. *Performer* was developed to enable an analysis of the performance of different trains over routes which have tight turns and steep grades. It allows the input of the maximum acceleration and deceleration to which passengers can be subjected, the grade, speed restrictions (to ensure passenger comfort through tight curves), and the elevation at every 132' along a study section. It calculates the train's performance taking account of static, rolling, aerodynamic and magnetic drag, reductions in the static and rolling drag which result from maglift, and changes in aerodynamic drag resulting from changes in elevation. It outputs the thrust, drag, velocity, acceleration or deceleration, and the power draw at selected intervals down to 0.1 seconds. It then calculates the time between stations, average velocities, peak power draw, the total power draw, the total cost of the power, and the average power cost per passenger mile.

For the purpose of this study, a very simple test track was assumed – the trains were accelerated in still air along a flat, straight course at sea level until they reached a maximum speed of 250 mph which they then maintained until they had traveled a total of 25 miles (40 km). Performance during the steady state 250 mph phase was then analyzed.

Test Train Simulations

The simulated performance of three trains was compared in runs along a virtual test track: 1) a high-speed, heavy, conventional-configuration train represented by the French TGV, with increased power to enable it to run at 250 mph, 2) a noncontact maglev train represented by the Transrapid TR06 and TR07, and 3), an EMSA monorail vehicle propelled by a Seraphim linear induction motor configured to provide significant magnetic lift as well as propulsion (Maglift Monorail). The TGV illustrates the problem of rolling friction which conventional trains experience, the Transrapid illustrates the noncontact maglev solution, first developed nearly 30 years ago to overcome this rolling friction, and the Maglift Monorail illustrates the newest solution which overcomes most of the rolling friction and the additional problems which the noncontact maglev technology introduces, namely, magnetic drag, high capital and operating costs, and technological risk.

The trains used in the test had the following characteristics:

Table 1. Train Characteristics

		Train TGV	*Maglev TR07*	*Maglift Monorail*
Segments # (1)		10	4	20
Size	- Length m	200	100	128
	- Width m	2.79	3.7	3.2
	- Height m	3.78	4.06	3.55
Riders	- # (2)	384	360	400
	- Area/Rider m^2	1.086	1.016	1.024
Weight	- Unloaded mt	386	180	170
	- Wgt/Rider mt	1.005	0.500	0.425
	- Loaded mt	424.4	216	210
	- Distributed mt/m	2.12	2.16	1.64
Power	- Mech MW (3)	15.0	22.0	12.0
	- Mech/Rider kW	39.1	57.3	30.0
	- Efficiency (3)	75%	68%	80%
Drag(4)	- a (Static)	3.82	---	1.89
	- b (Rolling)	0.0390	---	0.0193
	- c (Aerodyn)	0.000504	0.000367	0.000339
	- Cd (5)	1.00	0.65	0.75
	- Magnetic	---	(6)	(6)

(1) The TGV consists of two power cars plus eight passenger cars. Both the TR07 and the Maglift Monorail have distributed power with each segment acting as both power and passenger car.

(2) The number of passengers is estimated, assuming that seating is to first class standard and there are no baggage holds, conference rooms, galleys or bars. The TGV has narrower vehicles and so probably could not be configured to hold 384 passengers with 2 plus 2 seating (too narrow) or 2 plus 1 seating (too little leg room). To accommodate 384 passengers, the TGV would have to be configured with a mix of its first class and coach seats

(3) Mechanical power is the actual power applied by the motor in accelerating and maintaining speed, assuming 100% efficiency. Inefficiencies are considered when the

electric power to be supplied to the train is calculated. When the 2 MW of energy lost in the feeders and windings along the TR07 guideway is included in its efficiency calculations, the TR07's overall efficiency drops from 82% to 68% (Ref. 1). 0.90 was used for the power factor for the TGV and TR07. The efficiency of 80% used for the Seraphim motor in the Maglift Monorail includes the power factor and electrical conversion together since measurements were done with discrete pulses rather than AC.

(4) The drag is calculated using the formula $D=a+bV+cV^2$ where the first term is the static drag, the second is the rolling drag, and the third is the aerodynamic drag.

(5) The aerodynamic drag coefficient, Cd, is as used in the formula for aerodynamic drag, $Da=(1/2pV^2)CdAs$ where p is the air density, V is the air speed, and As is a reference area.

(6) The magnetic drag is the Foucault or eddy current effect experienced in the guideway feeders and windings with the EMS (electromagnetic suspension) technology used in the TR07. For the two-car TR06 this has a value of 11.25 kN at 400 km/hr (Ref. 2); for the four-car TR07 this has a value of 13.56 kN at 400 km/hr (Ref. 3). The Seraphim linear motor used in the monorail does not generate an appreciable amount of magnetic drag as it uses shorted coils for the reaction rail where power can be switched off when the interaction with eddy currents would otherwise produce drag losses.

French TGV

There are several high-speed, heavy trains with a conventional configuration which are commercially available. The French TGV is in revenue service in France and neighboring countries, the German InterCity Express (ICE) is in service in Germany, and the Japanese Shinkansen is in service in Japan. For the purpose of this study, the TGV was used to represent trains with a conventional configuration.

TGV

The TGV was tested at 320 mph (515 km/hr) on a straight track as a part of a demonstration test. In service it operates at speeds up to 186 mph (300 km/hr). Over the course of an actual trip, it achieves such speeds only occasionally and its average speed is significantly lower. For the purpose of this study, sufficient power is assumed for the TGV to reach a steady state speed of 250 mph (402 km/hr), enabling a comparison with the noncontact maglev and maglift trains which are designed to operate at such speeds and higher. In actual practice, it is doubtful if a conventional-configuration train could ever operate at such high speeds due to safety and instability concerns and limitations on the power which can be transmitted by traction through the drive wheels.

A ten-car train (two power cars and eight passenger cars) weighing 424.4 metric tons was modeled in the simulation. Drag was calculated using the formula: $Drag=a+bV+cV^2$. Using Skojvist's data (Ref. 4) for the TGV, a (the static drag constant) is set at 3.82, b (the rolling drag constant) is set at 0.0390, and c (the aerodynamic drag constant) is set at 0.000504 (Ref. 5). As the train accelerates, static drag stays constant, rolling drag increases steadily with speed, and aerodynamic drag increases exponentially (with velocity squared). At a steady speed of 250 mph (402 km/hr), the drag totals 100.6 kN (22,623 lbf) made up of: static drag 3.8 kN (859 lbf), rolling drag 15.7 kN (3,519 lbf), and aerodynamic drag 81.1 kN (18,245 lbf).

At 250 mph (402 km/hr), the aerodynamic drag swamps the static and rolling drag, accounting for 80.6% of the total - static and rolling drag are just 19.6% of the total. A conventional-configuration train like the TGV develops significant drag due to its exposed wheel sets, and pantograph arms which pick up power from the overhead catenary.

An important consideration for the transit system operator, is the electric power necessary to overcome the drag. In order to analyze the relative importance of the different sources of drag, and in order to make the different size trains comparable, the drag per passenger and the power cost per 1,000 passenger miles at a steady 250 mph was calculated (energy intensity). With 384 passengers in the TGV test train, the total drag per passenger is 262 N. Assuming that electric power costs $0.05 per kilowatt hour, the total power cost for the conventional train is $8.67 per 1,000 passenger miles, per Table 2:

Table 2. TGV Drag per Passenger & Power Cost per 1,000 Passenger Miles

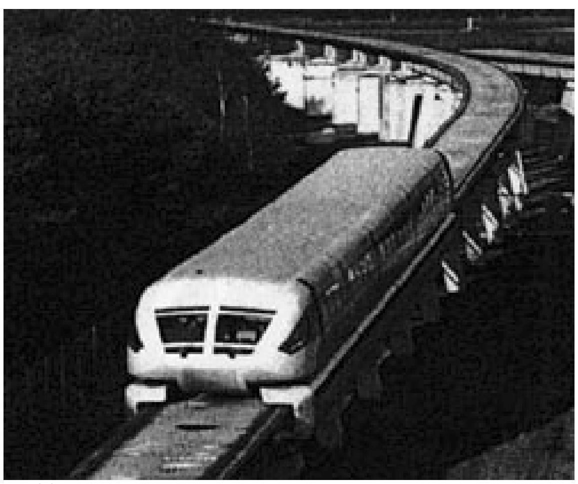
Source	*Drag*	*Cost*	*Percent*
Static	9.9 N	$0.33	3.8%
Rolling	40.8 N	1.34	15.6%
Aerodyn.	211.3 N	7.00	80.6%
Total	262.0 N	$8.67	100%

In assessing the total power cost of a trip, the additional power needed to accelerate the vehicle and then brake it would need to be added.

Conventional Noncontact Maglev

The Germans, Japanese, and more recently, the Americans, have worked to develop noncontact maglev vehicles which would reduce the drag. The idea was to eliminate the static and rolling drag by levitating the vehicles to the point that they lose contact with the guideway. The German Transrapid TR06 and TR07 are used as the representative of noncontact maglev systems.

.



TR06

The Transrapid noncontact maglev was tested at 280 mph (450 km/hr) on a test track as a part of demonstration tests. It has not yet been put into revenue service although it is expected to enter service by 2005 when the 185 mile (298 km) guideway from Hamburg to Berlin is scheduled for completion. It is expected to operate at speeds up to 300 mph (approximately 500 km/hr).

A two-car Transrapid noncontact maglev TR06 weighing 108 metric tons was modeled in the simulation. The TR06 was 20.2% larger in cross-sectional area than the TGV, and was 50 m (164') long. It did not have a pantograph for power pickup, and did not have wheelsets which cause turbulence, resulting in a Cd (drag coefficient) of 0.56 (Ref. 6) and an aerodynamic constant, c, of 0.000313. Aerodynamic drag was calculated using the formula: $Da=cV^2$. At a steady 250 mph (402 km/hr), the drag totaled 61.7 kN (13,865 lbf) made up of: magnetic drag 11.2 kN (2,525 lbf), and aerodynamic drag 50.4 kN (11,340 lbf).

The drag per passenger and the power cost per 1,000 passenger miles at a steady speed of 250 mph was calculated, assuming again that electric power costs $0.05 per kilowatt hour. With 180 passengers, the total drag per passenger with the TR06 is 342.6 N, and the total power cost rises to $11.61 per 1,000 passenger miles, per Table 3:

Table 3. Maglev TR06 Drag per Passenger & Power Cost per 1,000 Passenger Miles

Source	*Drag*	*Cost*	*Percent*
Magnetic	62.4 N	$2.11	18.2%
Aerodyn.	280.2 N	9.50	81.8%
Total	342.6 N	$11.61	100%

At a steady 250 mph (402 km/hr), the magnetic drag per passenger generated by the EMS noncontact maglev guidance and propulsion technology (62.4 N and costing $2.11 per 1,000 passenger miles) exceeds the static plus rolling drag in the conventional-configuration train (50.7 N and costing $1.67 per 1,000 passenger miles). Ironically, noncontact maglev and the resultant magnetic drag were introduced to eliminate the static and rolling drag in a conventional-configuration train.

Considering just the aerodynamic drag per passenger at a steady 250 mph, the TR06 generates higher drag per passenger (280.2 N) than the conventional-configuration TGV (211.3 N). Thus the power cost of overcoming aerodynamic drag on the TR06, $9.50 per 1,000 passenger miles, is also greater than the cost with the TGV, $7.00. However, this is partly because the TR06 has a smaller passenger capacity; a fair comparison would require trains of comparable capacity.

The TR06 was reported to have a Cd of 0.56 which is high for a train 50 m in length. An aerodynamically-efficient train without a pantograph could achieve a drag coefficient, Cd=0.3+0.0035*L where L is the train length in meters. For a 50 m train, this suggests that the Cd could be reduced to a low of 0.47. For a four-car, 100 m long, Transrapid train which is redesigned to be aerodynamically efficient, Cd would equal 0.65. Transrapid redesigned the TR06 as the TR07, making it more streamlined, and rearranging the magnets to reduce the magnetic drag.

TR07

Using a four-car TR07 for the test, and assuming that Transrapid achieved a Cd of 0.65, the drag at a steady 250 mph (402 km/hr), totals 72.8 kN (16,365 lbf) made up of: magnetic drag 13.5 kN (3,044 lbf), and aerodynamic drag 59.2 N (13,321 lbf). With the greatly reduced aerodynamic drag, the drag per passenger and the power cost per 1,000 passenger miles at a steady 250 mph fall to 202.2 N per passenger and $7.36 per 1,000 passenger miles respectively, per Table 4:

Table 4. Maglev TR07 Drag per Passenger & Power Cost per 1,000 Passenger Miles

Source	*Drag*	*Cost*	*Percent*
Magnetic	37.7 N	$1.37	18.6%
Aerodyn.	164.5 N	5.99	81.4%
Total	202.2 N	$7.36	100%

The magnetic drag per passenger generated by the TR07 (37.7 N and costing $1.37 per 1,000 passenger miles) is now less than the static plus rolling drag in the conventional-configuration train (50.7 N and costing $1.67 per 1,000 passenger miles). And the cost of power per 1,000 passenger miles at a steady 250 mph for the TR07, $7.36, is now less than the cost for the conventional-configuration TGV at $8.67.

Another form of noncontact maglev is that based on the EDS technology, as used by the Japanese and some aspiring American manufacturers. This approach also suffers from magnetic drag, but caused by the Joule effect. Even with a high-efficiency, "null flux" system that employs superconducting magnets, the magnetic drag is significant, about the same as for the EMS system used in the TR07. The Government Maglev System Assessment Team (Ref. 7) analyzed several new US maglev concepts and estimated that the two most efficient concepts would use 18% less power per person than the TR07 at steady cruising speeds. If this proves out, it would result in an electric power cost of approximately $6.04 per 1,000 people miles in our evaluation. Before these new concepts can be deployed, several technical challenges must be addressed, including:

- the development of techniques to prevent superconducting magnets from suddenly losing their magnetism, causing the vehicles to fall to the guideway (Ref. 8),
- the development of reliable on-board cryogenic chillers,
- a demonstration of the long term durability of the FRP (fiber reinforced plastic) prestress cables and reinforcing bars in the guideway beams, necessary because of the superconducting magnets, and
- the development of high-speed control systems for the integrated maglev vehicle-guideway system which allow simultaneous operation and control of trainsets that are accelerating, cruising, and decelerating on different sections of the same guideway at the same time.

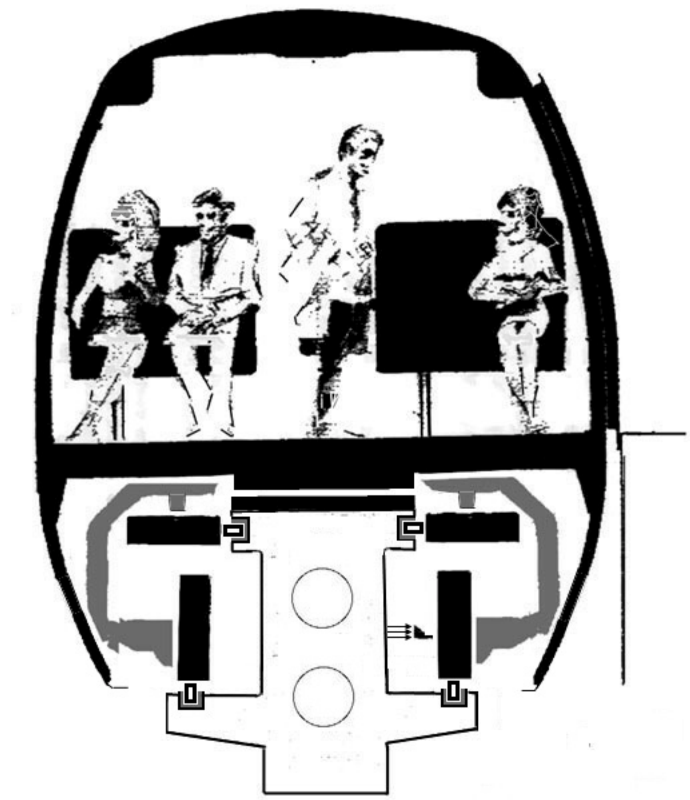
Maglift Monorail

A new monorail system is being developed by combining the EMSA vehicle and guideway design with a Seraphim linear induction motor. This combination generates a greater reduction in overall drag than noncontact maglev does, and it does so without incurring maglev's high costs or technological risks. Mounting the Seraphim motor horizontally on top of the guideway generates magnetic lift, because the motor generates a vertical lifting force as well as a horizontal propulsion force. This force could be sufficient to lift the vehicle off the guideway if not properly controlled, but since the goal is to optimize performance, the actual amount of "unweighting" depends on how the motor is optimized for operation. Like conventional noncontact maglev, maglift uses electromagnetic forces to lift the vehicle and propel it forward, so can be considered a form of maglev. However, maglift accomplishes this without superconducting or electro-magnets, magnetic drag, cryogenic cooling systems, active coils in the guideway that require careful alignment and maintenance, or complex control systems required to control both levitation and propulsion simultaneously.

The EMSA monorail was developed in Spain in the late 1980s where it was run extensively on a test track outside Seville. It is a "monorail" in that it runs along a single, elevated, guideway beam and the vehicles are significantly wider than the beam, the definition used by the Monorail Society (Ref. 9) to determine if a vehicle is indeed a monorail. However, unlike other monorails, it wraps around the beam and the weight is carried by pairs of wheels mounted at each end of the vehicle which run on steel rails mounted on the bottom flanges of the guideway beam. The suspension of this monorail is a simplification of the suspension on conventional-configuration trains: the wheels are flangeless (made of aluminum with a steel rim), it is guided and stabilized by horizontally-mounted wheels which run against the top of the guideway beam on the sides, the wheels are independently mounted (there is no fixed axle), and rotate freely as no traction forces are transmitted through the wheels.

The advantages of this simplified suspension include:

- Improved high-speed stability due to the elimination of "hunting" dynamics as there is no fixed axle, wheel flanges, or wheel-rail traction.
- Reduced rolling friction due to the elimination of the dry contact friction that can occur between conventional wheel flanges and the rail.
- Improved stability and cornering ability due to the low center of gravity, just 28" above the horizontally-mounted guide wheels.
- Improved safety as the wrap-around design and suspension structure make it virtually impossible for the vehicle to leave the guideway.



Cross-section of Maglift Monorail

In summary, the wrap-around-the-beam suspension gives the EMSA monorail a wide stance (slightly wider than a conventional train configuration), a low center of gravity, high-speed stability, and low rolling friction. Thus the EMSA monorail has the ability to operate safely and economically at high speeds.

The monorail is propelled by the Seraphim motor which was developed by Sandia National Laboratories as a means to launch satellites into low earth orbit (Ref. 5). The original Seraphim motor was designed to launch one ton satellites into orbit at 22,500 km/hr on a 1 km-long track having a 30% upward grade. The Seraphim motor is a relatively new form of LIM that generates thrust by pulsing an alternating current (<1kHz) through a driving coil when it is properly positioned over an unpowered reaction structure. The magnetic flux from the driving coil induces currents in the reaction structure, creating forces for propulsion or braking due to the interaction of the magnetic fluxes. This is unlike a conventional LIM where magnetic flux is embedded in the continuous reaction rail in order to create propulsive forces.

Since the Seraphim motor relies on the exclusion of flux from the reaction rail, it has the following advantages over conventional LIMs for use as a high-speed rail propulsion technology:

- It permits a larger gap between the active coil and the reaction rail, up to 2.5 cm (1"), and perhaps larger, which improves ride quality and relaxes guideway tolerances, significantly reducing construction and maintenance costs.
- Very low magnetic drag is induced in the reaction rail (assuming proper motor control), which improves motor efficiency.
- It is smaller, lighter, and more compact than a conventional LIM, and has been estimated to cost significantly less to build and operate (Ref. 5).
- The efficiency of the motor increases with speed.

The power of the Seraphim motor is limited only by the power available, the frequency of pulsing relative to the required energy input necessary for a desired speed of operation, and by the maximum acceleration/deceleration forces that can be comfortably accommodated by passengers (Ref. 10). A proof-of-concept motor sized to produce up to 18 kN of thrust per coilset was tested successfully at Sandia in 1995 (Ref. 5).

The Seraphim motor is mounted horizontally on the bottom of the monorail vehicle, with the reaction structure mounted on the top of the guideway beam. The reaction structure consists of shorted pancake coils with a diameter nearly equal to the width of the mounting flange. The active coils on the vehicle will be the same diameter, but will be cooled to enable continuous operation. This dual-coil configuration allows the utilization of larger operating gaps at high efficiency, simplifies the active coil support structure design, and allows the vehicle to maneuver through tighter curves than would be possible if the reaction structure was mounted vertically on the guideway. It also allows the utilization of the vertical component of thrust to provide magnetic lift (maglift) for the vehicle.

Magnetic lift is important because it reduces the weight on the vehicle suspension, reducing the static and rolling drag by an amount proportional to the reduced weight. The amount of maglift is proportional to the amount of forward thrust generated, and can be up to 300% of the forward thrust. The ratio of lift-to-propulsion force is determined by controlling when the active coil power is switched on relative to the position of the corresponding reaction coil. However, the practical amount of lift that can be used to advantage is less than the weight of the vehicle. This is because the amount of useful maglift available is a trade-off between the desired thrust, power availability, and system safety issues. It should also be noted that the amount of maglift is sensitive to the gap between the active and reaction coils, and if the vehicle was to start to lift from the guideway, the motor gap would increase, which would decrease the maglift force until the vehicle settles back down on the guideway. Thus maglift has a self-regulating, fail-safe limit which prevents the amount of magnetic lift which can be applied from exceeding the weight of the vehicle. For the purposes of this paper the amount of maglift that could be generated was arbitrarily limited to 80% of the weight of the vehicle.

Maglift Monorail

The performance of a twenty-segment flexible-fuselage Maglift Monorail weighing 210 metric tons was simulated. Drag was calculated using the formula: Drag = $W\%(a+bV)+cV^2$ where W% is the percentage of total vehicle weight remaining on the suspension after the maglift forces experienced at the given power level. Considering that the static drag is proportional to the vehicle's weight, the static constant, a, at full weight before any consideration is given to the maglift effect, was set at 1.89 which was obtained using the value for the TGV train and adjusting for the total weight. Likewise the rolling drag constant, b, is proportional to the train's weight and it was determined for the monorail by using the value for the TGV train and adjusting for the total weight, giving a value of 0.0193 at full weight before any consideration is given to the maglift effect. This is conservative as no account is being given to the elimination of flange/rail contact in the flangeless Maglift Monorail; even in the best case, the TGV suffers such contact on curves. The coefficient for aerodynamic drag, Cd, can be estimated for an aerodynamically-efficient train from the formula Cd=0.3+0.0035*L where L is the train length in meters. For the 128 m long Maglift Monorail, this indicates a Cd of 0.75. The aerodynamic drag constant, c, is proportional to both Cd and the cross-sectional area of the vehicle (a surrogate for the reference area, A_S). Thus considering the value for the TGV, c for the monorail is estimated at 0.000339.

At a steady speed of 250 mph (402 km/hr), the total drag on the monorail is 63.4 kN (14,254 lbf) made up of: static drag 1.7 kN (387 lbf), rolling drag 7.0 kN (1,583 lbf), and aerodynamic drag 54.6 kN (12,286 lbf). The drag per passenger with 400 passengers on the monorail is 158.5 N, and the power cost per 1,000 passenger miles at a steady 250 mph is $4.43, per Table 5:

Table 5. Monorail Drag per Passenger & Power Cost per 1,000 Passenger Miles

Source	*Drag*	*Cost*	*Percent*
Static	4.3 N	$0.12	2.7%
Rolling	17.6 N	0.49	11.1%
Aerodyn.	136.6 N	3.82	86.2%
Total	158.5 N	$4.43	100%

Compared to the conventional-configuration TGV, the Maglift Monorail cuts the static and rolling drag from 50.7 N per passenger to 21.9 N per passenger, a 57% reduction. Compared to the TR07, the static and rolling drag of the Maglift Monorail at 21.9 kN per passenger is 42% less than the magnetic drag on the TR07 at 37.7 kN per passenger. This shows the effect of the monorail's light-weight vehicle construction and the maglift effect. This reduction in static and rolling drag could be improved by adjusting the firing timing of the active coils in the Seraphim motor to increase the amount of maglift upthrust relative to driving thrust.

Analysis of Results

A comparison of the calculated power costs per 1,000 passenger miles for each system covered in this paper reveals that the Maglift Monorail system has the lowest cost, $4.43, versus $7.36 for the maglev TR07 and $8.67 for the TGV system. Maintenance costs have not been studied in this paper but it should be noted that the maintenance costs of a conventional noncontact maglev system are likely to be higher than those for a Maglift Monorail (or TGV) system as the entire guideway is, in effect, a powered switch. Maintenance costs of the Maglift Monorail are expected to be significantly lower because its guideway does not incorporate complex superconducting or electro-magnets and will not be actively switched.

A more complete analysis has to consider capital and maintenance costs as well. In discussing capital costs, it is important to use current costs and to account for all costs, including: land and environmental mitigation costs, the guideway, vehicles, stations, power supply, special structures such as tunnels or bridges, communication, control, safety, and support systems, soft costs such as engineering and project management, and contingencies. The Florida Overland Express (FOX) project was to use a version of the TGV train and was projected to cost of $20 million per mile, excluding rolling stock or contingencies. However, this system was projected to have a top speed of up to 200 mph (300 km/hr), much lower than the 250 mph (400 km/hr) speed used in this analysis. The FOX project was cancelled when a study projected that the capital cost would probably exceed this estimate and that its revenue would be less than projected (Ref. 11). The noncontact Transrapid maglev line which is being constructed from Hamburg to Berlin was estimated in 1996 to have a cost of $32.4 million per mile, excluding contingencies (Ref. 12), and this will be capable of 300 mph. This high capital cost is largely due to the expensive guideway which has to be built to close tolerances, and which has active coils and control systems along its entire length. The Maglift Monorail has been proposed for two corridors. Its all-inclusive projected capital cost is $21.8 million per mile in a mountainous corridor with tight curves and tunnels (and including $1 billion in contingencies); it will be able to reach speeds in excess of 240 mph in this corridor. In the other corridor, it will cost significantly less and will be able to reach speeds of 300 mph as this corridor is relatively flat and straight (Ref. 13). This is a low cost for an elevated system, and is due to the absence of active systems along the guideway, and to the low distributed weight of the monorail vehicles allowing for lighter beams.

No data was available on guideway and vehicle maintenance costs, but a qualitative evaluation is possible. Conventional maglev will have significantly higher maintenance costs than the Maglift Monorail due to its increased complexity: the maglev guideway is active with coils and control systems along its entire length whereas the monorail has a dumb, passive guideway which requires little maintenance; the maglev vehicles have electro-magnets and batteries (or superconducting magnets and chillers) compared to the simple, low-maintenance wheelsets used on the Maglift Monorail.

Table 6 gives a summary of the conventional-configuration train, noncontact maglev, and Maglift Monorail system characteristics:

Table 6. Summary

	Train	*Maglev*	*Maglift*
	TGV	*TR07*	*Monorail*
Top Speed (mph)	186	300	300
Power Cost (per 1,000 PMs)	$8.67	$7.36	$4.43
Capital Cost ($000,000/mile)	>$20	>$32.4	<$21.8
Maintenance Costs		High	Low
Technical Complexity		High	Low

The bottom line is that compared to the most modern high speed train using conventional technology, the TGV, these studies show that the Maglift Monorail will cost about the same or less to install, will be much less expensive to operate, and will be much faster. Compared to a noncontact maglev system, the Maglift Monorail costs much less to install, and is less expensive to operate. The Maglift Monorail, an integration of a simplified suspension with a simplified LIM, gives a break through in performance and cost. The source of the maglift's superior economics lies in four areas:

- Magnetic lift comes virtually free of charge. Additional care must be taken in placement of the powered coils on the vehicle, and tuning of the suspension to minimize noise, vibration, and optimize ride quality, but there is no significant additional capital cost.
- The Seraphim motor is simple and inexpensive, and generates virtually no magnetic drag.
- The EMSA monorail is light and stable, permitting high speeds with safety, and its unique suspension and wheel arrangement minimize rolling drag.
- The guideway, constituting the majority of the capital cost in most projects, is passive and hence relatively inexpensive.

It is difficult to justify the greatly increased capital cost of noncontact maglev to eliminate static and rolling drag, less than 20% of the total drag, when the magnetic drag which is introduced is nearly as great. Conventional noncontact maglev is an expensive but inefficient solution to a small problem – only a 4% reduction in total drag can be attributed to the complex maglev technology. It is also difficult to justify the greatly increased capital cost of noncontact maglev to reduce aerodynamic drag and improve dynamic stability which allow very high-speed operation, when these can be matched by an improved wheel suspension and vehicle design.

Conclusions

The Maglift Monorail is a simplification, improvement, and integration of two existing technologies which seems to offer significant advantages compared to alternatives. Compared to conventional-configuration trains such as the TGV, it offers performance and operating cost advantages. Compared to noncontact maglev systems, it offers significant capital cost and operating cost advantages.

In considering how to optimize high-speed rail transportation from performance and cost standpoints, the key to success is to consider the technical and cost trade-offs. Conventional noncontact maglev utilizes full levitation to eliminate rolling drag, but pays a high price in system complexity and magnetic drag. The Maglift Monorail system described in this paper presents an alternative approach that generates a greater reduction in overall drag than noncontact maglev does, and at significantly lower cost and risk. The vehicles are lighter and less expensive as simple wheelsets are used in the place of complex magnets, cooling systems, and control systems. The guideway, the major cost component of most systems, is much less expensive as the maglift guideway is passive while the noncontact maglev guideway has active coils and control systems along its entire length. Maglift achieves all this while using proven, low risk technology - wheelsets and

LIMs – thus doing away with all the technical uncertainty of noncontact maglev.

References

1. Julio Pinto Silva, EU 277 System. Lillehammer Award 1995. Secretariat Eureka, Brussels
2. Status of Operation Experiences for the Transrapid Facility by Merklinghaus and Steinmetz of the Industriennlagen-Betrie-Bsgesellschaft, IABG, 1988
3. The magnetic drag for the TR07 attributable to the magnetic guidance system was determined from the empirical equation, Dmag=A m $(1-1/e^{V/B})$ where A=30 N/t per Jean Pierre Pascal, 1983, Institut di Richerche des Transports, Arcusil CEDEX (Paris), m=206 t, V=400 km/hr, and B=108 km/hr assuming silicate steel, giving Dmag=6.32 kN. To this is added 2 x 3.63 kN which is the magnetic drag attributable to the lineal generators per Technology and Safety of the Transrapid System by Rasehbichler, Thyssen, Henschel, 1988.
4. Eric H. Sjokvist, Worldwide Development of Propulsion Systems for High-Speed Trains, Transportation Research Record 1177, Transportation Research Board, National Research Council, 1988 pp 54-83
5. Kelley, Turman, Marder, Rohwein & Aeschllman, Seraphim: A Propulsion Technology for Fast Trains, SAE Technical Paper Series # 951924
6. Figure 4: Running Drag of the TR06, Magnetbahn-Versuchsanlage, IABG
7. James H. Lever, Technical Assessment of Maglev System Concepts, Final Report by the Government Maglev System Assessment Team, October, 1998 p 184.
8. Hiroyuki Fujimoto, Developing a High-Temperature Superconducting Bulk Magnet for the Maglev Train of the Future, Journal of Metals, October 1998.
9. The Monorail Society, an organization based in Freemont, California. Web site www.monorails.org.
10. James H. Lever, Technical Assessment of Maglev System Concepts, Final Report by the Government Maglev System Assessment Team, October, 1998, p 132 and Appendix A.
11. Evaluation of the FDOT-FOX Miami-Orlando-Tampa High Speed Rail Proposal, James Madison Institute.
12. Transrapid International cost estimate in press release dated 16 December, 1997. This estimate was made in 1996 at an exchange rate of DM 1.70 per $US 1.00.
13. The Meneren Corporation, Internal paper.