Efficient and Affordable Maglev Opportunities in the United States

To travel rapidly at the lowest possible maximum speed, maglev systems for urban transport should reduce vehicle weights, use efficient vehicle shapes and employ high acceleration and braking rates.

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ABSTRACT | Maglev has the potential to be more efficient and affordable than alternative technologies for many transportation applications. To achieve this potential we need new designs that build on what we have learned from existing maglev designs, while taking advantage of supporting technology that did not exist when most of them were created. The keys to reducing energy intensity are to use light vehicles with low aerodynamic drag, use a linear synchronous motor that is excited in short sections, and operate with a dynamic schedule that achieves a high load factor. The key to affordability is to use small, light vehicles that can operate on less expensive guideways, and require less power for propulsion. This paper provides more details on these issues, provides estimates of what is feasible with today's technology, and discusses how to choose performance parameters, such as speed and acceleration, so as to maximize the probability that maglev will become the technology of choice for a wide range of applications. It also includes an historical perspective and recommendations for future development.

KEYWORDS | Automated people mover; linear motor; linear synchronous motor; maglev

I. INTRODUCTION

A transport system should be fast, efficient, and affordable. These conflicting objectives must be solved by a careful compromise that takes advantage of the strengths of the underlying technology. Operating maglev systems have demonstrated that linear motor propulsion of magnetically levitated vehicles provides fast, safe, comfortable, and efficient transportation over a wide speed range, but maglev is perceived to be expensive and not enough better than competing technology to justify major funding of new designs. The reality is that demonstrated maglev designs have efficiencies comparable to competitive technology and *can* be both less expensive and more efficient. To realize this potential we must develop next-generation maglev. This paper provides evidence to support this claim, with the term "E&A maglev" used to describe maglev designed from the perspective of *efficiency and affordability*. A major focus is on opportunities for applying E&A maglev in the United States.

Topics discussed in this paper can be explored in detail at a variety of internet sites, a few of which are given but many more are readily found.

II. OVERVIEW

This section contains personal views on steps that should be taken to achieve E&A maglev and the remaining sections provide evidence to support these views.

A. Speed Categories and Competition

It is important to match speed to application and recognize competing modes of transportation. Table 1 characterizes speed in five regions with typical applications, travel distance, and competition. In this table some commonly used acronyms are: Automated People Mover (APM); Personal Rapid Transit (PRT); High Speed Rail (HSR); Automated Electric Transportation (AET); Bus Rapid Transit (BRT).

Lest we focus too much on speed, higher acceleration and braking rates are often a more effective way of

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Manuscript received May 22, 2009; revised July 9, 2009.

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Digital Object Identifier: 10.1109/JPROC.2009.2030251

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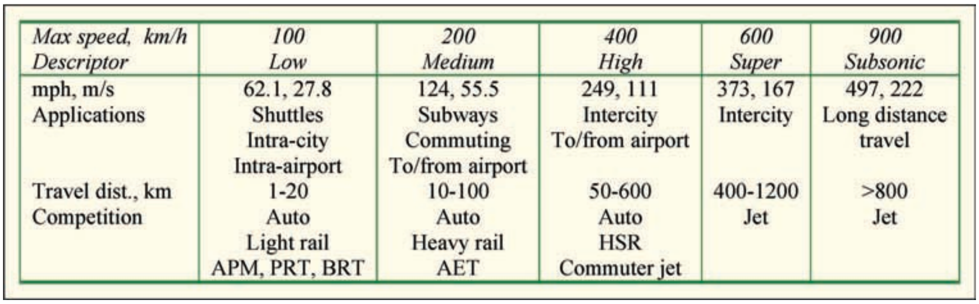
Table 1 Attributes of Five Speed Categories



Max speed, km/h *Descriptor*	*100* *Low*	*200* *Medium*	*400* *High*	*600* *Super*	*900* *Subsonic*
mph, m/s	62.1, 27.8	124, 55.5	249, 111	373, 167	497, 222
Applications	Shuttles Intra-city Intra-airport	Subways Commuting To/from airport	Intercity To/from airport	Intercity	Long distance travel
Travel dist., km	1-20	10-100	50-600	400-1200	>800
Competition	Auto Light rail APM, PRT, BRT	Auto Heavy rail AET	Auto HSR Commuter jet	Jet	Jet

reducing travel time. Fig. 1 shows a Transrapid (TR) simulation of an 8-car TR08 maglev train making a 421-km (261-mi) trip from Anaheim, CA, to Las Vegas, NV, with four intermediate stops. This route, like most routes in the United States, involves substantial slowing for turns and stops and crosses two mountain ranges with grades of up to 6.5%. The top speed is 500 km/h, but the average speed, not including stopped time, is only 271 km/h. Later we will see how a lower top speed but higher acceleration and braking rates allows the same travel time to be achieved with lower capital and operating cost and reduced energy consumption.

B. The Status of Maglev and Competing Technology

Thanks to multibillion dollar development projects in Germany, Japan, and China, the advantages of maglev have been proven in convincing ways in two speed regions:

- Low-speed maglev was implemented in a 600-m shuttle in Birmingham, U.K., that operated reliably from 1984 to 1995. The early Transrapid TR TR04 design evolved into HSST, and then Linimo with an 8.9-km line operating in Aichi Japan since 2005.[1] South Korea is installing low-speed maglev from Seoul to the airport using a variation of the Linimo system [16]. These electromagnetic suspension (EMS) designs were intended as upgrades for light rail and APM in the low-speed region, and have proven to be efficient and reliable, but not cost effective.
- Super-speed maglev was studied extensively in Germany, Japan, the United States, Canada, and elsewhere, with major test tracks constructed in Germany and Japan. These developments evolved into the operational TR EMS maglev system in Shanghai, China, in 2005, and the Yamanashi Test Line (YTL) ElectroDynamic Suspension (EDS) maglev in Yamanashi Prefecture, Japan, in 2004 [15]. These designs were intended as upgrades of HSR and competition for commuter jets.

There have been two new installations, major marketing efforts, and several false starts, but almost no major commitments to maglev of the type envisioned by the developers. One possible exception is the Central Japan Railway, which has made a commitment to fund and build the Tokaido Shinkansen Bypass from Tokyo to Nagoya starting in 2015, using their superconducting EDS maglev. In the last 30 years there have been substantial improvement in operational designs, but without major installations there have been no commitments to a test facility for a next-generation design. If one wants to install a proven maglev system today, the only choices are designs that have not changed as much as the competition has changed.

- HSR speed has increased operational speed more than 80%, locomotives have been eliminated by integrating propulsion into the cars so higher propulsive force is possible with lighter axle loadings, and three different manufacturers can provide trains designed to operate at 350–360 km/h (217–224 mi/h, 97–100 m/s).
- Commercial jets have evolved into lighter, more efficient, and more cost-effective designs for both short haul and long haul.
- Both light rail and APM technologies have been implemented in many places and are now reliable and cost effective for many applications.
- The bus has evolved into comfortable, efficient, and cost-effective transportation for intercity applications, and BRT is now operational in cities around the world with promises of substantial cost savings.

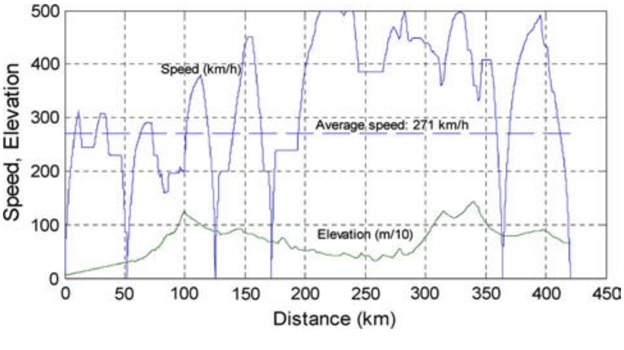


Fig. 1. ***Speed and elevation for simulated trip from Anaheim to Las Vegas on TR08.***

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[1] http://en.wikipedia.org.

- PRT has evolved from the Morgantown, WV, system [25] to an installation at Heathrow Airport, and plans by several companies to install other PRT systems in the near future.
- AET, or operation of electric cars on automated highways [8], is being proposed as an energy-efficient and cost-effective way to provide intercity transportation.
- And of course, the modern automobile is comfortable and cost effective for travel up to fairly long distances, and modern designs are very efficient.

Japan and Germany are still investing in improvements in their existing maglev technology, including the new Japanese MLX01 EDS vehicle using superconducting technology and the Transrapid TR09 using EMS. Both of these designs can be made more cost effective by making maximum use of supporting technology that did not exist when these designs were committed to expensive test facilities. Important supporting technology is covered by other papers in this Special Issue of the PROCEEDINGS OF THE IEEE. Here are a few examples.

- Evolution of high-energy permanent magnets allows EMS to be constructed with a 20-mm gap and an order of magnitude reduction in suspension power loss [7]. With a gap that is one-fourth of the stator width, the suspension magnets can provide passive guidance without the need for separate guidance rails and magnets. Permanent magnets can also be used for EDS [13].
- High-temperature superconductors are still improving. Designers of both EMS and EDS maglev should consider using them at high speeds where a higher field can allow a larger gap, and reduced guideway and propulsion cost.
- Powerful microprocessors with dedicated motor control features and mass produced semiconductor power devices make it possible to reduce the cost of power electronics. This makes it practical to achieve higher acceleration with shorter time penalties for slowing for curves and stopping at stations.
- The ability to return regenerated braking energy to the utility grid is now a more practical option, particularly if the peak power is not too large and the linear motor efficiency is high.
- The evolution of modern computer aided design tools make it possible to optimize a design before it is committed to expensive test facilities.

C. Why Has Maglev Not Become More Widely Used?

Here are some of the real and perceived problems with maglev.

- Fully developed low-speed maglev systems do not have significant performance or cost advantages over wheel-based systems. People responsible for installing new low-speed transport are more interested in avoiding risks than investing in new technology, even if it is less expensive and more efficient.
- Germany and Japan have worked the most to develop high-speed operational maglev systems, but both countries have excellent HSR. Citizens of these countries have shown reluctance to support a new technology that is *perceived* to be only marginally better than the latest HSR, but more expensive.
- China is currently operating a TR maglev system on a 30-km line from Pudong Airport to Shanghai, but has abandoned all plans to extend this line.

Although the TR and YTL developments have shortcomings, they have benefited from outstanding engineering that can be used as a solid base for next-generation maglev.

The TR development has proved that EMS can work reliably at speeds up to 500 km/h with a magnetic gap of 8 to 10 mm. The latest TR09 train has lower drag per seat and produces less external noise at 400 km/h than HSR at 350 km/h. The extensive documentation of route layout, guideway design, and many safety and comfort related issues can be used by any future developers and their new inductive power transfer system [6] could be the method of choice for providing all onboard power at all speeds.

The YTL test line holds a record of 581 km/h (361 mi/h) using superconducting EDS technology with a 100 mm magnetic gap. They have developed light weight, composite vehicles with particular attention to the problem of entering and exiting tunnels, an important part of any Super Speed route. The MLX01 train has low drag at high speed and can be used as the basis for a vehicle design for both EDS and EMS systems.

This paper provides a basis for the belief that maglev will be the winning technology for transporting people and cargo over a very wide range of speeds. A proposed E&A maglev will be discussed later, but a key feature is the use of small vehicles or short trains with rapid and efficient acceleration and regenerative braking.

D. Energy Intensity as a Measure of Transport Efficiency

The efficiency of people mover transportation is best measured as Energy Intensity (EI), the energy required to move one passenger one kilometer. Even when comparing similar vehicles using similar fuels, efficiency comparisons can be misleading because of variations in testing procedure, climatic conditions, load factor, etc. Attempts to compare the EI of different technologies is guaranteed to create confusion, disagreements, and misleading representations and interpretations. Consider data presented in the Transportation Energy Data Book [1], published and updated frequently by Oak Ridge

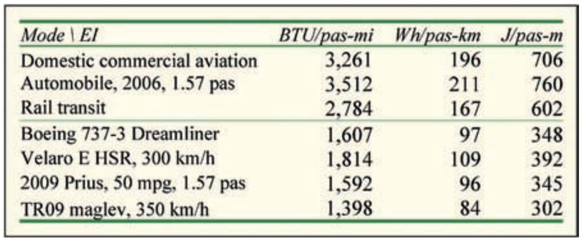
National Laboratory (ORNL). This book contains data comparing travel modes in the United States in terms of EI measured in BTUs per passenger-mile. For example, ORNL determined that the average personal car gets 22.7 mi/gal of gasoline. With a national average of 1.57 passengers per car we find EI = 3512 BTU/pas-mi. Comparing plug-in hybrids and all-electric cars with fossil fuel cars is particularly difficult. The ORNL approach assumes that electricity is generated with fossil fuels and that the efficiency from fuel source to power delivered is now 33%. This leads to an assumed energy equivalence of 1 Wh = 3600 J = 10.339 BTU. (See Appendix for other conversion factors and energy content data.)

For this paper an attempt was made to create a fair comparison. Table 2 shows the somewhat surprising conclusion: EI for the latest air, rail, maglev, and auto technologies are all substantially the same and significantly better than for the same modes a few years ago. ORNL gives EI values shown in Table 2 for existing automobile, rail, and air transit technology. EI for the 787-3 is based on Boeing's claim that aircraft entering the fleet today use 0.035 L per passenger-km and that the 787-3 uses 20% less than older aircraft [18]. Toyota claims the 2009 Prius will deliver 50 mpg. EI for the Velaro High Speed Train and TR09 are from Table 6. Data in this table can be used only as a rough guide, but the important fact is that modern technology is all quite comparable and substantially better than older technology.

In the future, an increasingly large fraction of power will be generated from non–fossil fuel sources, so the ORNL comparison will be increasingly unfair to electrically propelled vehicles. If wind turbines or solar cells convert electric power to hydrogen for fuel cell based electric cars, should we not penalize the fuel cells for the efficiency of the hydrogen conversion?

Argonne Laboratory has been charged by the U.S. Department of Energy with finding a way to compare EI for various types of cars. They are using a "well-to-wheel" philosophy, but any comparison must be interpreted with caution because the "well" is not the only source of electric energy. This paper avoids this problem by limiting most comparisons to electrically propelled vehicles with energy consumption measured in Wh/km or J/m (1 Wh/km = 3.6 J/m). There is still a problem of knowing what to assume for a test route, load factor, climate, etc. But at least there are fewer factors to confuse the issue.

Table 2 EI for Various Modes Assuming 1 Wh = 10.339 BTU



Mode \ EI	*BTU/pas-mi*	*Wh/pas-km*	*J/pas-m*
Domestic commercial aviation	3,261	196	706
Automobile, 2006, 1.57 pas	3,512	211	760
Rail transit	2,784	167	602
Boeing 737-3 Dreamliner	1,607	97	348
Velaro E HSR, 300 km/h	1,814	109	392
2009 Prius, 50 mpg, 1.57 pas	1,592	96	345
TR09 maglev, 350 km/h	1,398	84	302

I believe that E&A maglev should average EI $\leq$ 100 Wh/pas-km under operating conditions.

E. Summary

For three decades competing transportation technologies have seen dramatic changes that make them more efficient and cost effective. Operational maglev designs are both fast and efficient, but have not seen this same level of development. There is now a unique opportunity to invest in next-generation E&A maglev. This next generation can use existing designs as a base and create reductions in cost and EI by using supporting technology not available when operational designs were developed.

III. DESIGN ISSUES

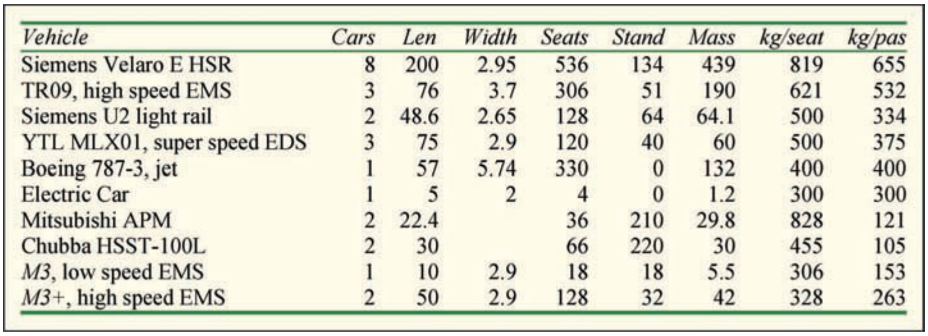
Maglev is similar to other transport technology: we can create a basic design that is almost independent of speed, but the implementation varies considerably according to the application. As always, the devil is in the details, three of which are discussed in this Section.

A. Vehicle

Choice of vehicle weight, shape and length dominate transport system design. In this paper the term vehicle also refers to trains with any number of mechanically coupled cars. There are three key issues that affect the EI of a transport system and are primarily determined by vehicle design.

1) For high-speed travel the dominant energy usage is to overcome aerodynamic drag. For constant speed travel EI is proportional to the drag force per passenger with 3.6 N/pas = 3.6 J/pas-m = 1 Wh/pas-km. Airplanes do much better than is possible for ground transportation because at an elevation of 12 000 m (39 370′) the pressure, and hence the drag force, is reduced by a factor of four. An airplane traveling 900 km/h (559 mi/h) is comparable in aerodynamic drag to a maglev vehicle traveling 450 km/h, and with a larger diameter body the energy efficiency can be quite good for long trips.
2) For low-speed travel the dominant energy loss is due to the need to supply kinetic energy to change a vehicle's speed, and this is typically lost when the vehicle brakes. For high-speed travel the problem still exists because there is typically a need to slow for turns to achieve acceptable lateral gee forces and to stop at stations. Regenerative braking can reduce the net loss by a factor of two or more provided the propulsion is reasonably efficient and there is a way to reuse the energy.

Table 3 Empty Vehicle Mass for Several Technologies; Dimensions in m, Mass in Mg



Vehicle	*Cars*	*Len*	*Width*	*Seats*	*Stand*	*Mass*	*kg/seat*	*kg/pas*
Siemens Velaro E HSR	8	200	2.95	536	134	439	819	655
TR09, high speed EMS	3	76	3.7	306	51	190	621	532
Siemens U2 light rail	2	48.6	2.65	128	64	64.1	500	334
YTL MLX01, super speed EDS	3	75	2.9	120	40	60	500	375
Boeing 787-3, jet	1	57	5.74	330	0	132	400	400
Electric Car	1	5	2	4	0	1.2	300	300
Mitsubishi APM	2	22.4		36	210	29.8	828	121
Chubba HSST-100L	2	30		66	220	30	455	105
M3, low speed EMS	1	10	2.9	18	18	5.5	306	153
M3+, high speed EMS	2	50	2.9	128	32	42	328	263

3) Suspension and propulsion losses are always significant. Not only is there a direct loss, such as wheel hysteresis and bearing friction or magnetic drag, but at even moderate speed the aerodynamic loss attributable to the suspension and propulsion components exceeds the direct losses.

With these facts in mind, consider the design aspects of vehicle weight, shape, and length.

1) Weight: All transport technology has been moving in the direction of reducing vehicle weight, and using regenerative braking. With energy conservation a major issue, this takes on new urgency. Table 3 gives examples of vehicle empty mass, empty mass per seat, and empty mass per passenger including standees (1 Mg is sometimes called a tonne, or metric ton, and equals 2205 lbs). The Boeing empty mass is the maximum takeoff weight less 100 kg per seat. The low-speed designs have mostly standees, as appropriate for low speed, and the others have seats for most passengers, as appropriate for higher speeds. For this paper we assume there are two E&A maglev designs, a low-speed version, designated *M3*, for urban applications and a high-speed version, designated *M3+*, for competition with HSR. They have the same basic design but *M3+* has stiffer guideway girders, higher power propulsion electronics and a vehicle that is a two-car train.

I believe maglev empty vehicle mass should be less than 200 kg/pas for low speed and less than 400 kg/seat for high speed.

2) Shape: Shape is important because it affects aerodynamic loss and noise, both external and internal. Even low-speed vehicles should have modest streamlining and high-speed vehicles need more extreme shapes. Fig. 2 shows examples of recent designs: Japanese Fastech 360 train designed for 360 km/h, Transrapid TR09 designed for 350–500 km/h, Japanese Yamanashi Test Line MLX01 designed for 550 km/h. The nose section is very important for high speed, particularly for vehicles entering and exiting tunnels. For HSR the main aerodynamic drag is on the body, wheels, and pantograph. Well-designed maglev vehicles have less drag and are quieter than modern high-speed trains, even when going substantially faster.

3) Length: Vehicle length is a critical parameter. The frontal area is constrained by the assumed need to provide height for standing headroom and width for at least four-abreast seating with reasonable comfort. With maglev the frontal area can be less than for conventional trains because the suspension has less frontal area and there is no pantograph. The minimum length is determined by passenger carrying ability, but with clusters of vehicles

Fig. 2. ***Fastech 360, TR09, MLX01.***

operating as virtual trains we do not need long trains for high capacity.

Long trains have a few advantages.

- Aerodynamic drag per seat is less but this advantage diminishes for trains longer than about 50 m.
- Higher capacity can be achieved with a given headway.
- Higher speeds imply longer trips and a need for more onboard amenities which can be shared by many passengers if the train is longer.

But with maglev there are more reasons to use uncoupled vehicles or short trains operating with shorter headway.

- Lighter vehicles can operate on lighter and less expensive guideways.
- With smaller vehicles it is easier to match supply to demand.
- With LSM propulsion it is possible to reduce headway and achieve high capacity with small vehicles.
- Short headway reduces wait time.
- LSM propulsion can be less expensive if there are more and lighter vehicles.
- With smaller and lighter vehicles it is less expensive to provide higher acceleration and braking rates and achieve good efficiency at these higher rates.
- Smaller vehicles can operate with smaller and less expensive stations.
- Lower peak power and more closely spaced vehicles make it easier to reuse regenerated braking energy and minimize electric utility peak power problems.

B. Speed and Acceleration

An important advantage of maglev is the ability to accelerate and brake much faster than is possible with rail, so for typical routes with stops, curves and hills, maglev does not need to be faster to deliver shorter travel time. This is evident in the plots in Fig. 3, which compare acceleration rates of three maglev designs with a Velaro high-speed train operating with a top speed of 320 km/h (199 mi/h). The Japanese MLX01 has the best acceleration, but all maglev designs can accelerate much faster than the Verlaro. The Japanese Fastech 360 and the Alstom TVE have acceleration attributes similar to Velaro due to practical limits on thrust and drag for steel wheels on steel rails.

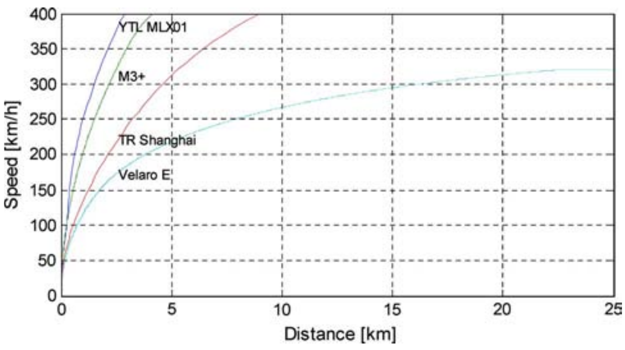


Fig. 3. ***Comparison of maglev with a high-speed train during acceleration.***

An important measure of performance is the time penalty for stopping. There is time lost in braking, unloading and loading, and accelerating, and these penalties can be calculated separately. For example, the *M3+* performance in Fig. 2 implies that for travel at 400 km/h the time penalty for acceleration to 400 km/h is only 37 seconds due to finite acceleration after a stop. For braking the deceleration rate is 1.6 m/s^2 for the whole deceleration so the time penalty is $t_p = (400/3.6/2 \times 1.6) = 35$ s. If we allow 60 s for stopped time the travel time is only increased by 2.2 min for every stop.

The time penalty for HSR is much higher as evidenced by the performance of the Velaro E on the 625-km (388-mi) run from Madrid to Barcelona, Spain. With a top speed of 320 km/h the nonstop travel time is 2 h 38 min for an average speed of 237 km/h, but this time is increased by 19 min if there is one stop at Zaragoza and additional stops cost at least 12 min each. This high time penalty for stopping poses a serious problem for U.S. applications where there are likely to be more stops: the fastest Acela in the Northeast Corridor stops a minimum of 10 times in the 650 km (404 mi) between Boston, MA, and Washington, DC. The same problem occurs in the proposed 695-km (432-mi) run between San Francisco and Los Angeles, CA, with 11 intermediate stations.

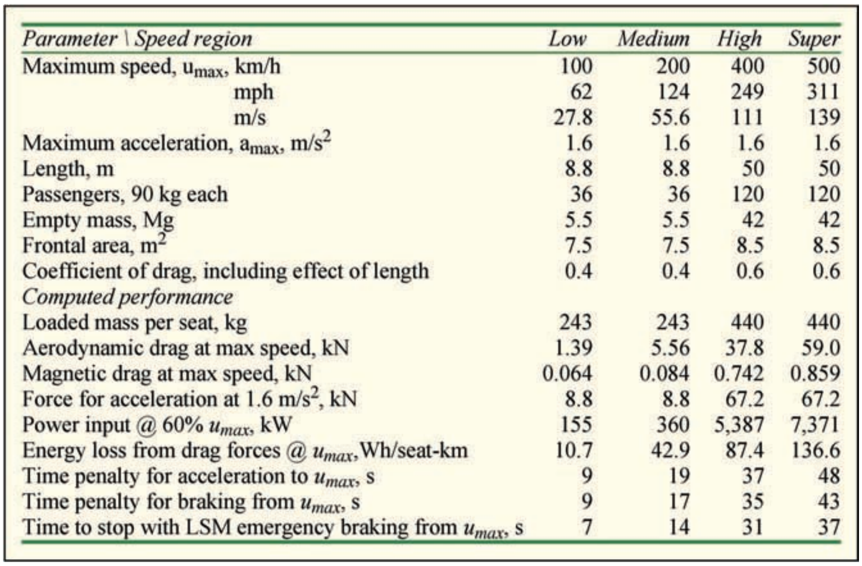
Table 4 gives suggested vehicle attributes and performance metrics for maglev vehicles operating in four speed regions. For low and medium speed the design is based on the *M3* vehicle shown in Fig. 4 and discussed later. For high and super speed the *M3+* vehicle is envisioned as a shortened version of a two-car MLX01 train, shown in Fig. 2, but with some features from TR09, a permanent magnet EMS suspension, and a power system designed to achieve high efficiency at accelerations up to 1.6 m/s^2.

In Table 4 the energy per seat-km is for 100% load, and does not include losses due to speed changes. The force and power for acceleration are based on an acceleration of 1.6 m/s^2 up to 60% of maximum speed and then constant inverter output power above that speed, and the ability to sustain a 1.6 m/s^2 braking rate at all speeds. For emergency braking the deceleration rate is allowed to be as high as 2.4 m/s^2 using both aerodynamic drag and LSM regenerative braking. Under extreme emergency it is possible to achieve even higher braking by using mechanical braking to supplement LSM braking.

Some observations:

- The force requirement for good acceleration and braking is greater than the force required for constant speed cruising at all speeds.

Table 4 Suggested Maglev Vehicle Attributes for Four Maximum Speeds



Parameter \ Speed region	*Low*	*Medium*	*High*	*Super*
Maximum speed, u_{max}, km/h	100	200	400	500
mph	62	124	249	311
m/s	27.8	55.6	111	139
Maximum acceleration, a_{max}, m/s^2	1.6	1.6	1.6	1.6
Length, m	8.8	8.8	50	50
Passengers, 90 kg each	36	36	120	120
Empty mass, Mg	5.5	5.5	42	42
Frontal area, m^2	7.5	7.5	8.5	8.5
Coefficient of drag, including effect of length	0.4	0.4	0.6	0.6
Computed performance				
Loaded mass per seat, kg	243	243	440	440
Aerodynamic drag at max speed, kN	1.39	5.56	37.8	59.0
Magnetic drag at max speed, kN	0.064	0.084	0.742	0.859
Force for acceleration at 1.6 m/s^2, kN	8.8	8.8	67.2	67.2
Power input @ 60% u_{max}, kW	155	360	5,387	7,371
Energy loss from drag forces @ u_{max}, Wh/seat-km	10.7	42.9	87.4	136.6
Time penalty for acceleration to u_{max}, s	9	19	37	48
Time penalty for braking from u_{max}, s	9	17	35	43
Time to stop with LSM emergency braking from u_{max}, s	7	14	31	37

- Magnetic drag is much less than aerodynamic drag.
- With rapid emergency braking that is not dependent on friction, it is possible to have very short headway and still meet a brick wall stopping criterion.

C. Operating Strategies

Maglev has the virtue that headways can be much shorter than with wheel based designs and this allows the use of smaller vehicles with more options for scheduling and greater ability to minimize unnecessary stops.

West Virginia University in Morgantown has operated a Group Rapid Transit (GRT) system [25] (similar to PRT but carrying 12–18 passengers) for more than 30 years and has converged on an operating strategy that is worthy of study.

- At times of peak demand the origin-destination pairs of riders can be accurately predicted and the highest capacity is obtained when the vehicles operate on a schedule.
- At times of high, but not peak, demand the operation is based on demand as signaled, by waiting riders. This avoids unnecessary vehicle travel and minimizes passenger trip time.
- At off peak most of the vehicles are removed from the loop and the remaining vehicles circulate around the loop stopping on demand.

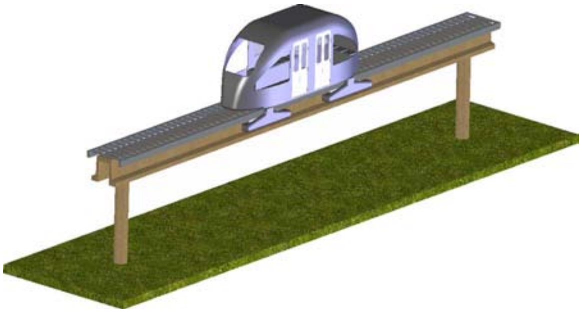


Fig. 4. ***Proposed M3 vehicle on existing ODU guideway.***

This type of flexible operation can increase both capacity and efficiency. It is most important to avoid a simplistic schedule that does not match supply to demand, such as operating long trains infrequently at off peak times or not adapting to daily or seasonal changes that are predictable. For example, for high-speed maglev between Los Angeles and San Francisco with 11 intermediate stations we can use a cluster of three 2-car trains each carrying 128 passengers. The trains could operate with one minute intracluster headway, which satisfies brick-wall stopping criteria, and 5-min spacing between clusters to create a capacity of 4608 passengers per hour per direction (pphpd) without standees. Scheduling would be like Morgantown. For rush hour each train stops at two or three intermediate stops based on predicted loads with a schedule that guarantees service between all pairs of stations at least once every hour. For low capacity a single vehicle every 15–30 min would stop at all stations. For intermediate loads the cluster spacing can be increased to 15 min so as to allow the lead train to go nonstop between Los Angeles and San Francisco while the other two trains in the cluster stop on a dynamic demand basis. This type of scheduling can create a substantial reduction in travel time and energy consumption that would not be possible with eight-car trains.

IV. THE *M3* URBAN MAGLEV SYSTEM

The *M3* maglev system has been developed by MagneMotion as part of the FTA Urban Maglev Project. This design is used as a baseline design to demonstrate the potential of E&A maglev. The ongoing construction of a full size test facility allows accurate estimates of efficiency and cost for low and medium speed maglev, and this data can be extrapolated to higher speeds with reasonable accuracy.

A. *M3* Design

The most important design requirements were specified by the Federal Transit Administration (FTA): operate at speeds up to 100 mi/h (44.5 m/s, 161 km/h); transport 12 000 people per hour per direction (pphpd); accelerate and brake at 1.6 m/s^2; and negotiate horizontal turns with a radius of 18.3 m (60′). These are carefully developed requirements, and *M3* meets them with a design that can be extended to much higher speeds. The acceleration limit is the maximum allowed by FTA for standing passengers and is a good choice for all maglev applications, except in countries where regulations limit acceleration to 1.5 m/s^2.

MagneMotion is now working with Old Dominion University (ODU), Norfolk, VA, to continue this development with the objective of testing a full size vehicle at speeds up to 100 km/h on an existing guideway at ODU. Details of this design, called *M3*, have been described in other papers [7]. The two most important features are:

- Use of a long stator linear synchronous motor (LSM) for propulsion. This allows all propulsion power and control systems to be on the guideway. There is no need to transfer propulsion power or safety-critical information to the vehicle and no dependence on mechanical forces for acceleration and braking. LSM can be less expensive and more efficient than linear induction motor (LIM) propulsion for maglev at any speed.
- Use of one set of permanent magnets to provide suspension and guidance forces in all dimensions and provide the field for LSM propulsion. The use of permanent magnets allows a larger magnetic gap and a more efficient suspension. The use of only one set of magnets simplifies the design and reduces weight, cost, and energy consumption. Permanent-magnet and electro-magnet EMS both have a Lift-to-Weight ratio of about 7 : 1. At maximum speed the permanent magnet control requires only 50 W/Mg with a gap of 20 mm as compared to more than 1 kW/Mg for electromagnet EMS with a gap of 10 mm. With a magnetic gap four times the rail width there is a natural guidance force of up to 0.4 g so there is no need for a separate guidance system and offset magnets allow active lateral damping.

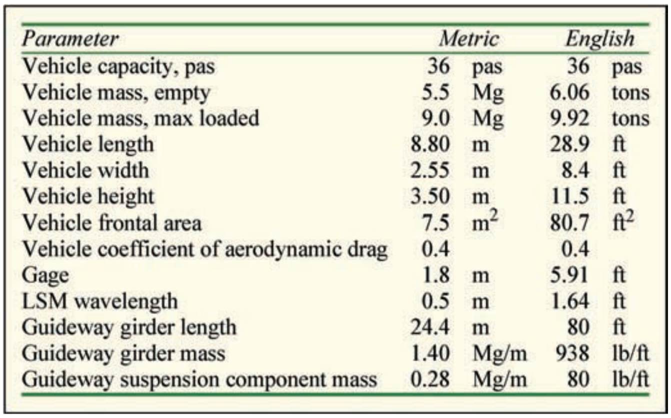
These are believed to be the best propulsion and suspension choices for speeds up to at least 400 km/h (249 mi/h). A working model has verified that analysis and simulations can accurately predict performance, so the discussion in this section of efficiency and cost are well substantiated at low speed and good predictors for higher speed.

Table 5 gives the key parameters for the *M3* maglev system being developed for installation at ODU [7]. Fig. 4 is a rendition of what a full size vehicle might look like on the ODU guideway. The vehicle has a shell of composite material in order to allow lightweight with streamlined shape. The suspension bogeys can be designed to rotate and pivot so as to allow short horizontal and vertical turns.

The guideway beams at ODU were inherited from a prior project and are not optimally designed, but simulations show that the vehicle ride quality is very good at speeds up to at least 100 km/h. (Here we define "very good ride quality" as an ISO2631-weighted vertical acceleration of less than 1 m/s^2.) With an optimally designed beam with the same mass, and with precamber matched to the vehicle mass, the ride quality is very good up to 180 km/h. A 3-D model tested in a wind tunnel at ODU verified the aerodynamic drag coefficient of the *M3* design.

M3 has a loading on the LSM stator of 70 kN/m^2 (10 psi), about the same as for TR09, but the stator width is 80 mm instead of 185 mm and the guideway suspension system mass is only half of that for TR. A key vehicle difference is the narrower body and use of composite materials to reduce the vehicle mass per unit length. The suspension provides passive guidance so there is no

Table 5 Parameters for ODU Maglev Installation



Parameter	*Metric*		*English*	
Vehicle capacity, pas	36	pas	36	pas
Vehicle mass, empty	5.5	Mg	6.06	tons
Vehicle mass, max loaded	9.0	Mg	9.92	tons
Vehicle length	8.80	m	28.9	ft
Vehicle width	2.55	m	8.4	ft
Vehicle height	3.50	m	11.5	ft
Vehicle frontal area	7.5	m^2	80.7	ft^2
Vehicle coefficient of aerodynamic drag	0.4		0.4	
Gage	1.8	m	5.91	ft
LSM wavelength	0.5	m	1.64	ft
Guideway girder length	24.4	m	80	ft
Guideway girder mass	1.40	Mg/m	938	lb/ft
Guideway suspension component mass	0.28	Mg/m	80	lb/ft

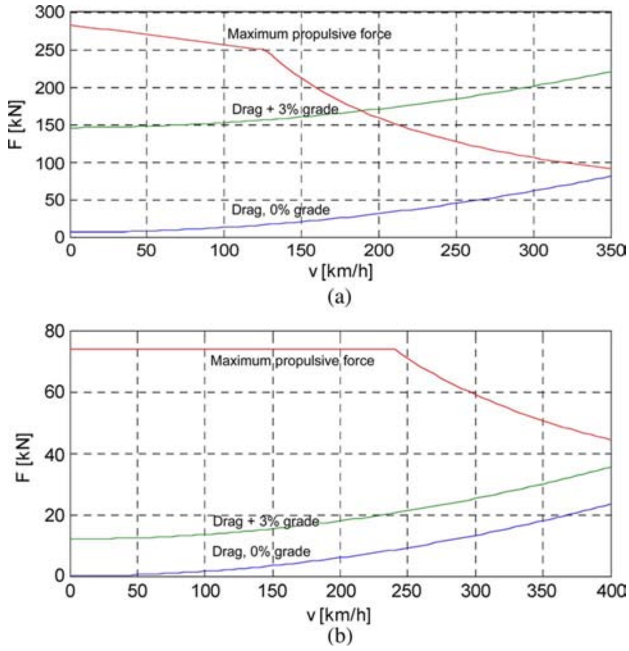


Fig. 5. ***Performance of Velaro and M3+.***

need for separate magnets on the vehicle and additional steel rails on the guideway.

An important feature of *M3* for urban applications is the use of small vehicles operating in clusters with "safe-follower" intracluster headway and "brick-wall" intercluster headway [10]. Safe-follower is the way we drive on a highway: allow room to stop if the car in front stops at the maximum possible rate, including allowance for response time. Brick-wall headway is the way most trains operate: allow enough headway to stop if the train ahead stops instantly. A cluster of vehicles (or short trains) is a virtual train (i.e. electronically coupled instead of mechanically coupled) and with propulsion that does not depend on friction or communication with a moving vehicle it is as safe as a conventional train. For high throughput the cluster operates with safe follower control but the intercluster headway is based on brick wall control.

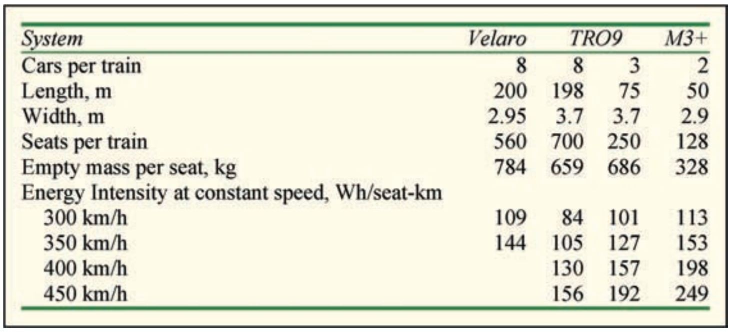
Most important, the use of a small light vehicle allows a major reduction in guideway cost and more flexible scheduling options that facilitate a higher load factor. For the proposed *M3+* 2-car train, with a maximum operating speed of 400 km/h and capacity of 4608 pphpd, the longer vehicle and reduced capacity requirements make it possible to operate all vehicles with brick-wall headway, but if higher capacity is required *M3+* could use safe follower control.

B. Vehicle Efficiency

A good place to start a discussion of vehicle efficiency is with the physics of aerodynamic drag. If we could remove the Velaro body from its suspension there is a basic drag that is hard to reduce. A good estimate of this drag is to assume a coefficient of drag for the frontal area of 0.15 and a coefficient of drag due to skin friction of $C_f = 0.0018$ (based on a characteristic length of 200 m, turbulent air flow, a speed of 320 km/h, and [22]). For the Velaro we can estimate the frontal area of the body alone as 9 m^2 and the skin area as 2000 m^2 giving a drag of 24 kN at 320 km/h. From the plot of Fig. 5 we can estimate that the actual aerodynamic drag is about 61 kN so more than half of the drag is due to the suspension components and pantograph. If we were to place a maglev suspension on this body the drag should be no more than 32 kN and operation at 420 km/h would have the same vehicle loss per km as HSR at 320 km/h. Since aerodynamic drag is what creates noise, the noise at 420 km/h should be no more than HSR noise at 320 km/h, not even counting the noise of the steel wheels on steel rails. This noise advantage has been substantiated by measurement on TR [23] and is a major advantage of maglev in congested areas.

Table 6 gives a comparison of EI at constant speed for the Velaro high-speed train, Transrapid TR09 maglev for two different train lengths, and proposed *M3+*. In order to make these comparisons fair, the following assumptions have been made. All three use cars (or sections) that are about 25 m long, so the data assumes 18 rows of passengers in the center cars and 16 rows in the end cars. TR09 is wider than the others, so five-abreast seating is assumed. Data in Table 6 for Velaro and TR09 is based on [2], [4]–[6]. For high-speed travel the constant-speed EI values in this Table are a good indicator of overall EI, provided acceleration and regenerative braking are reasonably

Table 6 Comparison of Vehicle Efficiency When Operating at Constant Speed



System	*Velaro*	*TRO9*		*M3+*
Cars per train	8	8	3	2
Length, m	200	198	75	50
Width, m	2.95	3.7	3.7	2.9
Seats per train	560	700	250	128
Empty mass per seat, kg	784	659	686	328
Energy Intensity at constant speed, Wh/seat-km				
300 km/h	109	84	101	113
350 km/h	144	105	127	153
400 km/h		130	157	198
450 km/h		156	192	249

efficient, so it is evident that we pay a high price in energy for high-speed travel. The objective should be to achieve an average operating speed that is as close as possible to the maximum speed.

Both three and eight-car TR09 trains are more efficient than an eight-car Velaro. The two-car *M3+* is the least efficient because it is short and narrow, but by using higher acceleration rates it can provide shorter travel time with a lower top speed, and by using clusters of trains the number of stops can be reduced so a high load factor is easier to achieve. For all designs the kinetic energy changes and aerodynamic drag are the dominant loss mechanisms. We can afford a more expensive vehicle if it is lighter and more efficient.

At high speeds the dominant loss is aerodynamic drag. If it were the only loss, then EI would increase as the square of the speed. This implies that if we compute the RMS (root-mean-square) of the speed for the whole trip and then compute the EI at that speed, the result would be close to the actual EI. This is surprisingly accurate because the energy lost during acceleration and braking is compensated by the energy savings due to reduced aerodynamic drag during the acceleration and braking phases. One aspect of reducing EI is to reduce the difference between RMS speed and average speed.

An electro-dynamic suspension (EDS) has significantly higher loss than EMS, a loss that leads to high EI at low speeds. However, because an EDS suspension can be constructed with less aerodynamic drag on the suspension components, an EDS suspension can be more efficient than EMS at speeds over about 450 km/h. The jury is still out on whether EDS or EMS is the best choice for speeds between 400 and 500 km/h, but EDS seems to have the advantages at speeds over 450 km/h.

In summary, with propulsion not dependent on friction and control not dependent on communication with a moving vehicle many of the reasons that make long trains desirable for wheel-based suspension are not relevant. For maglev to be most competitive it should play to its strengths and use smaller vehicles or short trains operating with short headway on lighter guideways.

C. LSM Efficiency

Examples in this section assume the use of regenerative braking and this creates a problem in describing the LSM efficiency for a complete trip. A good solution is to compute inefficiency, defined as the total loss divided by the total electromechanical power transfer via the linear motor. If $\acute{\iota}$ is the inefficiency, then for a motor the efficiency is $1/(1+\acute{\iota})$ and for a generator it is $(1-\acute{\iota})$. These are nearly the same when $\acute{\iota}$ is small but differ when $\acute{\iota}$ is large. For a trip which involves motor and generator action the trip $\acute{\iota}$ is the ratio of the sum of the LSM loss divided by the sum of the electromechanical energy transferred by the LSM.

Published papers have sometimes stated that linear motors are inefficient as compared with rotary motors. The correct statement is that designers must often make a compromise between efficiency and cost. For maglev LSM the duty cycle is low so it is possible to use much higher current densities in the winding than are possible for a rotary motor that must operate with 100% duty cycle. This allows us to opt for a design with lower efficiency and lower cost without creating excessive temperature rise in the stator. But we can also achieve high efficiency if the added cost can be justified.

It is important to make a distinction between motor efficiency and system efficiency. Bombardier has installed several transit systems with LIM propulsion and these systems are able to use lighter vehicles with smaller wheels and operational statistics show that the total energy consumption is typically less than with rotary motor powered transit systems. The LIM is not more efficient, but the system is. The rest of this section is devoted to an analysis of the efficiency of the LSM to show that the overall system efficiency can be outstanding. The design problem is to achieve a compromise between cost and efficiency.

The important criteria is to achieve good efficiency over a complete trip while producing less noise, requiring less maintenance, and being able to accelerate and brake rapidly so as to negotiate curves and stops. Fig. 5(a) and (b) shows propulsive and drag force vs. speed for Siemens Velaro high-speed train [2] and *M3+*. Note that maglev can maintain full speed up a 3% grade while HSR will have to slow dramatically and this has major implications on a route with hills and sharp turns. Maglev systems can be designed to negotiate 10% grades and this can be a major advantage in hilly terrain. For example, in the case of the Los Angeles to Los Vegas trip in Fig. 1 the trip distance and time could be reduced by allowing 10% grades.

1) Blocks and Subblocks: An LSM has the property that the stators are divided into blocks with a restriction that only one moving vehicle can be in one block at one time. The block length needs to be short enough to allow the desired vehicle headway, but otherwise can be quite long [10]. But if it is much longer than the vehicle, there will be substantial losses in the part of the stator that is not producing force. The way to reduce loss is to divide a block into subblocks with switches for each subblock that allow one inverter to excite more than one subblock. (Some papers use the term block to refer to what is here called a subblock.)

There are many ways to do this, but a simple way is shown in Fig. 6. Inverters A and B drive alternate subblocks with switches used to control which subblock is excited. This "leap-frog" scheme allows 2 inverters to drive an arbitrarily long block without exciting too long a stretch of stators that do not contribute to propulsion. Each subblock for each motor requires a 3-phase switch, but a switch costs much less than an inverter, so there is a major cost saving. The block length is determined by minimum

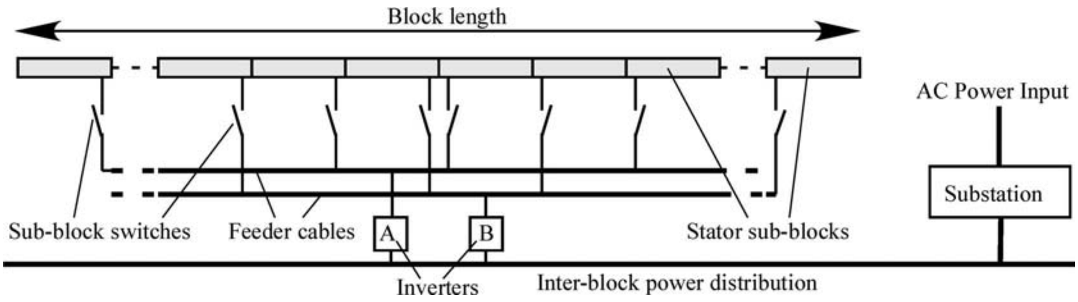


Fig. 6. *Leap-frog subblock switching scheme.*

vehicle headway but if it is too long the feeder cable power loss will be excessive.

As an example, if the vehicle is 10 m long and the subblock is 12.5 m long, 1/5 of the time there is only one inverter operational and 4/5 of the time there are two operational. From a loss perspective it is as though a 22.5-m block was active all of the time. There are ways to control the current to reduce this loss, but this can create pulsating forces, both horizontal and vertical, which would affect ride quality. For a conservative analysis we calculate loss on the basis that the active subblock length is the vehicle length plus the physical subblock length.

If the subblock length is at least twice the vehicle length, then it is possible to use three inverters for the combined port and starboard motors. With this scheme, called three-step or triplex, the inverters alternate sides. Both TR and YTL use this scheme because they have long subblocks.

For High and Super Speed the vehicle is long and the power high so there can be advantages in using three inverters per block per motor, with inverter A driving blocks 1, 4, 7, . . ., inverter B driving blocks 2, 5, 8, . . ., and inverter C driving blocks 3, 6, 9, ... At least two subblocks will be excited at all times and three subblocks will be excited part of the time. For *M3+* the vehicle is 50 m long and if the subblocks are 25 m long then the three inverters will always excite 75 m. The subblock length does not have to be constant and can vary with the terrain to reduce cost. Using more inverters with shorter subblocks leads to higher efficiency and helps reduce the voltage required to for the windings. Power electronic cost is almost proportional to inverter MVA rating so there is not a large cost disadvantage to using more and smaller inverters, and inverter cost is not dominant. This multiple inverter scheme has been used successfully for low-speed elevators lifting heavy loads and can be a good solution for high-speed maglev.

2) Power System: The power system design is critical to achieving high efficiency at reasonable cost and the optimum design depends markedly on the speed range and vehicle size. This section compares various designs of proposed and actual maglev installations.

Low and medium speed M3: For this speed range the power system resembles conventional transit with a dc bus used for interblock power transfer. For the power levels involved and with today's technology the most cost-effective way of exciting stators is to use IGBTs with a 1200-V rating powered from a 600- to 750-VDC bus. When the vehicle is being magnetically braked power is fed back to the bus and used by nearby vehicles, returned to the utility grid, or (hopefully not!) dissipated in resistors. The most efficient solution is to transmit ±750 VDC plus ground. With port and starboard inverters operating off of different polarities we can distribute most of the power at the 1500-V level. Rectifier substations can be located at intervals of 4–10 km as with conventional transit, except that the dual voltage provides redundancy and higher efficiency.

Electronics for converting ac to dc and then back to ac are a key part of the power system. Simulations show that the inefficiency of these over a complete trip is on the order of 4%–5%. When combined with losses in transformers the conversion typically has an average efficiency on the order of 92%. This efficiency is applicable to power being supplied either way, from dc bus to propulsion or the reverse.

TR09: TR09 is the latest TR vehicle. It has high vehicle efficiency but the LSM has low propulsion efficiency which makes it impractical to achieve high acceleration rates. This inefficiency is due to the propulsion system design, which is dictated by the decision to use wide, heavy trains of up to 10 cars operating at speeds up to 500 km/h. Following is an explanation of the origin of this inefficiency for the simulated trip from Anaheim to Las Vegas shown in Fig. 1.

The Anaheim to Las Vegas simulation assumed an eight-car TR08 train. TR08 is an older version of TR09 but the vehicle attributes are similar. The simulation assumed 480 passengers. The design used "12 substations with 36 blocks per substation and two blocks on," which in the language used here means a block length and substation spacing of 36 km and 2-km-long subblocks. With 216 subblocks the average subblock length is roughly 2 km, but varies with terrain. The eight-car train has a magnetic length of 197 m, so the subblock is about 10 times the train length, and they use the "three-step" switching scheme. The average block length is about 36 km so power has to be transmitted by feeder cables an average distance of 9 km. These long blocks and subblocks lead to an LSM inefficiency of about 30% for the Anaheim–Las Vegas trip. In addition, the substation inefficiency is about 12%.

The motor constant is given as an average of 42 N/A per car so to achieve 1 m/s^2 acceleration with a loaded car weight of 67 Mg the current must be 1600 Arms per phase per motor, and the resistance loss in 1.1 subblocks is 12 MW, essentially independent of how many cars are in the train. In order to reduce this loss the acceleration in Fig. 1 is rarely over 0.5 m/s^2.

In short, the motor inefficiency is an order of magnitude higher than for a comparable rotary motor. This is not due to faulty engineering, but is the only affordable solution for propelling wide, long, and relatively heavy super speed trains. The decision to use long trains was an attempt to provide direct competition with HSR before it was fully realized that maglev is most efficient and affordable when operated with short, light vehicles. If trains can go long distances with no need to slow for curves, then long trains are a good solution, but for typical routes with curves and stops it leads to high losses, limits on acceleration, and difficulty in maintaining a high load factor.

MLX01: The MLX01 is designed for operation at 550 km/h and uses a long stator LSM, but the wavelength is 2.7 m so the excitation frequency at maximum speed is only 56.6 Hz. There is no iron in the stator so there is more room for winding conductors and skin and eddy current effects are negligible, assuming the wire uses insulated strands. This makes it possible to achieve high acceleration with fair efficiency. The design is based on 80% operation in tunnels so slowing for turns is not too important. The evolution of high-temperature superconductors and better high-voltage semiconductor switches will help to reduce cost of this system and it is very likely that EDS is the best solution for speeds of 450 km/h and above. The chief problem with this design is that there are few corridors in the world where a straight enough guideway can be built without tunnels or where the relatively high cost of tunnels can be justified by transport demand. In spite of major efforts at streamlining the EI is unavoidably high because of the high aerodynamic drag force.

M3+ power system: This design assumes the use of a two-car train operating at speeds up to 400 km/h (249 mi/h), acceleration of 1.6 m/s^2 up to 60% of maximum speed, and LSM braking at 1.6 m/s^2 at all speeds.

For *M3+* the chain of design decisions starts with the use of a two-car train with minimum mass so the total force requirement is reduced, and there is a focus on reduced cost with a top speed of 400 km/h. Short trains require short headway, but with high acceleration and braking rates it is possible to get the same capacity as TR09 and HSR. For minimum cost it is most effective to use thyristors for subblock switching. For a cost-effective design this limits the stator excitation voltage to about 2.5 kV_{rms}. This reduced voltage also means less need for insulation so a high slot fill factor can be achieved. The problem is to reduce cost without limiting acceleration.

One option for interblock power transfer is a dc bus with voltages on the order of ±15 kV dc, but with available power semiconductor technology it may be more cost effective to use 60 Hz, 3-phase power. This is similar to the scheme used by HSR: pantographs pick up 25 kV single phase ac and transformers and rectifiers on the train generate 570–700 VDC for onboard inverters that drive rotary synchronous or asynchronous motors. A detailed study is needed to optimize the design, but for *M3+* assume the use of 3-phase ac for interblock power transfer with a voltage on the order of 33 kV that can be distributed using underground or in-guideway cables. At suitable intervals the 33 kV would be provided by connections to the utility grid.

Assuming a one minute minimum headway with a speed over 250 km/h and a vehicle length of 50 m, for most of the guideway we can use 4-km blocks, 25-m subblocks, and an inverter substation every 4 km that contains the inverters for a dual guideway. The inverters can be constructed using multilevel converters [11] for each of six inverters per block per direction. This scheme then uses essentially the same inverter modules as used by *M3* but eight times as many per block. The blocks are more than eight times longer, so the inverter and two-way rectifier cost per km is about the same, and does not dominate system cost. With this design the LSM inefficiency for a complete trip is about 8% and the substation inefficiency is about 12%.

Very possibly, future evolution of the silicon carbide MOSFET will make it feasible to use higher voltages with lower losses and reduced cost, but the proposed design achieves the E&A objective.

3) *Winding Impedance:* We have seen that power dissipation in the LSM winding and feeder cables is the primary LSM power loss under almost all conditions. This loss is proportional to the square of the phase currents and proportional to the winding and feeder cable resistance. The effective winding resistance increases with frequency due to hysteresis and eddy current losses in the stator.

The winding inductance also plays a major role at high currents and high speeds. The use of short subblocks helps, but even with short subblocks the inductance can create a need for excessively high inverter kVA rating. Simulations show that a good solution is to provide acceleration of 1.6 m/s^2 up to 60% of maximum speed and then limit inverter power output above that speed. This can reduce inverter kVA rating by a factor of two with only modest increase in acceleration time. This design allows regenerative braking at 1.6 m/s^2 over the whole speed range.

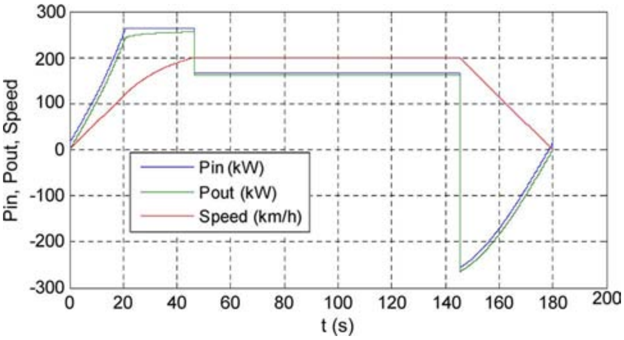


Fig. 7. ***Power in and power out for each LSM and speed versus time for an M3 trip of 8 km.***

D. Examples of Energy Intensity and LSM Inefficiency

In this section we use simulations to demonstrate the potential for low EI and low LSM inefficiency.

1) Energy Intensity Example for Medium Speed: In order to illustrate the potential for E&A maglev to achieve medium speed with high efficiency, Fig. 7 shows a simulation of power input and output for each LSM for an 8-km (5-mi) trip by an *M3* vehicle with a top speed of 200 km/h. By virtue of accelerating at 1.6 m/s^2 up to 60% of maximum speed and limiting power above that speed, we can achieve an average speed of 161 km/h (100 mi/h) with acceptable inverter size.

For Fig. 7 the vehicle was assumed to carry 27 passengers, 75% of the rated maximum load. The inverter and rectifier stations were assumed to have an overall efficiency of 92%. The total energy usage was 16.4 kWh giving EI = 76 Wh/km. The LSM inefficiency for the trip was 8.4% and for the cruise portion of the trip was 3.6%. Maximum power for the two motors is 530 kW and the inverter ratings are 460 kVA each.

The performance shown in Fig. 7 cannot be achieved by any commercially available wheel-based transport system and it shows that medium speed, but high acceleration can achieve results comparable to designs with higher speeds but lower acceleration. For example, the Pudong Airport to Shanghai TR maglev takes 7.5 min for a 30-km trip with a top speed of 430 km/h. The proposed 200 km/h design would take 9.67 min, or about 2 min longer, but at greatly reduced cost for construction and operation. The vehicles could start on demand so that high load factors are achieved and by using clusters of vehicles the capacity could exceed the capacity of the TR system. Average passenger wait times would be reduced from 7.5 min to less than a minute, so the perceived trip time is actually reduced.

2) Energy Intensity Example for High Speed: If the maximum speed is increased from 200 km/h to 400 km/h the *M3* design requires significant changes. The vehicle length should be greater in order to reduce aerodynamic drag per seat and to allow more onboard amenities. In this section an attempt is made to compare EI and LSM inefficiency of TR09 and *M3*+ for the Anaheim to Los Vegas trip. In order to make fair comparison, we assume that all cars are about 25 m long (this seems to be the norm) and that the center cars will have 18 rows of seats and the end cars 16 rows. Most high-speed trains have some cars for first class with fewer total seats, but for simplicity we assume all cars have the maximum number of seats. In computing energy efficiency we assume a 75% load factor, which is achievable with good scheduling, as witness the airlines which now average about 78%. For onboard power we assume 1 kW per seat plus power for an EMS suspension. For TR vehicles the 3.7-m width is sufficient for five seats per row but for *M3*+ the width is 2.9 m (the same as MLX01) so for long distance travel the maximum is four seats per row.

In order to make a performance comparison we created zones with maximum speeds that approximate the speed limits shown in the plot in Fig. 1. Fig. 8 shows how the two maglev designs compare in speed vs. distance. The travel time for TR08 is 92 min but only 88 min for *M3*+ in spite of the lower top speed. Table 7 compares other metrics. The acceleration and braking rates for *M3*+ are about three times larger than for TR08 so the travel time and EI are less. Additional advantages of *M*+ are: lower peak power and closer vehicle spacing makes it easier to use regenerated power; with a shorter travel time it takes fewer vehicles to handle the load and it is easier to deal with off peak loads; with more and smaller vehicles it is possible to limit any one vehicle to two intermediate stops with additional savings in time and energy.

The TR09 vehicle is more aerodynamically efficient but because of the higher maximum speed and large LSM losses the EI for the two designs are virtually the same. In actual usage the smaller trains for *M3*+ would have a lower EI because they are able to better match supply to demand, allow a reduction in the number of stops, and increase the average load factor. The high LSM inefficiency is the chief factor that prevents TR09 from achieving higher acceleration and thereby faster travel with lower maximum speed.

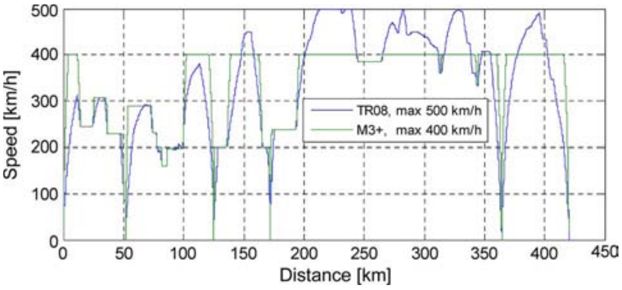
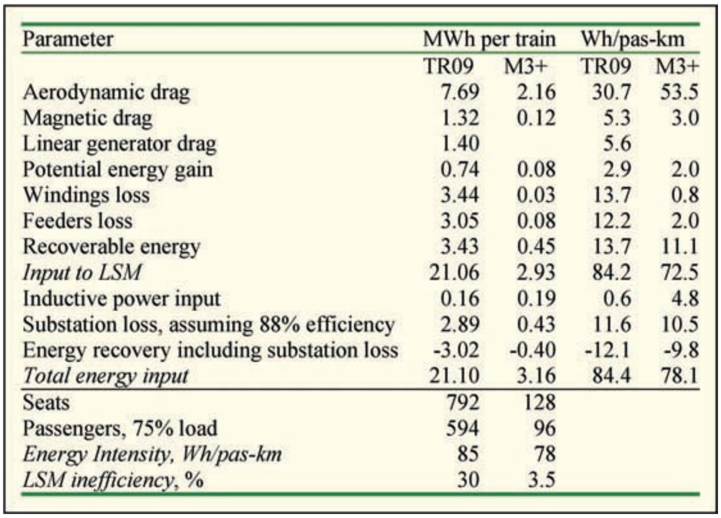


Fig. 8. ***An-LV trip for TR08 and M3+.***

Table 7 Performance Comparison of Eight-Car TR08 and *M3+* for Anaheim-Las Vegas Trip



Parameter	MWh per train		Wh/pas-km	
	TR09	M3+	TR09	M3+
Aerodynamic drag	7.69	2.16	30.7	53.5
Magnetic drag	1.32	0.12	5.3	3.0
Linear generator drag	1.40		5.6	
Potential energy gain	0.74	0.08	2.9	2.0
Windings loss	3.44	0.03	13.7	0.8
Feeders loss	3.05	0.08	12.2	2.0
Recoverable energy	3.43	0.45	13.7	11.1
Input to LSM	21.06	2.93	84.2	72.5
Inductive power input	0.16	0.19	0.6	4.8
Substation loss, assuming 88% efficiency	2.89	0.43	11.6	10.5
Energy recovery including substation loss	-3.02	-0.40	-12.1	-9.8
Total energy input	21.10	3.16	84.4	78.1
Seats	792	128		
Passengers, 75% load	594	96		
Energy Intensity, Wh/pas-km	85	78		
LSM inefficiency, %	30	3.5		

A good way to view the tradeoff between acceleration and speed is to plot contours of constant travel time in the acceleration vs. speed plane, as shown in Fig. 9. This figure also shows contours of constant EI. For example, we can achieve a travel time of 90 min by operating at 500 km/h maximum speed and 0.5 m/s^2 maximum acceleration, or we can decrease the maximum speed to 335 km/h and increase the acceleration to 1.6 m/s^2. The lower speed solution has EI = 55 Wh/km as compared with EI = 75 Wh/km for the high-speed solution. Although the details of this plot vary with the assumed speed zones and propulsion attributes, the general behavior will be the same for any practical route design.

The best way to achieve E&A maglev is to use the maximum practical acceleration and braking rates and the minimum maximum speed that achieves the desired travel time.

An interesting question is how maglev performance compares with HSR. Lacking a good model, the best we can do is make an educated guess. For the Madrid-Barcelona trip with a maximum speed of 320 km/h and an average speed of 237 km/hr we can guess that the RMS speed is about 280 km/h. Since aerodynamic drag dominates losses, and since part of the operation is at lower speeds, we can approximate the losses by using the value of 54.2 kN for drag at 280 km/h. Assuming a propulsion efficiency of 75%, a load factor of 75% or 303 passengers, and 1 kW/seat onboard power we find EI = 70 Wh/pas-km.

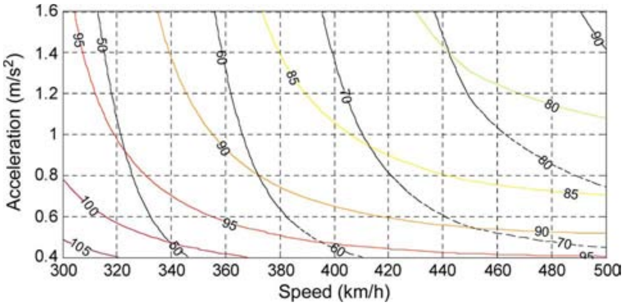


Fig. 9. ***Contours of constant travel time (minutes, colored) and EI (Wh/pas-km, black) in acceleration-speed plane.***

This is only a rough estimate but it shows that HSR is efficient but can only achieve an average speed on the order of 240 km/h (150 mi/h) even when making few stops. With maglev operating at a maximum speed of 400 km/h it is possible to achieve a lower EI, and an average speed on the order of 320 km/h, even when making fairly frequent stops.

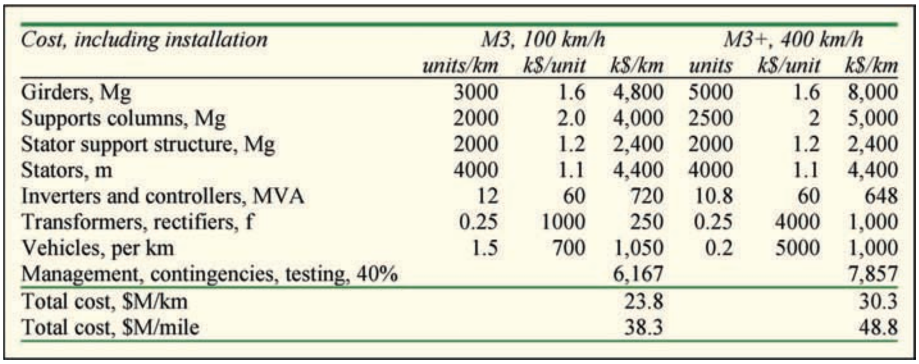
E. Cost

The cost of a low-speed *M3* is known from prototype construction and from this we can estimate the cost of a higher speed version. Table 8 shows cost for two designs with different top speeds and vehicle size, but the same basic guideway design. The principal difference is in girder stiffness, vehicle length, the number of turns per coil in the stator, and the inverter voltage and current ratings.

The inverter cost for *M3* is $60 per kVA, including the cost of controllers, power modules, filters, cabinets, etc. The higher power inverters for *M3+* are constructed from several modules similar to the ones used at low speed, so there is no difference in cost per MVA. The girder cost is nearly proportional to the mass. For higher speeds with longer vehicles the girders need to be heavier, but the stator loading per meter of guideway does not change, so stator cost per meter is the same. The costs in the table are for a dual guideway with the expectation that a single guideway would cost a little more than 50% of these values.

The cost of the low-speed design is competitive with the cost of light rail and less than the cost of APMs. The cost of the high-speed system is comparable to the cost of a new installation of HSR. For all speed ranges a maglev

Table 8 Estimated Cost for Dual Guideway *M3* and *M3+*



Cost, including installation	*M3, 100 km/h*			*M3+, 400 km/h*		
	units/km	*k$/unit*	*k$/km*	*units*	*k$/unit*	*k$/km*
Girders, Mg	3000	1.6	4,800	5000	1.6	8,000
Supports columns, Mg	2000	2.0	4,000	2500	2	5,000
Stator support structure, Mg	2000	1.2	2,400	2000	1.2	2,400
Stators, m	4000	1.1	4,400	4000	1.1	4,400
Inverters and controllers, MVA	12	60	720	10.8	60	648
Transformers, rectifiers, f	0.25	1000	250	0.25	4000	1,000
Vehicles, per km	1.5	700	1,050	0.2	5000	1,000
Management, contingencies, testing, 40%			6,167			7,857
Total cost, $M/km			23.8			30.3
Total cost, $M/mile			38.3			48.8

system designed with the E&A objective will provide faster travel, higher capacity, reduced maintenance, less noise, lower operating cost, and reduced energy consumption as compared with HSR.

The cost is about $24 million per kilometer for low and medium speed and 25% higher for high speed. By far the largest cost is for the guideway, stators, and stator support structure. These costs are nearly proportional to the mass and the cost advantage of *M3* as compared with TR09 is due to a reduction in these masses by more than a factor of two. Propulsion for TR09 requires 7.5 MVA per km compared with 10.8 MVA/km for *M3+*, but *M3+* uses lower voltages that tend to cost less per MVA and inverter cost is not dominant.

In short, the *M3+* design retains the average speed and vehicle efficiency of TR09 but with more efficient propulsion that allows higher acceleration, lower maximum speed for the same travel time, lower cost capital and operating cost, and greater operational flexibility.

V. APPLICATION EXAMPLES

A. Low Speed, Up to 100 km/h

In this speed range maglev can beat any competition on performance and cost, including both capital and operating cost. A good example is the APM contract for a Miami Airport APM to be installed by 2011. The complete system cost is $259 million for a 2.04-km-long dual guideway and eight vehicles. This system is slow and inefficient by the standards discussed here, but it has been proven to be reliable, the most important attribute to an airport. Someday maglev should be the only system considered for this application, but other applications will have to prove the reliability before this market is open to maglev.

Maglev can also compete with PRT. The Heathrow Ultra PRT installation [26] is a 3.8-km (2.36-mi) loop that could be serviced by a fleet of five 36-passenger *M3* vehicles circulating with headway of 1 min. There is no need for the land area and cost associated with offline loading and the system could handle several times as many passengers per hour for the same installation cost. Maglev with a noncontact suspension, minimal use of mechanical brakes, no pneumatic tires, no use of batteries for propulsion, and fewer vehicles should lead to dramatically lower maintenance cost with no increase in energy usage. This type of short, noncritical system is a good place to develop a reliable transport system with the ultimate objectives of replacing all wheel-based airport APMs.

Examples of near term applications in the United States include college campuses and entertainment centers where there is a need to allow people to travel distances too long for walking without the campus becoming cluttered with cars and parking lots. Once a design is proven in less demanding applications like this it should be the preferred choice for airport shuttles and a cost-effective alternative to light rail.

B. Medium Speed, Up to 200 km/h

In this speed range maglev offers outstanding opportunities for connecting airports to cities and as a replacement for commuter rail or heavy rail. For example, New York City is constructing a Second Avenue Subway 8.5 mi (13.7 km) long with 16 stations. The projected cost is about $2 billion per mile ($1.24 billion per km) and while most of this is for constructing tunnels there is a good chance that a fully proven maglev design could offer lower capital cost and much lower operating cost.

Maglev is very competitive for replacing commuter rail. In the United States there are many commuter rail lines that are not used to capacity at peak times and grossly underutilized at off peak times. Traveling at speeds up to 161 km/h (100 mi/h) and with shorter and fewer stops, typical travel time could be reduced by almost a factor of two with no increase in operating cost. Transportation from a city to a remote airport is another excellent application for medium speed maglev.

C. High Speed, Up to 400 km/h

In this speed range it is unlikely that maglev can be sold as a replacement for existing HSR, but it can provide higher performance at the same cost for any new installation.

Europe and Japan have excellent HSR service that is very cost-effective because a high percentage of travel is between large cities. Velaro trains are or will be operating in Spain, Germany, China, and Russia. The Japanese Fastech 360 train is now operating in Japan and the newest Alstom AGV is planned for France and Italy. These trains were designed for 350 or 360 km/h but technical problems have prevented significant commercial operation over 320 km/h. HSR will probably eventually operate at 360 km/h but not much higher. The AGV record of 574.8 km/h (357.2 mi/h) was achieved on a test run on a very straight section of track at great cost, and this is not indicative of a commercially viable operating speed.

We should perform a new study of the potential for maglev in lieu of HSR from San Diego to Sacramento, CA. Initial funding for this project has been voted with the objective of train service at speeds up to 360 km/h (224 mi/h). A study in 2005 made the following determination:

> Authority studies have shown that maglev technology would have higher potential maximum speeds and could accelerate and decelerate more quickly, than steel-wheel-on-steel-rail technology but would require more energy to operate and be more expensive to build [19].

For a given travel time TR09 maglev system would use less energy than any HSR and with E&A maglev both cost and efficiency arguments are mitigated. The other significant argument in favor of HSR was the need to use existing rail corridors. With light, quiet vehicles operating at speeds up to 400 km/h maglev can operate on a guideway that is high enough to be installed over an operational railroad and even use existing stations. Any right-of-way suitable for HSR can be used by maglev with the same top speed but much lower travel time. It can also connect to airports and other transportation hubs and, where necessary, it can be installed underground for less cost than for HSR. Maglev would offer significantly shorter travel times, lower noise, less maintenance, and less energy consumption for a given travel time. The existing rail lines can be then be used for freight and slow-speed passenger service.

The 695-km (432-mi) trip from San Francisco to Los Angeles is planned to take 2 : 38 for an average speed of 264 km/h (164 mi/h), the same time it currently takes for nonstop service on the 70-km-shorter Madrid-Barcelona route. It is doubtful that this trip time objective can be achieved for nonstop service and, more important, the plan includes 11 intermediate stations and there will be serious problems in using eight-car, slow accelerating trains to provide adequate service to these stations. Maglev could definitely meet this trip time objective *and* provide good service to the intermediate stations. If every E&A maglev train made three stops per trip then every station pair can be serviced at least once per hour with a total time penalty of only 5 min per trip while providing a San Francisco to Los Angeles trip time of 2 h.

Many countries that do not have extensive installations of high-speed train service now have plans to install HSR. E&A high-speed maglev should be considered for all of these applications and this creates a major potential market for maglev.

D. Super Speed, Up to 600 km/h

Most maglev development to date has been in this speed region, perceived as an upgrade to HSR. The only real competition is commercial jet, but there is an important question: Can super speed be justified in light of higher cost, greater noise, stringent requirements on straightness, and time and energy cost associated with the need to stop or slow for curves in the guideway. The minimum radius of curvature increases as the square of the speed, the propulsive power increases as the cube of speed, and external and internal noise and guideway tolerances become increasingly difficult to manage at speeds over 400 km/h.

In spite of the cost and performance issues, in the United States there are now four proposals for installing 500 km/h (311 mi/h) maglev systems based on TR technology. It is likely that 400 km/h E&A maglev could provide comparable or lower travel time at substantially lower cost.

There is an active proposal for maglev in England to connect London to Glasgow with a top speed of 400 km/h. Possibly a cooperative effort could develop a design that is suitable for both the U.K. and the United States.

E. Subsonic, Up to 900 km/h

This is the range where maglev is competitive with air for long trips, but it is also a range not accessible with any proven maglev design. It is highly probable that someday we will have partially evacuated tubes carrying passengers at speeds at or above 600 km/h, but it will take substantial funding to develop a propulsion and suspension system that is both efficient and affordable. This is a good domain for visionaries who want to grapple with the myriad problems that must be solved.

It is assumed that trip distances will be at least 800 km (500 mi) and travel must be in a very straight line, preferably in a partially evacuated tube to reduce drag. The tube pressure could gradually decrease as the vehicle accelerates into the tube so there is no need for pressure locks. Here is an idea based on the belief that we need basic concepts not currently developed in any detail.

Use high-temperature superconducting meander coils in the guideway to support a vehicle using EDS and use onboard fuel cells to power a short stator LSM for propulsion. The vehicle would be sized like a commuter jet with short wings used for suspension, LSM propulsion, and aerodynamic control. Rough cost estimates suggest that the hardware can be built at a reasonable cost *if* we can find a way to install the tubes at less cost than it now costs to build a subway. This is a variation on Hooke's 17th century idea of the Gravity Train,[1] but with a linear motor replacing gravity, and Bachelet's 1912 patent # 1 020 942 for reverse EDS, only on a much larger size and speed scale.

Others should come up with similar ideas with the objective that someday we can have ground transportation that is competitive with air for long distance travel. In the meantime, I believe the focus should be on E&A maglev at all speeds up to 400 km/h, with the ultimate objective of increasing speed with evacuated tube designs.

VI. U.S. MAGLEV DEVELOPMENT

A. A Short History of U.S. and U.K. Maglev Projects

Other papers in this Special Issue [14]–[17] have discussed the history of maglev, but primarily from the perspective of European and Asian efforts. Although Germany, Japan, China, and Korea have devoted far more resources to maglev development, the U.S. and U.K. have made some important contributions.

Emile Bachelet, an American citizen born in France, was far ahead of his time when he conceived of a way to suspend, guide, and propel an object using magnetic forces that Faraday had explored almost a century before. Bachelet worked in the United States and England and devised a maglev system that used EDS and LIM propulsion to drive a cigar shaped aluminum "vehicle" that was about 1 m long, and suspended by "reverse EDS." This was demonstrated in 1912 but there was not enough supporting technology to make it practical for transport. Graemiger worked on EMS in 1911 but little is known about this effort. Starting in 1922 in Germany Hermann Kemper developed an EMS design. This effort was also ahead of its time but was an important stimulus to the German attempts to build practical maglev systems.

The modern maglev era began in the 1960s with pioneering work that included:

- papers by Powell and Danby on an EDS system using superconducting magnets;
- EDS and EMS prototypes developed by what became the German TR consortium;
- studies by a Japanese group on linear motors and EDS designs;
- small prototype demonstrations in the United States and Canada;
- many published papers in technical journals.

The first commercial system was an airport-to-railroad station shuttle installed in Birmingham, U.K., in 1984. This system worked so well that it required very little maintenance and when it finally failed there were no spare parts available, so its developers abandoned it after eight years of successful operation. It has been replaced by a cable-propelled, wheel-suspended system and one of the old maglev vehicles is in the York Transportation Museum in England. This regressive development is particularly ironic since it occurred shortly before the United States initiated funding of the Urban Maglev Project.

Studies and experiments in Germany, Japan, the United States, Canada, and elsewhere showed the versatility of maglev but only Germany and Japan persevered with major experimental programs. The German TR program has shown that EMS designs can operate safely at speeds up to 500 km/h (311 mi/h) and the Japanese effort has demonstrated a five-car train operating at a speed of 563 km/h (343 mi/h) and two trains passing at a relative speed of 1026 km/h (638 mi/h).

After several false starts in Germany the TR consortium worked with China to construct a 30-km-long airport-to-city shuttle in Shanghai, China. This system now carries passengers 30 km in 7.5 min at speeds up to 430 km/h (267 mi/h). The Japanese and German maglev efforts always focused on trains because maglev was perceived as a new form of high-speed train. The emphasis on trains has had a profound effect on the nature of their developments. Historically, long trains developed as the most cost-effective way to move people and freight. Trains are also used for steel wheel suspended vehicles because their limited acceleration and deceleration and lack of precise position sensing makes it unsafe to operate individual vehicles with the short headway that would be needed to achieve the required capacity.

This early maglev work was followed by the National Maglev Initiative in 1987, spearheaded by Senator Patrick Moynihan with contributions by James Powell, Gordon Danby, and colleagues at Brookhaven National Laboratory. Four teams developed concepts for high and super speed maglev, all using individual vehicles with capacities on the order of 80 to 120 passengers. In the United States maglev systems must be able to compete with airplanes and automobiles and hence designers preferred individual vehicles operating with short headway under automatic control. Unfortunately, the U.S. Office of Management and Budget terminated the initiative before any hardware was built. Work on various aspects of maglev and linear motors continued for several years with support from the Federal Railway Administration. In 2002 the Federal Transit Administration initiated the Urban Maglev Project and is currently supporting continuing efforts at General Atomics and MagneMotion.

Here is a short summary of some of the early efforts:

- In 1942 Robert Goddard, of rocket fame, was issued a posthumous patent on a form of vacuum tube transportation that resembles space travel in a tube. He was not the first to suggest the use of evacuated tubes and had no suggestion for suspension or propulsion.
- In 1955 Gilbert showed how to use electronic control to stabilize EMS.
- In 1959 Polgren, from the U.K., proposed levitation via permanent magnets on the vehicle repelling permanent magnets on the guideway.

- Starting about 1962 Powell, later joined by Danby, developed an EDS design using superconducting magnets on the vehicle in conjunction with a "null flux" suspension that greatly improved the efficiency of EDS. The Japanese adopted a variation of this suspension for their super speed maglev development, leading to the latest MLX01.
- In late 1960 Guderjahn and Wipf proposed EDS for rocket launching.
- In October 1968 both SRI (Coffey, Chilton, Barbee) and Atomics International (Guderjahn, Wipf, *et al.*) presented papers on maglev at the Applied Superconductivity Conference in Gatlinburg, TN. These papers introduced the maglev concepts to the U.S. community.
- In November 1968 Howard Coffey wrote a Research Brief, "The use of superconducting magnets for suspension and guidance in high speed ground transportation," in which he used the term maglev to describe a "transport system using magnetic suspension and propulsion."
- In late 1960s and 1970s, with support from FRA, teams at Stanford Research Institute (Coffey, Chilton, Barbee, and others) and Ford Motor Company (Reitz, Borcherts, and others) built EDS and EMS maglev vehicles.
- Starting in 1969, with support from the National Science Foundation, an MIT team (Kolm, Thornton, and others) built the first operational long stator LSM for maglev and used it to propel an EDS vehicle with superconducting magnets.

In summary, the U.S. work was particularly important in developing superconducting EDS and long stator LSM propulsion technology. References [24]–[34] are representative of the earliest U.S. publications.

B. Early U.S. Patents

Some of the important early work is described in U.S. patents, a few of which are described in Table 9. Some of these patents are seminal, having been referenced by more than 50 later patents.

C. Present U.S. Efforts

The Urban Maglev Project is currently supporting two projects, one at General Atomics and one at MagneMotion. The objective of these projects is to install an operational system at a University in the United States. There are maglev research projects at Brooklyn Polytechnic University and at Old Dominion University, but none of the existing projects have enough funding to complete an operational system.

D. Future U.S. Maglev Development

In March 2009 the U.S. Government Accountability Office submitted a hundred page report to Congress on *HSR* [20]. This report considered maglev a form of HSR and did not recommend a specific technology. One of their key recommendations was:

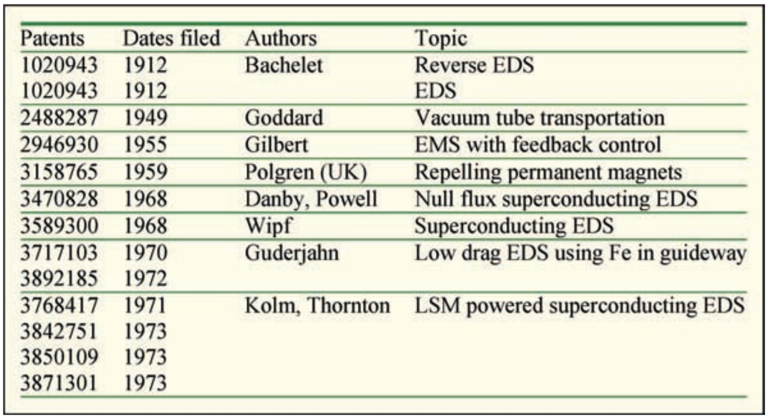
> Develop a written strategic vision for high speed rail, particularly in relation to the role high speed rail systems can play in the national transportation system, clearly identifying potential objectives and goals for high speed rail systems and the roles federal and other stakeholders should play in achieving each objective and goal.

In April 2009 the Federal Railway Administration submitted a report to Congress on a *Vision for High Speed Rail in America* [21]. This document elucidated four Strategic Transportation Goals:

- Ensure safe and efficient transportation choices.
- Build a foundation for economic competitiveness.
- Promote energy efficiency and environmental quality.
- Support interconnected livable communities.

Maglev can play a major role in achieving the objectives elucidated in these reports.

Table 9 Early U.S. Maglev Patents



Patents	Dates filed	Authors	Topic
1020943	1912	Bachelet	Reverse EDS
1020943	1912		EDS
2488287	1949	Goddard	Vacuum tube transportation
2946930	1955	Gilbert	EMS with feedback control
3158765	1959	Polgren (UK)	Repelling permanent magnets
3470828	1968	Danby, Powell	Null flux superconducting EDS
3589300	1968	Wipf	Superconducting EDS
3717103	1970	Guderjahn	Low drag EDS using Fe in guideway
3892185	1972		
3768417	1971	Kolm, Thornton	LSM powered superconducting EDS
3842751	1973		
3850109	1973		
3871301	1973		

The rest of this section describes ideas that should be considered.

There are four active proposals for super-speed maglev installations in the United States, but none have sufficient funding to create an operational system. More details on these can be found in [38] and on the Internet. Equally important, there are several proposals for wheel-based transit systems that are amenable to maglev, if there was a proven design that was clearly Efficient and Affordable. Following are a few examples.

- California has initiated an HSR Project for San Diego to Sacramento via Los Angeles and San Francisco;
- Construction of the new Second Avenue Subway in New York City shows the cost of conventional technology and studies should be made of cost for a comparable maglev system;
- Miami, Atlanta, Chicago, and many other large airports are installing or upgrading APM installations;
- Several college campuses would like to install people movers to alleviate parking and congestion problems;
- Several cities are planning urban light rail or bus rapid transit.

The total cost of all of these projects is in excess of \$100 billion and none of this is proposed to employ U.S.-originated technology. The only significant contributions of U.S. technology to modern public transportation are commercial aircraft manufactured by Boeing. In the areas of HSR, APM, PRT, and maglev, there is no U.S.-originated technology that has been developed to the point of commercial application. Here is a recommendation to change this:

The United States should fund three efforts:

1) Continue the Urban Maglev Project to the point that at least one installation is operational. The design should be completed and tested to the point it can be seriously considered for all of the low and medium speed applications listed in Table 1.
2) Fund a team to complete a detailed design of a maglev system for high-speed maglev. The team should study the MLX01, TR09, and proposed *M3+* designs and decide which features of each are best with a particular focus on how newer technology (including particularly high-energy permanent magnets, high-temperature superconductors, and microprocessor-controlled power electronics) might facilitate major reductions in cost and EI. The initial design should be focused on developing E&A maglev operating at speeds up to 400 km/h with the potential to increase this speed when the technology matures. If detailed analysis shows that E&A maglev is competitive with HSR and suitable for multiple installations in the United States, then a full-scale test track should be constructed and the design completed to the point that it is ready for commercial application.
3) Fund preliminary studies of subsonic maglev with design and simulation done in sufficient detail to determine if aircraft-like speeds can be achieved with justifiable cost for installation and operation. The performance should be cost competitive with air travel for routes over 1000 km that have sufficient demand. If the initial studies are promising a follow-on development should be funded.

The total cost of this proposal is a very small fraction of the money that might be spent on foreign transportation technology over the next few decades. Many U.S. companies have expertise that could be applied with major benefits to both the environment and the economy.

The United States should explore the possibility of creating a maglev development project in consort with other countries that are currently exploring major installations of HSR or maglev including: the U.K., China, Korea, England, Switzerland, and several countries in South America and the Middle East.

VII. SUMMARY

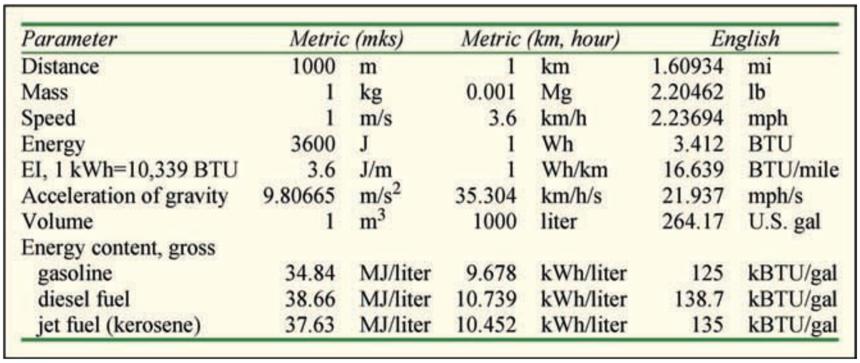
The keys to fast and efficient transportation are:

- Minimize vehicle weight so guideways can be light and kinetic energy reduced.
- Use a vehicle shape and size that minimizes aerodynamic loss.
- Operate vehicles in a way that achieves a high load factor.
- Use the maximum practical acceleration and braking rates so as to achieve the desired travel time with the lowest possible maximum speed.

Maglev offers the best way to achieve these goals: the suspension system allows more efficient vehicles; linear synchronous motor propulsion allows the vehicle to be light and avoids the need to transfer propulsion power to the vehicle; a propulsion system that does not depend on communication with the vehicle for control or on friction for braking can operate safely with a short headway; rapid acceleration reduces the time penalty for stopping and slowing for curves; and small vehicles operating with short headway make it possible to better match supply to demand and achieve a high load factor.

Most important: focusing on reducing travel time instead of increasing speed can lead to a system that is less expensive to build and operate as compared with wheel-based technology. Maglev has the ability to achieve much higher acceleration and braking rates than steel wheels on steel rail. Designs that take advantage of this fact will be the most efficient and cost effective. Maglev's greatly reduced noise, improved ride quality, and reduced energy consumption will make it much easier to sell high-speed ground transportation.

Table 10 Conversion Constants and Energy Content



Parameter	*Metric (mks)*		*Metric (km, hour)*		*English*	
Distance	1000	m	1	km	1.60934	mi
Mass	1	kg	0.001	Mg	2.20462	lb
Speed	1	m/s	3.6	km/h	2.23694	mph
Energy	3600	J	1	Wh	3.412	BTU
EI, 1 kWh=10,339 BTU	3.6	J/m	1	Wh/km	16.639	BTU/mile
Acceleration of gravity	9.80665	m/s^2	35.304	km/h/s	21.937	mph/s
Volume	1	m^3	1000	liter	264.17	U.S. gal
Energy content, gross						
gasoline	34.84	MJ/liter	9.678	kWh/liter	125	kBTU/gal
diesel fuel	38.66	MJ/liter	10.739	kWh/liter	138.7	kBTU/gal
jet fuel (kerosene)	37.63	MJ/liter	10.452	kWh/liter	135	kBTU/gal

Maglev can and should be the transportation technology of choice for many applications over a wide speed range in the United States and elsewhere. If we develop next-generation maglev with a focus on E&A, then capital cost will be comparable to or less than for competing wheel-based technology and operating cost, energy consumption, travel time, and maintenance will all be reduced. There is a window of opportunity for the United States to play a major role in this development before many billions of dollars are committed to technology that is slower and less efficient. When this technology is employed to develop E&A maglev, market pull rather than technology push can lead to widespread installations. ■

APPENDIX
CONVERSION CONSTANTS

Table 10 provides a number of conversion constants and the energy content of various fuels.

Acknowledgment

In 40 years of working on maglev and linear motor development I have benefited from the work and ideas of many outstanding people. Thanks to: Henry Kolm who directed the MIT Magneplane project; the many participants in the National Maglev Initiative; and the Department of Transportation, particularly FRA and FTA, for support and management of U.S. maglev development. I owe a dept to Tracy Clark, Brian Perreault, and Marc Thompson for their MIT research that was crucial to continuing the effort. Tracy and Brian have made major contributions to the MagneMotion *M3* Maglev project, as have Jim Wieler, Mike Bottasso, Jesse Mendenhall, Steve Levine, Todd Webber, and many more, including our vendors. I thank John Harding and John Coffey for contributions to the early history of U.S. maglev. Particular acknowledgement goes to Senator Daniel Patrick Moynihan, without whose effort there would have been very little early support of U.S. maglev. Perhaps *M3* should stand for Moynihan Memorial Maglev.

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