Comparison of High-Speed Rail and Maglev Systems

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Abstract: European and Japanese high-speed rail (HSR) and magnetically levitated (maglev) systems were each developed to respond to specific transportation needs within local economic, social, and political constraints. Not only is maglev technology substantially different from that of HSR, but also HSR and maglev systems differ in trainset design, track characteristics, cost structure, and cost sensitivity to design changes. This paper attempts to go beyond the traditional technology comparison table and focuses on the characteristics and conditions for which existing European and Japanese systems were developed. The technologies considered are the French train a grand vitesse (TGV), the Swedish X2000, the German Intercity Express (ICE) and Transrapid, and the Japanese Shinkansen, MLU, and high-speed surface train (HSST).

INTRODUCTION

All the privately financed high-speed rail (HSR) and magnetically levitated (maglev) projects proposed in the 1980s and early 1990s failed to reach the implementation stage. There is a growing realization that public participation may be necessary for the successful implementation of high-speed rail (HSR) or maglev systems and integration with existing transportation modes. Public assistance may involve direct subsidy, right-of-way acquisition, grade separation of crossings, and/or tax incentive provisions. Public financial participation will require state transportation officials to play a more active role in studying the need for and role of HSR within a comprehensive and balanced transportation policy, matching need and technology within local constraints, and selecting suitable alignments and track infrastructure. A review of the characteristics and underlying objectives for which each of the existing HSR and maglev systems was developed would assist planners in better matching technology with local need. The technologies reviewed are the Shinkansen, train a grande vitesse (TGV), Intercity Express (ICE), and X2000 HSR systems and the Transrapid, MLU, and HSST maglev systems. The emphasis is on operational HSR technologies proposed for the U.S. market. Table 1 summarizes the characteristics of the Shinkansen, TGV, ICE, X2000 and Transrapid, MLU, and high-speed surface train (HSST) maglev systems.

THE JAPANESE SHINKANSEN

It was no coincidence that the first high-speed train was developed in Japan. The Shinkansen or bullet train started operation between Tokyo and Osaka in 1964, 17 years before the first French HSR line carried passengers. The Japanese government had two priorities: to reduce energy consumption and to create new development centers to reduce the pressure on large cities. Japan's total dependence on imported oil and the instability and unpredictability of oil supply have made energy conservation a top national priority for both economic and strategic reasons. Japan had in the past favored nuclear energy. Public opposition to building new plants, however, reemphasized the need for more efficient energy use. High-speed trains use less energy than airplanes and automobiles. The electric energy needed to operate the trains can be generated from various sources and is not totally dependent on imported fuel. The ridership on Shinkansen lines has consistently been high resulting in significant energy savings.

The other primary objective for developing the Shinkansen was growth management. Japan has a high population density. The rapid economic recovery was accompanied with migration to urban areas, especially to the largest cities. There was a need for new transportation facilities, but the cost of right of way in Tokyo and Osaka was among the most expensive in the world. Uncontrolled growth in large cities would have lowered highways' level of service below acceptable levels. The solution devised by the government was to develop secondary urban areas outside Tokyo and Osaka for industrial and urban relocation (Hagiwara 1977). These areas would most effectively be linked with a HSR system because air transport is too expensive for daily commuting and the trip duration by car or conventional rail is excessive.

In summary, the development of the Shinkansen was not motivated primarily by the creation of a new technology, a low cost system, or an ultra high-speed train. What the Japanese government was interested in was a high capacity and reasonably fast train that was adequate for long-distance work commuting. The Shinkansen improved on the steel rail technology but did not create technological breakthroughs. Further, the track cost was very expensive due to difficult terrain, the need for numerous tunnels and special structures, and design complications in an earthquake-prone area.

The top speed of the first Shinkansen train service did not exceed 218 km/h (136 mph). The average speed was much lower due to route alignment and in order to reduce energy consumption and noise emission. In later years, lighter and more powerful trains in addition to improved alignment and extensive use of noise barrier permitted operation at significantly higher speeds. The most recent Shinkansen (Super Hikari, Series 300) is capable of a top speed of 270 km/h (168 mph). The Super Hikari has incorporated many features found in the French and German high-speed trains.

The Shinkansen has a modular structure, which means that cars can be added or taken off a train. All cars are self-propelled and, therefore, can be added to a train without affecting the train's acceleration rate. The propulsion is based on electric power supplied through an overhead catenary power distribution system. All Shinkansen lines are grade-separated, built on exclusive right of way. Japan's difficult terrain and limited right of way have required the construction of numerous tunnels and bridges. For instance, the 515-km line between Tokyo and Osaka has 66 tunnels and more than 3,100 bridges, accounting for almost one-third of the distance; and the rail link

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TABLE 1. Comparison of Operating HSR and Maglev Trainsets

Technology (1)	TGV-A (2)	ICE (3)	X2000 (4)	Transrapid (5)
Trainset composition	1P-10T-1P	1P-10T-1P	1P-5T	1P-4T-1P
Trainset length (m)	237.6	410.7	140	153.1
Total weight (t)	484	950	338	342
Capacity (passengers)	485	759	255	608
Weight per passenger	1.0	1.25	1.32	0.56
Top speed (km/h)	300/320	280/300	200/240	350/500
Maximum gradient (%)	5	4	3	10
Maximum superelevation (degree)	7.1	7.1	6 + 6 tilt	12
Power car weight (t)	67.8	78.2	73	45
Starting effort (kN)	212	200	160	—
Continuous rating (kW)	8,800	9,600	3,260	(1.5 kA)
One-h rating (kW)	10,400	—	—	—
Continue with rating weight (kW/t)	18.2	10.1	9.64	—

to the north island of Hokkaido required the construction of a $5.6 billion 51-km Seikan Tunnel and other special structures (Vranich 1991).

Right after the Tokyo-Osaka Shinkansen line was opened, it experienced a phenomenal increase in ridership and has since consistently operated at a profit. Additional Shinkansen lines serving less populated cities were gradually added to the rail network. The operation of some of these newer lines is still subsidized by the government. Japan has more than 1,300 mi of high-speed tracks, and more lines are planned. The Shinkansen lines are carrying more than 125,000,000 passengers annually with a perfect safety record and a 99% on-time arrival rate (Vranich 1991).

THE FRENCH TGV

The development of the French TGV train was in response to different criteria than the Japanese Shinkansen. The French government was interested primarily in a cost-effective system and a technology they could export. The initial planning was for the Paris-Lyon route, France's most traveled corridor. Rail and highway traffic on that corridor were near saturation levels. The choices were to add tracks to the old rail line or to construct an entirely new line. An important advantage of building a new high-speed line dedicated to passenger service is that the momentum generated by traveling at high speed would allow the train to climb steeper slopes without significant loss of velocity. Thus the alignment for the new route can be shorter and with fewer curves than the old line, which reduces right-of-way needs and construction cost. In addition, the amount of earthwork activities (i.e., cut, fill, disposal) are greatly reduced.

The initial feasibility studies indicated that a high-speed line for exclusive passenger service would be cost-effective and achieve high returns on investment. Several factors specific to France made high rates of return possible. First, the Paris-Lyon corridor was heavily traveled, which ensured high ridership, especially since the train (TGV) offered a significant speed advantage over both conventional rail and automobiles. Second, the TGV system uses the standard rail gauge. TGV trains can operate on the existing rail network at lower speeds and serve existing stations thereby minimizing the need for passenger transfer, which solve the problem of access to downtown areas and allowed the staged upgrade of existing lines permitting TGV trains to operate at incrementally higher speeds. Third, the alignment between Paris and Lyon did not require numerous special structures. No tunnels and no long bridges were needed. Fourth, the line was located mainly in farm lands, which allowed the government to move quickly and negotiate with farmers to acquire the land at minimum litigation cost. Fifth, the French legal system made it easier to acquire right of way for a new line. If a rail project was considered by the government to be "in the national interest," objections to new lines were legally unable to delay construction work. Finally, the track structure and the operation of the TGV system were designed to reduce cost. For instance, a ballasted track was used instead of the more expensive slab track used in Germany and Japan. Only TGV trainsets of equal length and power operated on each line. This uniformity of operation simplified the tasks of scheduling, signaling, monitoring, training, and maintaining the track and trains.

The French government was also interested in developing a technology it could export. It was a question of national pride and economic necessity. French manufacturers had to compete with German industry. Since the rapprochement policies undertaken by Chancellor Adenauer and General de Gaulles, Germany has become France's top economic partner in both export and import. Achieving a rail speed record was more than a technological triumph. It was essentially a powerful marketing tool.

Reducing dependency on foreign oil was also an important criterion. This was evident in France's reliance on nuclear power more than any other European country. The TGV was designed to be energy efficient. Despite the fact that energy consumption rate increases with speed, the TGV consumes less energy per seat-mile than conventional commuter trains due to the utilization of lightweight materials, improvement in the aerodynamic design, and incorporation of advanced technology.

The most important technical advances achieved by the TGV are the following:

1. TGV system operates in a fixed trainset formation. A trainset formation improves aerodynamics, lowers noise and vibration levels, and reduces operation and maintenance costs.
2. A trainset is propelled by one power car at each end. This push-pull operation is more efficient and less costly to build and service than the all-powered cars of the Shinkansen. Further, a trainset can easily reverse operation by simply switching track (the end power car becomes the front car and vice versa).
3. The TGV-Atlantic trainsets (second generation) use three-phase synchronous motors. Synchronous motors are self-commutating (no need for a commutator) and easier to maintain because a commutator would require reprofiling roughly every 300,000 km (187,500 mi). They are also lighter, more powerful, and more energy efficient than asynchronous motors.
4. Other technological improvements include a novel air-sprung suspension for intercar dampening, a computer-controlled wheel slip prevention mechanism, regenerative braking, and fail-safe electric brakes (eddy current) that operate independently of the power supply.

The Paris-Lyon TGV-SE line has attracted more ridership than predicted. It has proven to be a high technical and commercial success. The line continues to operate at a substantial profit. Revenues from the TGV-SE line paid back the infrastructure cost in 10 years instead of the originally projected 15. The TGV Atlantic (TGV-A) line became fully operational in 1991. While the Paris-Lyon line has no tunnels, the TGV-A line required 7.6 km (4.75 mi) of tunnels and 3.5 km (2.2 mi) of viaducts. In addition, new TGV lines linking France to Belgium and England were recently completed. All the new TGV lines are expected to operate at profit, although their rate of return is expected to be smaller than that of the initial TGV-SE line. The TGV rolling stock has earned a reputation of reliability, dependability, energy-efficiency, and safety. The

French National Railways' master plan calls for the building of a 2,000-mi network of 14 new TGV lines by the year 2015 (''La Vie'' 1990).

In summary, the TGV system was developed with an eye on export and cost-effectiveness. The speed record, the esthetics of the trainset, the low track cost, and the financial success of the first line were all important marketable attributes. The French government has been actively promoting the system throughout the world with a measure of success (e.g., Spain, Belgium, South Korea, Taiwan, Florida, Texas, etc.). The TGV is being promoted as a low-cost, high-speed system. Every effort was exerted to improve the cost-effectiveness of the system such as the use of a ballasted track, fixed trainset formation, and exclusive operation of uniform TGV trainsets; developing a cost-effective construction technique; and minimizing earthwork by allowing higher grades.

THE GERMAN ICE

The German and French industries began developing high-speed trains at about the same time. However, the German ICE train was introduced in 1991, 10 years after the TGV started service on the Paris-Lyon line. The Germans had different priorities in developing a high-speed rail system than the French and Japanese. Germany is located in central Europe and views its role as a bridge between Eastern and Western Europe. It was important to develop a rail network that would offer fast service for both passenger and freight trains and become an integral part of the German multimodal transport network for internal mobility and product export. These concerns were heightened by the reunification of Germany. Unlike the French attempt to minimize the TGV overall cost per mile, cost-effectiveness played a secondary role in the development of the ICE. For instance, a slab track was selected instead of the cheaper ballast track to support higher axle loading, alignment was kept at a low grade to allow freight train operation, numerous tunnels were constructed to ensure proper alignment, and advanced technology was used in trains and along the track. Although the Spanish government selected TGV trainsets for the new Madrid-Seville line; signaling equipments, power distribution systems, and track equipments were ordered from German manufacturers. The asynchronous motors of the ICE are less powerful than the synchronous motors of the TGV. Nonetheless, it is believed that the ICE trainsets and the signaling/monitoring equipments are technically slightly more advanced than those of the TGV. The ICE power car uses advanced three-phase asynchronous motors designed without wearing parts. The ICE trains are certified for maximum commercial speeds ranging from 250 to 300 km/h (156–167 mph). The traction and braking systems are largely computer controlled. The ICE is capable of regenerative braking that recovers energy during the braking phase. European countries use different power supply environments for their rail system. The ICE-M is designed to automatically identify the voltage and frequency being provided by the overhead wires and transform it to the required voltage.

The ICE passenger cars are manufactured with an aluminum body shell that provides significant weight saving and reduced dynamic loading. Aluminum is also used in the major components for the power car, such as the transformers and the gears housing. The ICE train has the lowest drag coefficient of all operating HSR systems due to a streamlined design, smooth outside surfaces, and flush-fit windows and doors. It is also quieter than the TGV because it is equipped with wheel noise absorbers and selected components are covered with noise-absorbing materials. The ICE cars are pressurized and the inside pressure is regulated by the air-conditioning (AC) system.

Unlike the fixed formation of a TGV trainset, the ICE has a modular design, which provides the flexibility to adjust the number of cars in a train to suit the demand. An ICE train has a power unit on each end and can comprise any number of passenger cars between six and 14. The ability to safely run trains of various lengths requires more sophisticated communication and signaling systems than for the TGV. Safety is ensured by heavy reliance on computer chips and optoelectronic (fiber optics) data links. The ICE like the TGV is equipped with a comprehensive computerized diagnostic system that checks all the equipment throughout the train. Each microprocessor subsystem possesses a self-diagnostic capability, and communicates with a central diagnostic unit that receives, analyzes, and stores all relevant reports. Diagnostic reports are displayed on a screen located in the power unit. Should a malfunction occur, the diagnostic system identifies the cause and displays it on a special screen in view of the driver, and simultaneously recommends an action to be taken (''ICE Facts'' 1992). The ICE uses three braking systems designed to improve passenger comfort and reduce maintenance cost. First, a regenerative brake is applied, then an eddy-current brake (based on electromagnetic attraction that acts independently of wheel/rail adhesion) is used, and finally, a disk brake is applied if necessary.

The first ICE operation was on the newly constructed Stuttgart-Mannheim and Hanover-Wurzburg lines. These two lines and the Cologne-Frankfurt line (scheduled for completion in 1996) will provide 800 km (500 mi) of new ICE track. In addition, the German Federal Railway (DB) is in the process of upgrading 3,200 km (2,000 mi) of existing tracks for ICE standards. The ICE trains currently operate at a sustained speed of 250 km/h (156 mph) on new lines and 200 km/h (125 mph) on upgraded lines.

The cost per mile of the ICE lines in Germany is two to three times that of the early TGV lines. There are many reasons for this cost disparity, the most important being the following:

1. The ICE uses slab tracks that allow mixed traffic with priority freight trains. The TGV tracks are ballasted and designed for exclusive passenger use. The TGV weight is limited to 17 t per axle (18.7 t per axle).
2. The signals and communications on the ICE lines must accommodate mixed traffic and variable-size ICE trains, while only fixed TGV trainsets having exactly the same number of cars per trainset operate on TGV lines.
3. The topography of the ICE lines is more difficult than that of the early TGV lines. Furthermore, because the ICE track must accommodate freight trains with less powerful tractive power, grades were limited to 1.25% as opposed to 3.5% for the TGV. As a result, the ICE lines required more extensive earthwork, numerous tunnels, and expensive special engineering structures.
4. The German legal system requires public disclosures and public hearings before plans for new rail lines can be approved. The ICE lines generated 360 lawsuits and 10,700 objections, which resulted in years of delay before construction could start. The French legal environment makes it easier to acquire right of way for a new line as explained earlier.

The first ICE line started operation in 1991. Early indications are that the ICE fulfilled the technical, financial, and safety expectations. The system is well received by the public and ridership is higher than expected. The reunification of Germany modified early rail-expansion plans. Current plans call for the completion of a new line between Hanover and Berlin. The competition is between the ICE and Transrapid. Other ICE new and upgraded lines are also planned. German rail experts anticipate a 30% ridership increase in the next few years.

THE ABB X2000

The X2000 is a tilt train developed by Asea Brown Boveri (ABB) and first used in commercial operation by the Swedish State Railways (SJ). The ABB Group was formed as the result of a 50-50 merger of the electronic divisions of the Swedish Asea and the Swiss BBC Brown Boveri company.

The purpose of developing the X2000 was to provide a train that can achieve higher speeds on existing tracks, thus reducing the travel time without the need to build a new line or extensively upgrade existing ones. ABB was interested in diversification due to the low demand for nuclear power plants. The company believed that there was growth potential for the HSR market because HSR provided the best answer to highway and airport congestion and to the pollution of the environment. ABB has shown strong interest in exporting the X2000 primarily to the U.S. market. The reason is that the United States, except for the northeast corridor between Washington, D.C. and New York, has not developed an HSR system and the dominance of air travel would not justify heavy investments in completely new lines. ABB owned about 80% of the stock of the Florida High Speed Rail Corporation and has indicated its continued interest in building a system in Florida based on the new 1995 request for proposal.

The first X2000 operation began in 1990 on a line 456 km (284 mi) long between Stockholm and Gothenburg. The travel time was reduced from four and a half hours to under three hours. SJ plans to utilize the X2000 in other Swedish corridors.

The X2000 offers an innovative body tilting mechanism and suspension system that enable the train to travel around curves 25–35% faster than a nontilt train and still provide the same passenger comfort level. High speed at curves is possible because the tilt mechanism partially balances the lateral acceleration caused by traveling around a curve. Achieving the same level of speed improvement for nontilt trains may require expense curve excursions from existing rights of way. The X2000 uses self-steering trucks that align the wheels on the rails on curves. The trucks improve the distribution of dynamic loading on the rails. Self-steering trucks, however, limit the maximum speed achievable on tangent tacks to a maximum of 250 km/h (155 mph). The TGV and ICE employ a truck design with a stiff primary suspension to avoid unwanted oscillations at very high speeds. Another concern is that the active tilt mechanisms add weight to each passenger car and increase the train set's mechanical complexity (Hopkins 1990). These concerns have caused some European manufacturers to abandon tilt train research.

Tilt control can be passive or active. A passive-tilt mechanism is caused directly by the unbalanced lateral forces acting at the car body center of gravity. The Spanish Talco Pendular train is an example of this technology. The X2000 uses a more complex active-tilt mechanism. The advantages of an active tilt is that the tilt operation can be controlled and monitored. A microprocessor sequentially activates the tilt mechanism of each car to ensure a comfortable transition. A computer located in each car monitors the tilt operation and performs redundant checks. The active-tilt technology principles are also used by the Canadian LRC and the Italian ETR train systems.

The active-tilting mechanism on the X2000 is adjusted to cancel about 70% of the unbalanced lateral acceleration. It is disabled at low speeds. The power car is not equipped with a tilt mechanism to ensure a good alignment between the pantograph and the catenary line. In addition to active tilt, the X2000 uses a flexible suspension system that allows axles to move independently on the rigid truck frame and keeps wheels aligned with the track (U.S. DOT 1991). The flexible suspension reduces the wheel rail forces and lateral-to-vertical force ratios while negotiating curves.

The X2000 trainset that was tested in the United States consisted of one power car and five or six passenger cars. A configuration with two power cars (one on each end) can have up to 12 intermediate passenger cars. Each power car carries four AC asynchronous traction motors, capable of delivering 3,200 kW (4,300 hp). The X2000 top speed is 240 km/h (150 mph).

The coach body is made of a steel frame. Modular construction is utilized and components are replaced via an opening in the roof. The floor is made out of wood and is isolated from the steel frame to reduce noise. Side windows are made of multilayer safety glass, designed to minimize the risk of injury during derailment. The X2000 has three braking systems: a disk brake, a regenerative dynamic brake, and an electromagnet brake.

The operation of the X2000 in Sweden has been successful. The trial runs on the northeast corridor have generated positive reactions from the public and the media. Amtrak is planning to replace its Metroliner fleet with 26 high-performance trains. A decision has not yet been made on the technology, although the X2000 seems to be a good candidate. ABB has offered to build the trains at its plant located in the state of New York.

THE TRANSRAPID, MLU, AND HSST MAGLEV SYSTEMS

The two common objectives of developing these maglev systems were to capture a share of a potential new lucrative market and to develop an environmentally friendly ground transportation technology. In the 1980s, many believed maglev systems would become the transit mode of choice for intercity travels. The justifications provided were varied. From a technical perspective, maglev systems could achieve much higher speeds than HSR because they are not limited by the wheel/rail adhesion factor and they operate without friction. The high traveling speed permits grades of up to 10%, compared with a maximum of 5% for HSR. Steeper slopes would result in significant reduction in earthwork activities, fewer tunnels and special structures, and shorter alignment in rolling terrains. The disturbance to the environment would be minimized. In addition, the frictionless operation reduces vibration, noise pollution, and maintenance resulting from wear. Maglev-exclusive guideway can be theoretically designed for much higher superelevation rates, allowing trains to travel 20–40% faster on curves. All maglev systems are constructed using lightweight materials and alloy plates similar to airplanes. The reduction in weight is translated into higher acceleration rates and lower energy consumption than HSR, at a comparable speed. For all these reasons, maglev systems were considered feasible along interstates' rights of way. The systems would compete favorably with air travel for distances below 1,000 km (620 mi). Airport capacity could be more efficiently used for longer trips.

The Germans were interested in a system that could be quickly developed and certified. In the 1970s, they experimented with electrodynamic systems (EDS) and electromagnetic systems (EMS). In 1977, the German government selected the simpler EMS technology based on conventional attractive magnetic forces. Planning for a test facility in Emsland began in 1979. In 1981, a partnership to develop the Transrapid maglev system was formed between the government, the German National Railways, Lufthansa airline, and leading German companies such as Thyssen, Messerschmitt Boelkow Blohm, and Krauss-Maffei. The Transrapid 07 was certified as operationally ready by the German government in 1992. It is being considered for a new line linking Hamburg to Berlin. In the United States, Transrapid systems were considered in feasibility studies for the California-Nevada corridors, the Orlando corridor, and other locations.

Transrapid 07 is designed for speeds of 400–500 km/h

(250–310 mph) and is capable of climbing up to 10% grades. The system requires a completely dedicated guideway that can be either elevated or near grade. Transrapid vehicles levitate by using the forces of attraction between individually controlled electromagnets arranged under the floor of the vehicle and ferromagnetic rails (stator packages) installed under the guideway. Independent suspension is provided for each magnet. A synchronous long-stator linear motor is used to propel and brake the train. Thrust is controlled by changing the intensity and frequency of a three-phase current. All critical components are error-tolerant and designed with a high functional redundancy. Operational safety is enhanced by energizing only the section of the guideway on which the train is traveling. Derailment is not possible because the suspension system wraps around the guideway (Gaede and Kunz 1989). Transrapid consumes 30% less energy than a high-speed train traveling at the same speed. Energy consumption, however, rises rapidly at higher speeds because of air resistance that increases with the square of the speed. A Transrapid trainset can consist of two to 10 sections. A two-section trainset has a capacity of 156 passengers, a ten-section trainset can carry a maximum of 1,060 passengers.

The MLU maglev system is being developed by the Japanese National Railways (JNR). The Japanese have selected the EDS technology for the MLU, which is based on superconductive dynamic levitation. Breakthrough in superconductive technology can directly benefit the MLU system. The benefits are realized in reduced energy transmission losses and lighter vehicles due to the diminished need for on-board refrigeration. A new MLU test track was recently completed. The test track has a U-shape guideway that contains coils for propulsion and guidance in the sidewalls and coils for suspension on the horizontal surface. Similar to Transrapid, MLU propulsion is provided by synchronous linear motors. The vehicle is levitated by repulsive forces between the magnetic field in the guideway and the superconducting coils of the same polarity in the vehicle's underside. Superconducting dynamic levitation is effective only at speeds above 100 km/h (62 mph). At lower speeds, the vehicle is supported and guided by pneumatic wheels that retract when the train's speed reaches 160 km/h (100 mph). Transrapid, on the other hand, can levitate at rest.

The MLU system tolerates an air gap between the vehicle's magnets and guideway of about 10 cm, which is 10 times greater than the gap allowed for the Transrapid system. The Japanese are hoping that advances in superconductivity, the light weight of superconductive magnets, and larger vehicle/guideway gap would lead to lighter vehicles and less costly infrastructure. Another advantage of the MLU's EDS technology is its inherent stability. If the vehicle equilibrium position is disturbed by high wind or passenger movement, the intensity of the repulsive magnetic field varies and creates counteracting forces that tend to restore the vehicle to its initial position. On the other hand, the EMS technology is inherently unstable. Disturbances in the equilibrium position tend to generate forces that accentuate the unbalancing forces. Therefore, the air gap of EMS systems must be monitored continuously and continuous adjustments of the magnetic forces are required.

The HSST maglev system is being developed in Japan to serve primarily as a fast people mover in urban areas. HSST vehicles levitate using an attractive electromagnetic suspension (EMS), similar to that of Transrapid. However, the propulsion system is provided in the vehicle by linear induction motors instead of the guideway, which makes the HSST less suitable for very high speeds. The HSST guideway is much simpler and less expensive than that of the Transrapid or MLU systems. Because air resistance increases with the square of the speed, the propulsion force produced by the magnets needs to be four times as large to double the speed from 200 to 400 km/h. By limiting the maximum speed to 200 km/h, the HSST can use much smaller and lighter magnets, thereby significantly reducing vehicle and guideway costs. Slower speeds allow a smaller turning radius, which combined with low noise, low vibration, low maintenance, and fast acceleration rates make the HSST ideal for urban settings.

The development of the HSST technology began in 1975. The first prototype (HSST-1) was tested in 1977. The second prototype (HSST-2) was introduced in 1978. It has eight seats and was designed for a top speed of 100 km/h (62 mph). The third prototype (HSST-3) has 48 seats and was demonstrated at the World Exhibition in Vancouver, Canada. The newest prototype (HSST-4) is designed for a top speed of 200 km/h (125 mph) and accommodates 70 passengers.

The HSST is being viewed as a fast short-distance transportation system suitable for urban environments. It is primarily marketed as a noiseless, low-vibration people mover system. It can operate on a small turning radius, and the system's stations can be integrated with buildings and parking facilities. The HSST was considered for the Orlando Demonstration Maglev Project, instead of the more expensive Transrapid, prior to the cancellation of the Demonstration Project.

Although the primary objective in investing in these maglev systems was to develop an advanced and new transportation technology, the specific strategies differed between systems. The German developed the Transrapid using conventional magnetic technology for speed implementation. The Japanese opted for the more complex superconductive magnets for the MLU system despite the uncertainties inherent in superconductive research. Their reasoning was that EDS technology is ultimately more suitable than EMS for very high-speed maglev systems. On the other hand, the HSST system was developed as a low-cost maglev system designed to operate at medium speeds in urban areas. The lower speed required fewer magnets. Vehicles are lightweight and a much simpler guideway is needed. The HSST linear induction propulsion also serves to reduce the guideway's complexity and cost.

Maglev expectations expressed in the 1980s did not materialize. The global recession of past years made government funds scarce and dampened financial institutions' interest in unproven technologies. Further, the maglev guideway cost remains quite expensive and energy consumption increases rapidly with speed.

SUMMARY OF CHARACTERISTICS

The HSR and maglev systems were each developed for specific purposes. The cost structure of these systems reflect design criteria and corridor conditions. The Japanese Shinkansen was developed primarily to link new urban centers, thereby relieving the growth pressures on largest cities. The French TGV was designed as a low-cost high-speed system for exclusive passenger use. The reliance on ballasted track and the use of fixed-formation trainsets helped reduce the system's construction and operation costs. The German ICE incorporates technologically advanced components and its slab track and way equipments are designed for mixed traffic with freight trains. To accommodate slower freight trains, the track was restricted to low grades, which required numerous tunnels and bridges. The ICE's track cost per mile is significantly higher than that of the early TGV lines, which required very few special structures. The ABB X2000 was developed for low investment alternatives. Its tilting mechanism reduces lateral acceleration and allows higher speeds on curves. The X2000 is a good solution for corridors subject to numerous horizontal curves or for incremental alignment improvements. The Transrapid maglev was developed using conventional EMS technology for speedy implementation. The Japanese MLU is be-

TABLE 2. Objectives for Developing HSR and Maglev Systems

Technology (1)	Year (2)	Main developmental objectives (3)	Infrastructure cost (4)
Japanese Shinkansen (HSR)	1963	Link new development centers to relieve growth pressure on largest cities, improve mobility, and reduce energy consumption.	Very high due to difficult terrain and need for many tunnels and special structures.
French TGV (HSR)	1981	Develop an exportable low-cost high-speed rail system for exclusive passenger use. Minimize the use of special structures by allowing high grade.	Low due to ballasted track, exclusive TGV operation of trainsets with fixed formation, and easy terrain.
German ICE (HSR)	1991	Develop a high-speed rail network for passenger and freight taking advantage of Germany's central location in Europe. Emphasis on modal integration.	Very high. Concrete track. Low allowable grades requiring numerous tunnels and bridges.
Swedish-Swiss ABB X2000 (HSR)	1990	Develop a train that can travel at a higher speed on an existing track. Identify worldwide potential market and promote system.	Low cost if only requirement is track upgrade.
German Transrapid (maglev)	1992	Develop a maglev system that can be quickly implemented and possibly exported, using proven magnetic propulsion technology.	High because track is elevated and high construction quality is required.
Japanese MLU (maglev)	Still in design stages	Long-term investment in EDS technology with the expectation that EDS is ultimately more suitable for maglev than EDS.	Very high at present. Complex technology and guideway design.
Japanese HSST (maglev)	Still in design stages	Developed as an advanced urban people mover. Advantages are fast acceleration, low noise and vibration, short turning radii, and simple guideway design.	Relatively low due to conventional EMS system, smaller magnets, and lighter vehicle and guideway.

ing developed with the long-term objective of capitalizing on the benefits of superconductivity. Advances in superconductive research could potentially lead to improved energy efficiency, reduced train weight, and simplified guideway design. On the other hand, the HSST maglev is being developed primarily as a noiseless, low-vibration, cost-effective people mover. Table 2 summarizes the main objectives for developing each HSR and maglev system.

CONCLUSION

States interested in implementing a HSR or maglev system have a large choice of technologies. Even new technologies are being proposed for the U.S. market. For instance, a new maglev system with permanent magnets and a X2000 running on fossil fuel are being proposed for implementation in Florida.

Selection of the appropriate technology for each state will depend primarily on acceptable funding levels, transportation objectives, and implementation schedule. Maglev systems require high investment cost, but they are fully grade-separated and minimize right-of-way needs. The ICE is an expensive HSR system; however, its modular structure makes it adaptable to varying demand levels and its track and signaling equipments are designed for mixed use with freight trains. The TGV is a cost-effective HSR system when it is designed for high-speed service on grade-separated lines dedicated for exclusive passenger use. Straight alignment, line electrification, grade separation, and the use of uniform TGV train sets are all required for revenue operation at very high speed, which make the TGV less suitable for incremental implementation. The X2000 is designed for a lower operating speed than the TGV or the ICE; however, it is the best suited for phased implementation because it can maximize the utilization of existing rail tracks. The incremental implementation of the system is further enhanced than the development of the fossil fuel X2000, which makes line electrification unnecessary, thereby reducing cost and allowing quick implementation.

APPENDIX. REFERENCES

Gaede, P. J., and Kunz, S. (1989). *The coach body, transrapid Maglev system.* Hestra-Verlag, Darmstadt, Germany.

Hagiwara, S. (1977). "Possible socioeconomic effects of the development of the high-speed rail service system in underdeveloped areas in Japan." *Rep.*, Michigan State Univ., East Lansing, Mich.

Hopkins, J. B. (1990). *Innovative technology for intercity passenger systems.* U.S. Dept. of Transp., Washington, D.C.

"ICE facts and aspects." (1992). *Verband der Deutschen Bahnindustrie e.V.* (VDB), Frankfurt, Germany.

"La Vie Du Rail." (1990). "French Super Train Album," Spec. Ed., Paris, France.

U.S. Department of Transportation (DOT). (1991). "Safety relevant observations on the X2000 tilting train." *Moving America: new direction, new opportunities,* Federal Railroad Admin., Washington, D.C.

Vranich, J. (1991). *Supertrains: solution to America's transportation gridlock.* St. Martin's Press, New York, N.Y.