Comparative Evaluation of Technologies for High-Speed Ground Transport

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ABSTRACT

A comparative assessment of two technologies for high-speed ground transport (HSGT) is presented in this paper. The two technologies are (a) a magnetic levitation technology that is based on the principle of magnetic attraction and uses an active long stator, and (b) a conventional wheel-on-rail technology. A description of each technology and the major conclusions of a detailed comparative study that was performed on a specific Canadian route (high-speed service between Montreal and Ottawa through Mirabel International Airport) are given. For each technology, a conceptual system design is outlined. Capital and operating cost estimates are presented and discussed. Key issues that resulted from an evaluation of physical and functional impacts are discussed; emphasis is placed on the problems associated with insertion of HSGT lines in urban and rural areas and on whether existing or new rights-of-way should be used.

In recent years, several comparative assessment studies were performed on various high-speed ground transport (HSGT) systems. These studies often compared conventional railway technology with magnetic levitation technology; the Paris-Frankfort and Los Angeles-Las Vegas studies are of this type.

These studies were often performed by private companies that were promoting a particular system; this tended to cast doubts on the objectivity of the studies. Moreover, even if their conclusions were often found in newspaper headlines, the analyses on which these conclusions were based were seldom made public. As a result, agencies responsible for planning or operating intercity passenger transport systems and services were not able to gather from these studies more than a minimum amount of data on the technical and financial parameters of HSGT systems, even though such data would have been very useful to them.

Partly to remedy this situation, the Advanced Technology Division of Transport Development Centre, Transport Canada, decided in 1981 to undertake a comparative technology assessment of HSGT systems. Because HSGT systems were not directly integrated into the Canadian intercity passenger transport planning process, this study was to compile and structure detailed data on HSGT systems for future use by appropriate agencies.

The specific objective of the study (1) was to compare, by reference to a specific Canadian application, two HSGT systems: (a) one that used magnetic principles and techniques for vehicle support, guidance, and propulsion; and (b) one that used conventional railway techniques and equipment. The goal of the study was to identify the key differences between these two technologies to evaluate their effects on level of service, capital and operating costs, and various physical, socioeconomic, and functional impacts. In the process, useful data were to be generated for use in planning at a later date.

METHODOLOGY

The location for the study was given: a high-speed service route between Ottawa and Montreal with at least one intermediate station at Mirabel International Airport (Figure 1). This route was chosen because it had the advantages of being well documented (2-5) and, at the time of the study, free of any planning controversy. A disadvantage of using this route was that the short length of the corridor (200 km) was less than the ideal length for implementation of an HSGT system.

FIGURE 1 Key topographical features of Ottawa-Mirabel-Montreal corridor.

Although it could limit the generalization of the conclusions, the use of a given corridor as a test bed for analysis has significant advantages. In particular, this approach facilitates the development of a well-adapted system design that takes into consideration physical as well as institutional constraints; it thus provides good indications of a technology's flexibility and responsiveness to given conditions.

The main steps in the study were the following:

1. Description of the two technologies;
2. Formulation of common service specifications;
3. Development of traffic forecasts;
4. Definition of preliminary system design, adapted to the route;
5. Estimation of capital and operating costs; and
6. Identification and evaluation of impacts of the two systems.

The purpose of defining a technology reference for each system was to establish from the outset the most significant technical parameters that characterize each technology; in other words, to identify precisely the items that were being compared--dimensions, speed, acceleration, technical principles, and so forth. Taken together, these parameters are the basis for each system's configuration and performance.

Common service specifications were developed to be used as a basis for system definition. The use of common service specifications eliminated from the comparison any advantage or preference factor that was not technology related.

A complete conceptual system design was then defined for each technology; the definition met (or exceeded) the service specifications. The definition covered all system components: general configuration, routing, fleet size, track or guideway layout, infrastructure, structures and bridges, power and control equipment, stations, and facilities and auxiliary equipment, as well as operation and maintenance procedures and personnel.

A detailed engineering estimate of capital and operating costs was developed for each system; the same assumptions and procedures were used for developing the estimates for both systems. A financial analysis was performed on each system to determine the revenue requirements necessary for profitable and solvent operation and the corresponding ticket cost.

Finally, major differences in impacts between the two systems were identified. Impacts that were considered included technical risks, energy impacts, socioeconomic impacts, and aesthetic and environmental impacts.

Each of these steps will be discussed in more detail in the following sections.

DESCRIPTION OF THE TWO TECHNOLOGIES

The two technologies compared are the magnetic levitation (attraction mode) and the conventional wheel-on-rail technology; these two HSGT systems will be referred to as "Maglev" and "Rail" (capitalized). Table 1 gives their major differences in fundamental technical principles.

Maglev System

For magnetic levitation, the technology reference that was used was the TransRapid system developed in the Federal Republic of Germany; the system is based on magnetic attraction principles and uses an active long stator.

The vehicle is made up of two identical sections that can be uncoupled for maintenance (see Figure 2). The basic bidirectional consist is 54 m long, 3.7 m wide, and 4.2 m high. It can be lengthened by adding up to four intermediate sections between the two end sections.

Levitation and guidance forces are provided by magnetic attraction between controlled electromagnets that are located in the bogies and equipment mounted on the guideway. Figure 3 shows a cross section of the Maglev vehicle.

Propulsion is provided by a synchronous linear motor; its long stator consists of two groups of steel laminations intertwined with cable windings and fixed to the guideway. After being energized with on-board batteries, the vehicle is magnetically attracted to a field wave that is traveling through the stator; there is no mechanical contact for power collection.

To maintain the stringent positional tolerances that are necessary for efficient operation of this levitation process the vehicle must be carried on a rigid structure. The usual design of the structure is a box girder made of prestressed concrete; the beam is normally 25 m long and 1.8 m deep. The guideway can be built at grade; in this case the beam will rest directly on appropriate foundations. For an elevated guideway, a pier may be added between beams and foundations.

The maximum operating speed is 400 km/hr. The guideway geometry is dictated by technical constraints and comfort requirements. By using a 12-degree superelevation and limiting lateral acceleration to 1.0 m/sec^2 for comfort, the minimum radius of horizontal curves is 4000 m at 400 km/hr and that of vertical curves is 25 000 m. The maximum gradient is 3.5 percent for long distances and 5 percent for short distances. In urban areas, where maximum speed cannot be reached because there are short distances between stations, speed is normally 200 km/hr; this reduces aerodynamic noise and permits greater flexibility in guideway routing.

Rail System

Several railway systems currently in operation can offer the performance specified in this study; there are thus many options from which a Rail technology can be selected. Except for the vehicle, most of these systems have several similarities; these common points were used to define the Rail technology option in this study.

Because consistent high-speed operation with diesel equipment would severely damage the track, the Rail technology will use electrified equipment.

TABLE 1 Major Technology Differences Between Rail System and Maglev System

Subsystem	Function	Maglev System	Rail System
Vehicle	Support	Magnetic control of horizontal air gap	Wheels, axles, and bogies on steel rails
	Suspension	Mechanical damping between car body and bogies and magnetic control of air gap between bogies and guideway	Pneumatic and mechanical damping at car-body-truck and truck-axle contacts
	Guidance	Magnetic control of vertical air gap between guideway edges and vehicle	Wheel tread shape and flange-rail contact
	Transmission of propulsion and braking forces	Contact-free magnetic attraction of vehicle by traveling field wave	Wheel-rail adhesion
	Traction motors	Synchronous linear	Direct current rotary
Guideway equipment	Support	Controlled electromagnets on steel or prestressed concrete beam resting on slabs or piles	Steel rail on ties and ballast
	Guidance	Magnetic attraction to guidance rails on beam edges	Steel rail
	Propulsion	Linear motor stator (active)	Wheel-rail contact (passive rail)
Power supply and distribution	Current type	4,000 to 6,000 V, 0 to 250 Hz	25,000 V, 60 Hz, 1Φ
	Distribution	Stator and circuit connections	Catenary

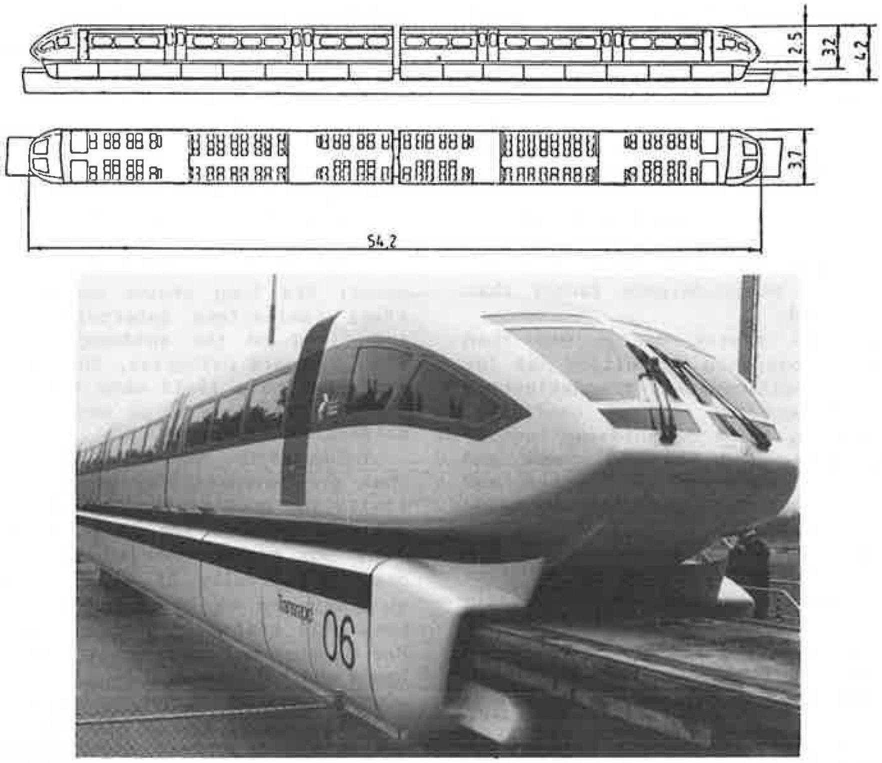

FIGURE 2 Maglev vehicle, main dimensions and general view.

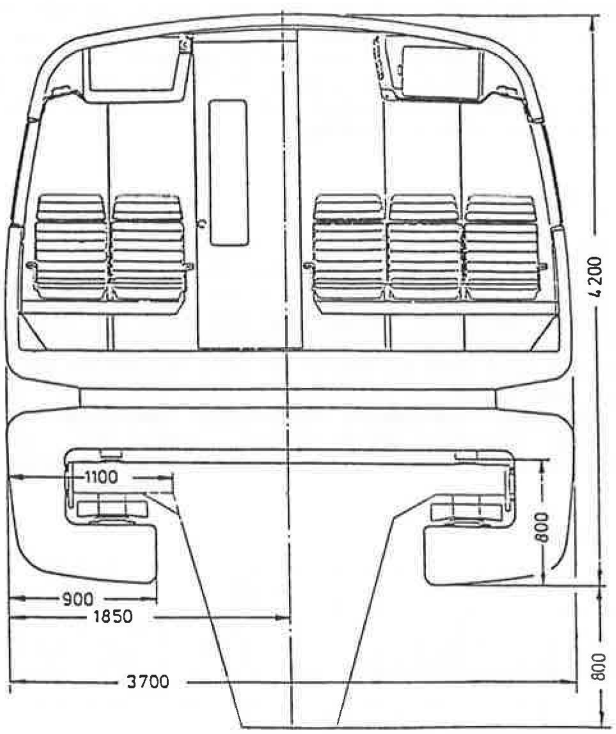

FIGURE 3 Cross section of Maglev vehicle on guideway.

Power received from the utility at 115 or 230 kV, 60 Hz will be transformed to 25 kV and fed to the train from an overhead catenary. The overhead wire will normally be suspended from a flexible structure, but catenary bridges will be used at locations where there are three or more tracks in the right-of-way.

Frequent high-speed operation implies the elimination of all grade crossings and operation on an exclusive double track. The track infrastructure will be designed to ensure that maintenance requirements are reasonable, despite the high speed and frequency of service. The quality of roadbed and thickness of ballast and subballast will be consistent with these requirements.

It was assumed that the vehicle would be engineered and built in Canada. The configuration would be a self-propelled, bidirectional consist, normally uncoupled only for maintenance. The car design could be similar to that of an LRC (light rapid comfortable) coach (an electric version of that train is envisioned). Each car would be 26 m long and 3.2 m wide.

The maximum operating speed was given as 200 km/hr, which is usually considered to be the lower limit for classification in the HSGT category. The track geometry is dictated by technical constraints and comfort requirements. With a maximum superelevation of 6 degrees and a lateral acceleration limited to 1.0 m/sec^2 to maintain passenger comfort, the minimum radius of horizontal curvature is 2400 m and that of vertical curvature is 20 000 m. The maximum gradient is 2.5 percent, given the assumed power ratio.

FORMULATION OF SERVICE SPECIFICATIONS

Service specifications were developed from an analysis of observed travel demand and modal split between Montreal and Ottawa. A target market was identified, its specific needs were evaluated, and the corresponding service strategy was developed. This strategy was translated into service specifications, which were then used as common performance guidelines in system definition for both technologies.

The Montreal-Ottawa intercity market currently

TABLE 2 Performance and Service Specifications

Subject Area	Parameter	Specification
Geographic coverage	Terminal location	Montreal: Central Station Ottawa: VIA Station
	Intermediate stations and their location	Mirabel: Under terminal building Ottawa: none Montreal: possibly a suburban station, easily accessible from West Island
Quality of service	Travel time	Terminal-to-terminal travel time not to exceed 75 min
	Operating schedule	15 hr/day, 7 days/week
	Frequency	1 departure/hr on average; higher frequency during peak periods
	Delays	No delays on line due to operational constraints
Safety	Collision protection	Automatic anticollision; automatic antioverspeed; automatic route protection; no grade crossings; emergency braking rate: 4 m/sec^2 (maximum)
	Train operation	Continuous speed control
	Train supervision	Automatic train location; two-way communication with central; centrally controlled public address system
Ride comfort	Lateral acceleration	1 m/sec^2 (maximum)
	Vertical acceleration	1 m/sec^2 (maximum)
	Jerk	0.5 m/sec^3 (maximum)
	Vibrations	International Standard Organisation reduced comfort boundary for 75-min trip

involves about 3.5 million trips per year (in both directions). The modal split is 1 percent air, 10 percent rail, 17 percent bus, and 72 percent automobile. The overall trip purpose split is 37 percent business and 63 percent pleasure. By mode, the trip purpose split is 90 percent business by air, 45 percent by rail, 31 percent by bus, and 35 percent by automobile.

The potential market for Montreal-Ottawa HSGT service was broken down into the following segments:

1. Intercity traffic: The new HSGT service would replace the existing rail service and also attract passengers from competing modes--air, bus, and automobile;
2. Airport traffic: This would consist of Mirabel air travelers who originate or terminate in Montreal or Ottawa (who are now using a ground access mode or connecting air service), as well as air travelers who connect between Dorval and Mirabel;
3. Induced traffic: Some persons would use HSGT for a trip they would not have made if HSGT service did not exist;
4. Through traffic: Some travelers would use HSGT on a leg of a longer trip in the Quebec-Windsor corridor (e.g., from Montreal to Toronto through Ottawa); and
5. Commuter traffic: Residents of the Montreal region would use the HSGT service for commuting (Mirabel is within commuting distance of the Montreal central business district).

Among these segments, intercity traffic was clearly the target market and the service strategy was developed in view of this market's needs. The resulting service specifications are given in Table 2.

DEVELOPMENT OF TRAVEL FORECASTS

Traffic forecasts for the Maglev system and for the Rail system were prepared separately for the intercity, airport-access, and induced-demand segments. The forecasts were prepared based on data from an intercity travel demand model developed by the Canadian Ministry of Transport, which uses it for strategic corridor planning. This multimode model is calibrated annually by using traffic data; it is a proprietary model. Through traffic and commuter traffic were ignored. Figure 4 shows the predicted evolution of total traffic with time for both systems.

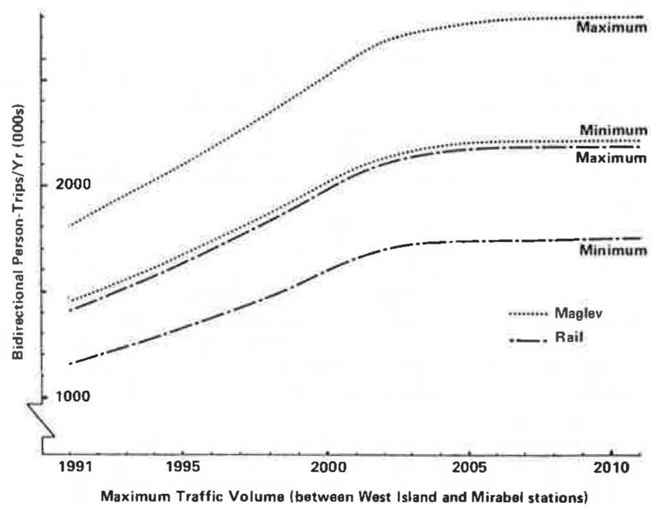

FIGURE 4 Forecasts of total future levels of traffic for Maglev system and Rail system.

DEFINITION OF SYSTEM DESIGN

Based on the service specifications and traffic forecasts, a conceptual system design was developed for each technology. This hypothetical system was adapted to the physical and functional requirements of the Montreal-Mirabel-Ottawa route. It was assumed that revenue service would be initiated in 1991.

The object of system definition was to identify, enumerate, and dimension, at least summarily, all subsystems and equipment necessary for operating the service as specified. The conceptual design thus developed served as a basis for estimating construction costs as well as operating and maintenance costs, and for evaluating impacts.

System definition was initiated by investigating the various implementation possibilities for each system. This led to route selection and evaluation of right-of-way requirements, type of use (shared or exclusive) and ownership (lease or acquisition), and track or guideway layout (single or double).

The next step was to define the track or guideway; this included its mechanical design (dictated by technology); its implementation (in tunnel, at grade, or on a structure); and the conceptual design of the infrastructure used to transmit vehicle loads to the ground, as well as that of the structures required to overcome various obstacles found on the route. The next step was to evaluate fleet size (the vehicle design having been dictated by technology) and the requirements for fixed mechanical, electrical, and electronic equipment for propulsion, braking, and control.

The system-definition task was completed by preparing schematic designs for stations, yards, and maintenance facilities and equipment (fixed and mobile). Then, operating and maintenance procedures were developed to serve as a basis for determining staff requirements for evaluating operating costs.

System definition was probably the most fundamental part of the study because it helped identify real (as opposed to assumed) differences between the two technologies; it thus served as an objective and realistic basis for cost estimation.

Two major differences between the two technologies were also analyzed during this phase; they are discussed below.

Infrastructure

There is a significant difference between the two technologies in their infrastructure design. This difference has major impacts on route selection, as well as on the infrastructure construction costs. This difference is related to technology and the means used to transmit dynamic vehicle loads to the ground.

In the Rail technology, vehicle loads are concentrated at the axles. These axle loads are supported by the rails and transmitted by the ties, which distribute them to the ballast; the ballast then spreads the axle loads over the roadbed. The wheel-rail-tie-ballast subsystem constitutes a flexible structure, which deforms slightly when distributing concentrated vehicle loads at the time of train passage.

In the Maglev technology, vehicle loads are applied along four bogies in each car-body section. These distributed loads are transmitted to the guideway beam through a magnetically controlled air gap. The guideway beam concentrates these loads at its ends and transmits them to foundation elements, which distribute them to the ground at a reduced pressure.

The fundamental difference between the two technologies is in the structural flexibility of the infrastructure. The railway track can, without compromising safety, deform slightly when a train passes. In contrast, for the Maglev technology analyzed, the magnetic guideway beam must remain rigid to prevent excessive variations in the thickness of the air gap because such variations would reduce the efficiency of the magnetic levitation. Moreover, this difference in principles directly influences construction cost, as will be seen in the next section.

The difference in construction costs will influence the guideway configuration. For a Maglev system, the construction cost of an elevated guideway is only 10 percent greater than that of a guideway at grade because the only difference between the two types of guideways is the introduction of a 5-m pier between the beam and the foundation (in addition to some minor foundation strengthening). Thus, it can be less expensive to build an elevated Maglev guideway than to build a guideway at grade at locations where there are grade separation structures at cross streets and roads; in urban areas it often is less expensive. A railway track could also be built on an elevated structure, but the additional construction cost would be high; therefore this type of configuration is rarely built.

In this analysis, the following configurations were adopted in the designing of the infrastructure. The Rail system will be built at grade along most of the route, except for 6 km that will be in tunnels. The Maglev guideway will be built mainly as an elevated guideway. Near Ottawa, it will be at grade in a lightly used Railway right-of-way. Near the Montreal CBD, the guideway will be supported by a structure built over existing railway tracks. The key features of the route, right-of-way, and infrastructure configuration as defined for the systems envisioned in this study are given in Table 3.

Power Supply and Distribution

This is the second major difference between the two technologies. Because of its influence on capital and operating costs, some discussion is warranted.

In the Rail technology, the vehicle is assumed to be powered by single-phase 25 kV alternative current. Power is received from the utility at 115 to 230 kV at three wayside substations, where it is transformed and sent over the track in an overhead catenary. This type of system is well-known and relatively simple. In the Maglev technology, the magnetic attraction process used by the German TransRapid system requires current at variable frequency (0 to 250 Hz) and variable voltage (0 to 6 kV). Each Maglev wayside substation performs complex transformation and rectification operations and is, as a result, more expensive than the corresponding Rail substation.

In the Rail technology, power collection is done through friction between the vehicle-mounted pantograph and the overhead catenary. Power is conditioned on board and then transmitted through rotary traction motors to the wheels that propel the vehicle by friction on the rails. In the Maglev technology, there is no mechanical contact during power collec-

TABLE 3 General Features of Route, Right-of-Way, and Guideway-Track Configuration

Subsystem	Feature	Maglev System	Rail System
Route	Length (km)	189.5	190.7
	Proportion on existing right-of-way (%)	14.6	59.8
	Proportion on new right-of-way (%)	85.4	40.2
Right-of-way (as a proportion of route length)	Area (ha)	493.5	410.4
	Proportion rented for shared pathway (%)	0.0	2.8
	Proportion rented for exclusive pathway (%)	14.6	57.0
	Proportion acquired (%)	85.4	40.2
Guideway-track configuration (as a proportion of route length)	Tunnel (%)	0.0	3.4
	Depressed (%)	0.6	0.0
	At grade (%)	5.8	96.6
	Elevated (%)	93.6	0.0

tion. The vehicle is magnetically attracted to a field wave that travels along the active long stator; propulsion itself is friction-free. To achieve this efficiently, the Maglev guideway is subdivided into sections 400 m long, which are fed consecutively. This subdivision implies complex circuit connections and switching operations.

As a result of its increased complexity and its greater power demand (for 400 km/hr instead of 200 km/hr), the Maglev system requires 10 wayside substations whereas the Rail system, at the assumed level of speed and traffic, requires only 3. Significant efforts will be devoted to development of the Maglev power supply and distribution subsystems in the next several years to reduce their complexity. Work has started and interesting new solutions are already being investigated.

COST ESTIMATION AND FINANCIAL ANALYSIS

Construction Costs

Table 4 gives comparative estimates of construction costs for the Maglev system and the Rail system. In conformity with the objective of the study, relative costs are presented with the total construction cost for the Rail system as the base. Significant differences between the estimated construction costs for both systems are discussed in the following paragraphs.

TABLE 4 Comparative Construction Costs for Maglev System and Rail System

Item	Capital Costs (relative to Rail costs)		
	Maglev System	Rail System	Cost Ratio (Maglev/Rail)
Vehicles	18	15	1.18
Infrastructure			
Land acquisition	2	1	4.69
Site preparation	3	9	0.30
Foundations	29	13	2.14
Piers	11		–
Guideway beams and bearings	61		–
Grade separations	2	6	–
Special structures	8	7	0.94
River and stream crossings	1	12	0.09
Guidance rails-track	18	18	0.96
Turnouts	5	2	2.10
Subtotal	140	68	2.04
Power and control			
Power supply	27	1	51.06
Power distribution	33	6	5.42
Signalling	16	6	2.66
Communications	1	1	1.00
Subtotal	77	14	5.53
Facilities			
Stations	1	1	2.29
Maintenance building	1	1	1.00
Maintenance equipment	1	1	1.00
Subtotal	3	3	1.30
Total construction cost	238	100	2.38

In Table 4, "Land acquisition" refers to the acquisition of land and the relocation of buildings that are necessary for creation of a new right-of-way; it does not include the leasing of space from railways. Because Maglev is on a new right-of-way for a larger proportion of the route (85.4 percent versus 40.2 percent for Rail), the cost of land acquisition is more important for the Maglev technology.

In the Maglev technology, "Site preparation" consists only of clearing the right-of-way and building an access road. Grading to the route geometry is not needed because the height of guideway piers can be varied with the terrain. Site preparation is more expensive in the Rail technology because it requires preparation of a roadbed to tight geometric and compaction standards to support the track foundation structure.

In the Rail technology, the item "Foundations" corresponds to laying the track foundation layer, subballast, and ballast; this can be done with a high degree of mechanization. Foundations for the Maglev system consist of a large number of discrete elements (slabs or pile caps); these must be individually built in place and are less adaptable to mechanized construction methods. This explains the cost differential between the two technologies.

Use of piers in the Maglev system is mainly a result of the decision to use an elevated guideway; piers are not a technology requirement. Although not strictly comparable, grade separations in the Rail system are perhaps the closest equivalent to the piers in the Maglev system.

Maglev guideway beams and bearings, for which there is no direct equivalent in the Rail system, are clearly a requirement that results from the use of magnetic attraction technology; they are needed to ensure the stringent positional tolerances that are required for the air gap.

Use of special structures is route-related. For the Rail system, the main special structure is a tunnel in Mirabel. For the Maglev system, special structures include rigid frames used to carry the guideway beams over railway tracks (approximately 14.6 percent of the route by length). Conventional bridges and culverts are used to cross rivers and streams in the Rail system. For the Maglev system, because the cost of the elevated guideway has already been accounted for, Table 4 shows only the additional cost incurred for use of longer guideway beams and higher piers where required.

Rail track and Maglev guidance rails have essentially the same guidance function. Railway tracks also have a support function, a function that is filled by guideway beams in the Maglev system. There is not a large difference between these costs.

For both systems, power is supplied to vehicle consists through substations. In the Maglev system, substations are more complex because of the need to supply power to the active stator with variable frequency and voltage, as explained in the previous section, Power Supply and Distribution. The substations are also more numerous; 10 are needed for the Maglev system as opposed to 3 for the Rail system.

There is also a large difference in power distribution costs. This is due to two factors: (a) the relatively low power factor of the linear motor, which requires a large number of circuit connections, and (b) the high level of technology of the active long stator. In contrast, the Rail power system is more tolerant of voltage variations, and the catenary design and production methods are more industrialized.

Operating Costs

There are five major components of operating costs: operating salaries and material costs, maintenance labor and supply costs, power supply and energy consumption charges, land and building rentals, and administration. The estimated values of each component for both systems in 1991 are given in Table 5.

On start-up, Maglev operating costs are lower than those of Rail; this is mainly due to the higher productivity of train crews, which results from the higher speed of the trains in this system. Over

TABLE 5 Comparative Annual Costs in 1991

Component	Annaul Cost (relative to Rail costs)		Rationale for Difference
	Maglev	Rail	
Operation			
Train crews	13.5	22.7	Shorter Maglev turnaround
Stations	20.9	17.7	Greater Maglev traffic
Reservations	3.4	2.7	Greater Maglev traffic
System	3.3	3.9	Shorter Maglev turnaround
Subtotal	41.1	47.0	
Maintenance			
Vehicles	14.6	17.5	Fewer Maglev vehicles
Infrastructure	14.4	7.5	More elaborate for Maglev
Power and control	29.2	3.5	More complex for Maglev
Facilities	0.8	5.3	Rail includes more items
Subtotal	59.0	33.8	
Energy	28.4	4.3	Greater Maglev speed; higher fixed monthly charges for installed power
Rentals	21.9	8.4	Maglev uses full right-of-way width over railways
Administration			
On operation (8%)	3.3	3.8	NA[a]
On labor (8%)	4.7	2.7	
Subtotal	8.0	6.5	
Total	158.4	100.0	

[a]NA = not applicable.

time, with an increase in the level of traffic, Maglev operating costs eventually become higher than those of Rail; this is related to Maglev's higher level of traffic.

The Maglev-to-Rail ratio of maintenance costs is similar to the ratio of their capital costs, and the relationship does not change noticeably over time. Care should be exerted when drawing conclusions about the difference in their maintenance costs; whereas Rail maintenance costs were estimated by comparing observed costs on similar systems, Maglev maintenance costs were derived analytically. This was done conservatively, using industry factors that relate maintenance costs to the life of components and their capital costs. In reality, Maglev maintenance costs could be significantly lower than the value shown, but this will not be known until some experience is gained in revenue service.

In 1991, the Maglev-to-Rail power-cost ratio will be 6.7; this ratio will increase slightly over time. This significant difference is related to speed and technology. It results mainly from the larger number of substations for Maglev (10 versus 3 for Rail); this implies significantly higher monthly fixed charges for installed power.

The Maglev-to-Rail ratio of leasing costs is 2.6; this appears to be in contradiction to Rail's much more extensive use of existing railway rights-of-way and requires some explanation. When implemented along a rail right-of-way, the Maglev guideway must be built over the tracks. This precludes any other use of the air rights above them, and therefore leasing costs must apply to the full width of the right-of-way. Rail, in comparison, uses only a 15 m strip at the edge of the right-of-way rather than its full width; controlled level crossing for occasional industrial access is possible. Furthermore, near downtown Montreal, leasing costs for space in the Mount Royal Tunnel (the most expensive segment of the route) are shared between the Rail system and commuter services.

Administrative costs are almost equal for both systems; they do not change over time.

As seen in Table 5, the Maglev-to-Rail ratio of annual costs is 1.58. Over time, this ratio would tend to increase slightly because of an increase in the level of traffic.

Ticket Cost

To establish whether the capital investment for an HSGT system can be recovered from the revenues generated, a ticket cost can be calculated that would produce revenues that allow full recovery of capital and operating expenditures, including applicable financial charges. This type of financial analysis is a better method for comparing systems with significant differences in traffic volume, such as in this case, by netting out the effects of that factor.

By using this method of analysis, the average ticket cost for Rail in 1991 would be $68.87 and the cost for Maglev would be $116.01, a ratio of 178 percent, favoring Rail. Currently, a comparable one-way ticket between Montreal and Ottawa costs $25.00 by rail and $80.00 by air (1983 Canadian dollars).

As capital recovery charges diminish over the years, reflecting asset depreciation, the average ticket cost also varies (even in real terms, i.e., netting out the effect of inflation). The Maglev-to-Rail ratio remains higher than 1, but the comparison is more difficult. This is why the annual values for the average ticket cost were condensed in a single value, the single-price average ticket cost, a price that would not vary (in real terms) during the 20-year analysis period. The single-price average ticket cost, calculated over 20 years, is $57.14 for Rail and $93.69 for Maglev, which is a ratio of 164 percent.

Sensitivity Analysis for Ticket Cost

The objective of the sensitivity analysis was to explore how much the basic conclusion of the financial analysis (i.e., that, over time, a Maglev ticket is 164 percent more expensive than a Rail ticket) would be modified as a result of changes in the values of several underlying system and financial parameters.

The first parameter that was tested was traffic volume. As expected with any capital-intensive project, the unit ticket cost declined with an increase in passenger volume. For example, doubling the ridership resulted in the following reductions in unit ticket costs: 39 percent for Rail and 40 percent for Maglev. The elasticity of both systems in this regard was the same, that is, similar passenger volume increases (in percent) produced similar ticket cost reductions (in percent). Inflation also had the same effect on both systems and, whether changes in the general price level or differential cost escalation for specific components were considered, the ticket cost ratio remained approximately 165 percent. This was because both systems had a similar cost structure.

Sensitivity analyses were performed on other parameters and no significant change in the above conclusions was observed. If, however, some technological development allowed a significant reduction in the capital cost of the Maglev power supply and distribution subsystem, the Maglev-to-Rail ratio of ticket cost would decrease below 165 percent, a difference that would probably be noticeable. A reduction in the Maglev maintenance costs would have the same effect.

Another cost difference factor that should be analyzed in detail is the difference in maximum speed of the two systems. The difference between 200 km/hr and 400 km/hr introduces cost differentials that are not technology related. A significant change in maximum speeds can not be investigated through sensitivity analysis techniques, however, because it would imply partial system redefinition. This was unfortunately beyond the scope of the study, but it constitutes an interesting subject for further research.

System Optimization

To this point, this analysis has been conducted on two basic systems: the basic Maglev system, which was assumed to be built with a double guideway, and the basic Rail system, which was assumed to have a double track. This was a reasonable approach for undertaking system definition and cost estimation because when a new HSGT system is built in Canada, it will probably be built from Montreal to Toronto through Ottawa, and this will require either a double track or guideway, if the system is to offer the required capacity.

When matching costs and revenues in this evaluation of ticket cost, however, it is more logical to consider only the costs that are incurred in providing the service that generates the revenues under consideration. That is, if the passenger demand between Ottawa and Montreal does not justify the building of a double track or guideway, then a less costly system should be considered. In reality, the necessary capacity can be obtained with predominantly single-track systems. This is why system optimization was undertaken.

An optimized Rail system would require only 297 km of single track instead of 418 km in the base case; two passing sections of 20 km must be provided and the track would be double on Montreal Island. The cost of subballast, ballast, track materials and construction, catenary, and wayside signaling equipment would be reduced in proportion to track length. Right-of-way acquisition, roadbed preparation, and structure and station construction costs would be the same as for a double-track system because these facilities would be built initially according to their ultimate design specifications. The capital cost of a single-track Rail system would be 16.5 percent less than that of the basic double-track system.

An optimized Maglev system would require only 224 km of equivalent single guideway instead of 379 km in the base case; one passing section of 25 km must be provided as well as two double sections of 5 km near terminals. The cost of guideway beams and bearings, guideway foundations and piers (except over railways), stator, guidance rails, circuit connections, and information system would be reduced accordingly. Right-of-way acquisition, site preparation, bridge foundations and piers, and station construction costs would be the same as for the double-guideway system. The capital cost of a single-guideway Maglev system would thus be 32.9 percent less than that of the basic double-guideway system.

Operating costs will not change after optimization, except for infrastructure maintenance. As a result of optimization, the Maglev-to-Rail ratio of single-price ticket cost would be 135 percent instead of 164 percent. This reflects the significant relative importance of the guideway and its equipment on the Maglev construction costs; it is related to technology.

IDENTIFICATION AND EVALUATION OF IMPACTS OF THE TWO SYSTEMS

For evaluation purposes, impacts resulting from the implementation or operation of an HSGT system may be grouped as follows:

1. Technical risks;
2. Energy impacts related to speed and technology;
3. Socioeconomic impacts; and
4. Aesthetic and environmental impacts related to the presence of the system and emphasized by the intensiveness of its operation.

Each of these impacts will be discussed in more detail in the following paragraphs.

Technical risks must be considered because they could delay the system from commissioning or reduce its availability. These risks will be greater for Maglev, which has not yet been placed in revenue service. Two aspects of these risks should be considered: (a) possible technical modifications to the system as a revenue service version is being developed from the prototype (this would tend to reduce costs), and (b) technology adaptation to Canadian climatic conditions (this is also a problem for the Rail technology).

Three components of energy impacts should be noted: (a) annual direct energy consumption for system operation (primarily vehicle propulsion), (b) once-over indirect energy consumption for system implementation, and (c) energy savings from modal shifts. Maglev has a higher direct energy consumption both due to its higher speed and technology. Maglev also has a significantly greater indirect energy consumption due to its higher construction cost. Finally, due to its higher speed, Maglev will attract more automobile drivers and passengers and reduce petroleum consumption. (Overall, however, energy consumption is probably not a highly significant factor in this case.)

Among socioeconomic factors, two impacts should be noted: the creation of temporary jobs for construction of the system and creation of permanent jobs for continued operation and maintenance of the system. Maglev will create approximately twice as many temporary jobs as will Rail; this corresponds roughly to the difference in construction costs, adjusted for technology and proportion manufactured in Canada. Maglev will create about 20 percent more permanent jobs, due in part to its higher maintenance costs. This difference would increase with an increase in the level of traffic and would be reduced if Maglev maintenance cost estimates were revised downward.

Two significant physical impacts are noise and visual intrusion. Traveling at low speed in urban areas, Rail will be noisier because of the friction in its running gear. Traveling at high speed in rural areas, Maglev will be noisier because of skin friction due to its greater aerodynamic drag. In both cases, the level of disturbance will probably not be significant.

Visual impacts are mainly due to the presence of the infrastructure. With its elevated guideway, Maglev would create a greater visual intrusion in urban areas and less disruption in rural areas. This is discussed in greater detail in the following two sections.

INSERTION OF HSGT RIGHTS-OF-WAY IN THE ENVIRONMENT

From the short impact analysis presented in the preceding section, it appears that most physical impacts (noise and visual intrusion) and some functional impacts (e.g., community disruption) are directly related to the presence of the right-of-way and the infrastructure used for operating HSGT systems. The presence of the facility consumes space that could be used for other purposes, and the movement of high-speed vehicles on it may be perceived as an additional source of danger.

In this study, the detailed analysis of Rail and Maglev routes on low-scale maps provided an opportunity to assess these effects in a variety of representative situations. The quality of the assessment was enhanced by the availability of data and previous studies, numerous site visits, and members of the study team having had substantial experience with the areas studied. The following observations were made during the route analyses.

These observations are presented below as answers to the following questions: Can it be done? How? What will the impacts be? First, the possibility of using existing rights-of-way is analyzed and, second, problems associated with the creation of new rights-of-way are considered. Inferences drawn from these observations are presented separately for urban and rural areas.

Use of Existing Rights-of-Way

The use of existing railway rights-of-way for operating HSGT services appears to be a potential solution. In the study area, there are numerous railway rights-of-way, and most are presently underutilized. Thirty meters in width, they typically carry only one track even though there is room for five or perhaps six tracks.

For the Rail technology, use of existing railways presents no major technical or operational problem. An exclusive double track for a high-speed train would typically be placed on the edge of the right-of-way, on the side with the fewest industrial spurs (these could still be accessed occasionally across high-speed tracks with proper protection). If there is no room for two more tracks, the high-speed operation could (with possibly some degradation in level of service) share tracks with conventional railway services for a short distance; adequate signal interlocking would ensure the safety of the joint operation.

In an urban area, the insertion of two additional tracks in an existing railway right-of-way would attract little attention. The situation could be different in a rural area, however; it would be different in the area between Montreal and Ottawa. In that corridor existing rail lines cut across numerous farm properties. With today's almost nonexistent rail traffic, farm operations are conducted as if there were no track. Frequent operation of high-speed trains would change farm operation dramatically. The right-of-way could have to be fenced to preclude uncontrolled crossing by farmers, their animals, and their machinery. The impact of this intrusion would be significant, and corrective measures (which would probably be expensive) would have to be taken to mitigate the impacts. These measures have been analyzed in some detail, but no solution has been found that was simple, inexpensive, and satisfactory.

Inserting a Maglev guideway on an existing railway is more difficult. Placing a double guideway at grade on the edge of the right-of-way would require an area of approximately 15 m, which would consume half of the available width. In some cases, the remaining width could be sufficient for accommodating existing traffic and serve railside industries; access to one side of the right-of-way would be practically impossible.

A different solution was considered in this study: the construction of an elevated guideway above existing tracks. The guideway beams would be supported on a rigid frame designed to provide a 12- to 18-m wide clearance for railway operations. The construction of an elevated guideway creates significant visual (and possibly noise) intrusion; its construction above railway tracks may alleviate the problem because the rail line often crosses industrial rather than residential neighborhoods.

Use of existing expressway rights-of-way was also investigated. This appears to be a good solution considering both its physical impacts and disruption effects. Many North American expressways are built with a large median, which would accommodate a Rail system or a Maglev system.

However, this potentially attractive solution is not easy to implement. Even on expressways that have space available in the median, most, if not all, structures that cross the median would have to be rebuilt. Drainage would have to be reorganized, as would snow removal processes, because medians are used to accumulate snow. In rural areas, this approach is probably feasible. In urban areas, however, the median is often too narrow. Access to and egress from the expressway would probably require major structural work. In this case, then, costs, rather than impacts, dominate the discussion. In the study, no expressways were found that had an appropriate alignment for building an HSGT system in the median.

Creation of New Rights-of-Way

The creation of a new right-of-way in an urban area today is only a last-resort solution because of associated high costs and negative impacts. It was not found necessary to resort to that solution in the study. If it were found to be necessary the guideway would probably have to be built underground. In this case, Maglev would be at a cost disadvantage because of the broader tunnel gauge that is required for the vehicle analyzed.

The creation of a new right-of-way in a rural area encounters fewer problems. Land acquisition costs are low and, due to low intensity of land-use, physical impacts are not a major issue. Disruption effects must be considered, however. In this case, Maglev has an advantage in routing flexibility because an elevated Maglev guideway does not create a physical barrier that would disrupt communities or interfere with human activities such as farming.

In summary, the insertion of HSGT guideways is likely to create unfavorable environmental impacts. These will be smallest when implementing an exclusive double track in an existing railway right-of-way in an urban area. In a rural area, depending on intensity of land use, that solution may lose much of its appeal because of the disruptive effect of the barrier created by the fence around the right-of-way. Maglev guideways at grade could be implemented in existing railways only under certain conditions, but they could be built on a structure over existing tracks.

In general, the creation of new rights-of-way in a dense urban area is likely to require underground construction; in this case the Rail system would have a cost advantage because of its smaller tunnel cross section. The creation of a new right-of-way in a rural area might be made more acceptable by using an elevated construction that would have reduced disruptive effects; in this case, the Maglev infrastructure would have an advantage.

SUMMARY AND CONCLUSIONS

The objective of this study was to establish the major differences in costs and impacts that result from the technological differences between two high-speed guided ground transport systems by using two types of technologies for vehicle support, guidance, and propulsion: magnetic attraction and conventional wheel-on-rail contact.

The comparison was made between two HSGT systems: the TransRapid long-stator magnetic-levitation system that was developed in the Federal Republic of Germany, which has a maximum operating speed of 400 km/hr; and a Rail system that uses bidirectional consists powered at 25 kV alternating current, which has a maximum operating speed of 200 km/hr.

To realistically compare the two technologies, conceptual designs for both systems were prepared by using a well-documented route: high-speed service between Montreal and Ottawa (an airline distance of approximately 200 km) with two intermediate stops. Both systems were designed for the same market on the basis of identical service specifications. Predicted differences in estimated ridership thus resulted primarily from the travel time differential, which was due to the difference in maximum operating speeds.

A detailed estimation of construction costs showed that those of a Maglev system would be approximately 2.38 times those of a Rail system. The ratio results primarily from analysis of two technological characteristics of the Maglev system: the rigid structure that is needed to maintain the appropriate air gap for efficient operation of the magnetic attraction process, and the complex power conversion apparatus that is used to supply the active long stator with current at variable frequency and voltage.

A detailed estimation of operating, maintenance, and other recurring costs was also performed. The Maglev-to-Rail ratio of costs was approximately 1.58. Over time, as the level of traffic increases, the ratio will tend to increase slightly.

Ticket cost was estimated by considering the estimated capital and operating costs and the revenues necessary to render each operation profitable and solvent. Calculated over a period of 20 years, a one-way ticket between Montreal and Ottawa would cost on average $57 for Rail and $94 for Maglev (1983 Canadian dollars). A comparable ticket currently costs $25 by rail and $80 by air.

A detailed sensitivity analysis was performed on these results by using the economic indicators that are usually susceptible to variations. The above conclusions were not found to vary significantly under any reasonable set of assumptions.

Changes in capital and operating costs, however, could alter the difference between ticket costs for the Maglev system and the Rail system. The occurrence of such changes is probable in two specific cases for the Maglev system:

1. Development of a less complex power supply and distribution system (this work is already in progress); and
2. Actual experience with system maintenance. (Due to lack of experience, a conservative approach was used in the study, and this may have led to an overestimation of the Maglev maintenance costs.)

Concerning impacts, the comparative evaluation identified significant differences between the two systems on several aspects; these are discussed below.

The first difference is the technical maturity of both systems. Whereas railways have been operated for more than 100 years, Maglev systems have been in development for less than 20 years. As a result, there are currently a greater number of risks associated with the decision to implement a Maglev system. Over time, with continued systematic testing and eventual revenue operation, Maglev will progressively bridge that gap.

The second difference between the two systems concerns the physical and functional impacts associated with the presence of the right-of-way and the infrastructure, and the resulting flexibility (or lack of it) that a system has if those impacts are to be maintained at an acceptable level.

In dense urban areas, if a new right-of-way must be created, it will probably be built underground; in this case the Maglev system will incur higher costs because its vehicle is wider. If existing railway rights-of-way are to be used, a Rail system would be easier to insert in them; existing expressways are not likely to provide suitable lodging for an HSGT guideway in an urban area.

In rural areas, creation of a new right-of-way encounters fewer problems. The most economical solution is to insert the HSGT at grade in an existing railway right-of-way or in the median of an existing expressway. For a railway, however, the need to protect the HSGT with fences will disrupt rural activities to an extent that could be intolerable. An elevated guideway would then be a logical choice; in that case, the additional cost of raising the guideway would be much lower if a Maglev were used than if a Rail technology were used.

RECOMMENDATIONS

The major conclusions that were drawn from a comparative assessment of two HSGT technologies, Maglev and Rail, have been presented in this paper. Significant differences in capital and operating costs were found; these differences result in a Maglev ticket cost that is 135 to 164 percent of that of a Rail ticket. This difference was due mainly to the high capital cost of Maglev's complex wayside power conversion equipment and rigid guideway beams, and to high fixed charges for installed power. This conclusion should be interpreted in light of three significant characteristics of the study from which it was drawn.

First, the route that was used as the basis for this study is not the ideal one for the implementation of an HSGT system; the distance is too short (200 km) and the market potential is too low. As a result, capital costs may appear high in relation to the level of traffic, which results in relatively high ticket costs. This tends to raise doubts about the feasibility of implementing an HSGT system in that corridor. This was known before the study was begun; however, feasibility of implementing the system was not the primary concern of the study. The choice of a short distance over which to implement the system tends to bias the comparison in favor of the Rail technology. For a longer distance the ratio of capital costs would be about the same, but because of the higher speed and greater travel time savings of Maglev, its competitive advantage and greater attractiveness to potential riders would be enhanced. The Maglev-to-Rail ratio of ticket cost would decrease. A future comparative assessment similar to this one should be based on an application that has a minimum terminal-to-terminal distance of 300 to 400 km.

Second, the difference between the speeds of the two systems is large; the speed of one system is twice the maximum speed of the other. These speeds were specified at the outset. The result is that the comparison of the two systems measures two types of effects: those due to speed and those due only to technology. A reduction in the speed gap would not only lower all cost ratios, but moreover would allow the measurement of the effect of technology alone. A future comparative assessment similar to this one should consider systems that have a difference in maximum operating speeds that is less than 100 km/hr; ideally, the difference should be less than 50 km/hr.

Third, it is difficult to make a comparison between a mature system and a new system. The speed with which the developing system will reach maturity is a matter of speculation, and assumptions may range from severely pessimistic estimates to overly optimistic estimates. In this case, a somewhat conservative approach was used for evaluating costs of the Maglev system. Three examples of this conservatism should be noted: (a) the Maglev guideway was assumed to be built by using conventional construction techniques, whereas new methods would probably be developed, which would lower the costs of this system; (b) the cost of the Maglev propulsion system was based on that of the prototype; and (c) maintenance costs for Maglev were estimated by comparing observed costs on similar existing systems, whereas efficient techniques that are specific to the Maglev system would be developed. (The scope of the study did not allow sufficient analysis of how these developments could reduce the costs of the Maglev system.) Similar cost reductions could also be possible for Rail. A similar comparative assessment should include a careful analysis of expected developments in construction and manufacturing methods as well as in operating and maintenance procedures to assess their effects on capital and operating costs.

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